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Original Article

Superficial stabilization of volcanic-ash derived soils with cement on road infrastructure slopes

Estabilización superficial de suelos derivados de cenizas volcánicas con cemento en taludes de infraestructura vial

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Abstract

Introduction: this project proposes an alternative solution to mitigate unfavorable behaviors typical of volcanic ash-derived soils (VADS), especially in slope configurations. These soils often present stability challenges, limiting their use in engineering projects. The aim is to provide a solution that allows for the stabilization of such soils in areas where they are needed for infrastructure projects.
Objetive: the goal of this study was to evaluate the effectiveness of VADS-cement mixtures as a solution to improve the strength and stability of these soils, particularly under extreme weathering conditions, such as those occurring in slopes.
Methodology: laboratory tests were conducted using VADS samples mixed with cement in various proportions. These samples were subjected to cycles simulating the action of weathering to assess their behavior under extreme conditions. The tests included unconfined compressive strength and mass loss analysis due to immersion and drying cycles, simulating the effects of wear over time
Results: the results showed a significant increase in the strength of VADS treated with cement, with an increase of up to 400% in unconfined compressive strength when using 12-15% cement. Additionally, the samples showed good performance under weathering conditions, especially those with 15% cement, which exhibited an acceptable mass loss after the immersion and drying cycles.
Conclusions: treating VADS with cement in proportions ranging from 13% to 15% significantly improves the physical properties of the soils, enhancing their strength and durability. This improvement makes it feasible to use these soils in the construction of infrastructure, particularly in slope stabilization, offering an effective alternative for projects in areas with volcanic ash-derived soils.

Keywords: Portland cement, Volcanic ash, Stabilization, Strength, Slope.

Resumen

Introducción: el presente proyecto aborda una alternativa para mitigar comportamientos desfavorables típicos de los suelos derivados de cenizas volcánicas (SDCV), especialmente en su configuración como talud. Estos terrenos suelen presentar desafíos en su estabilidad, lo que limita su uso en proyectos de ingeniería. La propuesta busca generar una solución que permita estabilizar estos suelos en zonas que requieran su utilización en proyectos de infraestructura.
Objectivo: el objetivo del estudio fue evaluar la efectividad de las mezclas de SDCV con cemento como una solución para mejorar la resistencia y la estabilidad de estos suelos, especialmente en condiciones de intemperismo extremo, como podría ocurrir en taludes.
Metodología: se realizaron pruebas de laboratorio utilizando muestras de SDCV mezcladas con cemento en diferentes proporciones. Estas muestras fueron sometidas a ciclos que simulan la acción del intemperismo para evaluar su comportamiento en condiciones extremas. Los ensayos incluyeron pruebas de resistencia a la compresión no confinada y análisis de pérdida de masa debido a la inmersión y el secado, lo que permite simular los efectos del desgaste en el tiempo
Resultados: los resultados mostraron un aumento significativo en la resistencia de los SDCV tratados con cemento, con un incremento de hasta un 400% en la resistencia a la compresión no confinada cuando se utilizó un 12-15% de cemento. Además, las muestras demostraron un buen comportamiento ante el intemperismo, especialmente aquellas con un 15% de cemento, que presentaron una pérdida de masa aceptable tras los ciclos de inmersión y secado
Conclusiones: el tratamiento de SDCV con cemento en proporciones de entre 13% y 15% mejora notablemente las propiedades físicas de los suelos, aumentando su resistencia y durabilidad. Este mejoramiento hace viable el uso de estos suelos en la construcción de infraestructuras viales, particularmente en la estabilización de taludes, ofreciendo una alternativa efectiva para proyectos en zonas con suelos derivados

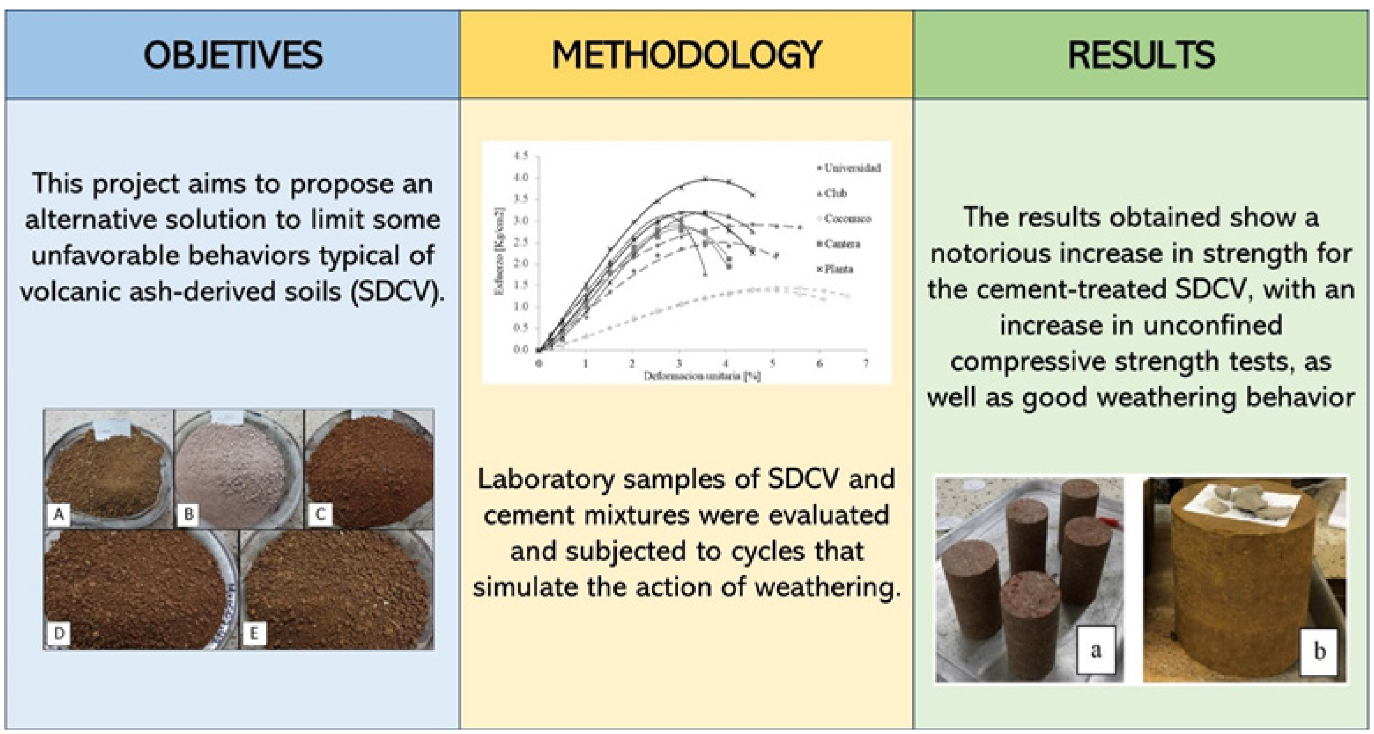
Palabras clave: cemento portland, Cenizas volcánicas, Estabilización, Resistencia, Talud.

Contribution to the literature

Why was it done?
The research offer an alternative solution to reduce some unfavorable behaviors from volcanic-ash derived soils (SDCV), mainly in slope configuration to generate the possibility of soil stabilization in areas where engineering projects might require it, specially in the Colombian andean region, where infraestructure is on volcanic-ash derived soils.

What were the most relevant results?
The improvement of SDCV modified with cement (in percentages between 13% and 15%) marks a notorious difference between a before and after in aspects such as increased resistance and a positive change in physical characteristics such as durability.

What do these provide results?
This demonstrates a feasible option that can be used in road infrastructure works, soil stabilization and mainly in soil slopes.



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Introduction

Around the world, soils derived from volcanic ashes or Andisols (1)(2) are exclusively distributed in regions where active or recently extinct volcanos are located. Such deposits fill approximately 0,84% of the planet surface (3). That value may increment considering the worldwide volcanic activity, as an example, the volcanic eruption of 2021 in Tajogaite (Spain), with and estimated ash deposit of 200 million m^3 (4).

Most of volcanic ashes are originated from pyroclastic and/or epiclastic volcanos. Pyroclastic (2) includes the deposited materials out form dense currents, which are ballistic bombs close to the source and widely spread by the ramifications. On the other hand, epiclastic are those volcaniclastic materials that had been removed and restock over the landscape after emplacement, among them: volcanic debris from avalanche, volcanic debris flow, flood on the volcano flank and tephra spread by winds. Most volcanic soil, floods had their origins in tephra, which is the most spread volcanic product (5).

Volcanic ash structure is function to the moist content and controls its geomechanics behavior, which are part of allophonic materials (2), a special group of alluvium of volcanic origin (6). Andisols are classified in two types: Allophonic, on environments with a precipitation less than 1000 mm/yr; and non-allophonic on places with precipitation over 1000 mm/yr. (7).

Volcanic ashes contribute on clay minerals formation whose presence is almost exclusive in that type of ground. The properties, structure and morphology of such minerals stablish the rates of soil properties and the way they interact with other particles, air or liquids (8).

The amount of water on SDCV is greatly controlled by its permeability (k) and it would be the water dynamic one of the main mechanisms in charge of determine its mechanical properties for this type of soil (9). SDCV, overall presents permeability values higher when comparing to others soils, due to the micro-structural characteristics of the clay particles and open structure.

Grounds with open structure are typical to have cementation bonds (10), which is defined as a system that links the soil particles forming aggregates (8) and is a consequence of precipitation and crystallization of a certain compound (11). However, such cement bindings are susceptible to disintegration because of the load and humidifying process, which finally brings the ground matrix to collapse, phenomena known as de-cementation (10).

Ground stabilization has become a viable option to improve ground properties and its resilience on different mechanical loads or environmental conditions (12). Among the different stabilization techniques is the cement-soil one, which consists of adding a determined percentage of cement to the soil with the purpose to improve its physical and mechanical properties. Cement is closely mixed with the soil producing a compact structure (13) resulting in a dense material in which the cement will favor the mechanical resistance making it more stable to weathering and environmental conditions that might be exposed to (13).

The cement-base establishers work well independently of the type of soil, minerals and cure conditions. Overall, the increment of the cement amount cement-soil mixture increases the non-

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confined resistance and the moisture optimal level (14,15). Additionally, stabilized ground using cement, offers economic efficiency and a low carbon footprint (16).

In recent years, some studies had determined the optimal rate of cement for ground stabilization with values around 5-7% for low cement percentage (17,18) and 10% when using stabilization, and 7% for nano-improvement (19) and 9% for lower values of resistance to non-confined compress – UCS (20). Also, international regulation, -Portland Cement Association (PCA)- mentions that for soils A-7-5, the optimal percentage is normally between 10% to 16% (21).

SDCV soils, in the Andean Colombian region, represent a 4.5 % (2) to 8.5 % (7) of the territory and are generally characterized by residual soils formed out from alteration and reaction between volcanic ashes and rock. When these types of soils are subjected to the intense cycles of wetness and sear, -typical of the tropical areas-, a change in the structure and effort state is produce due to the wide range of moisture, causing one of the greatest issues on road-geotechnology known as the slope instability, manifested as superficial, or instability by superficial flaking (22)

Frequent slopes caused by superficial flaking occur in Colombian roads, specifically in areas where ground is derived from volcanic-ash soils which correspond to an 11.6% of the Colombian territory (23). Re-stabilization of them implies a great economic investment and future maintenance work while construction and during service stage. Therefore, considering that the Andean Region is located in the middle of the country being the most populated and economically active (24), the idea of a research to discover the behavior of volcanic-ash soils originated in Popayan (Cauca), with the purpose of evaluating the effectiveness of mixtures to improve the knowledge regarding such material, as well as to look for alternatives to settle ground made of these types of soil.

Methodology

The procedure for present research started with the geolocation of 5 testing sites in the urban area of Popayan. Studies conducted by IGAC (25) and SGC (26) show the soils of the region and its distribution pattern in Cauca and within Popayan. This aspect represents great help to help define those places that might have SDCV. Being the matter of studying a superficial stabilization, samples were extracted out form eroded slopes no more than 10 meters of depth, allowing optimal depth to represent SDCV. Table 1 shows the geographic coordinates of high range of the places tested corresponding to the distance to the eroded slope (taken from the crown of the slope to the surface of the excavation), and the approximated depth.

Table 1. Samples location

Location	**Coordinates**		**Aproximated depth**
	North	West	
University	2°26’48.34”N	76°35’49.91”O	8.55m to 9m
Club	2°27’56.97”N	76°34’40.21”O	4m to 4.5m
Coconuco	2°26’51.13”N	76°35’12.65”O	2.5m to 3.5m
Quarry	2°26’45.38”N	76°35’17.16”O	4.5m to 5m
Power plant	2°25’54.28”N	76°37’14.92”O	8m to 10m

Afterwards, field work was carried following the technical specification as suggested by INVIAS 2013 (27), handbook regarding samples handling. Table 2.

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Table 2. Regulations guide for samples handling

Regulation	Activity
I.N.V.E-103	Soil samples conservation and transportation.
I.N.V.E-104	Soil samples of unaltered samples from superficial soil.
I.N.V.E-105	Soil samples through thin layer tubes.
I.N.V.E-148	CBR Of compacted soils in lab and over clean samples.

Three sampling sessions. First, two specimens of each location were taken using Shelby tubes (thin layered) for "unaltered samples" extraction to work on the simple compression trials (kPa), natural moist assessment (w%), permeability (k) and unit mass (kg/m^3) calculations.

For the second trial, 6 inches Proctor Standar cast were used, using mallet and cutting-ring and for the CBR (%) cylinder extraction form unaltered sample. Total of 2 blocks for each.

Finally, the altered sample was performed by using sacks. Such specimens would be used for trials like: Attenberg limits, specific gravity, granulometric, compaction, simple compression from reshaped sample, and cement stabilization.

Characterized trials of natural state samples and without stabilization

After setting the samples, relevant soil properties for the study were studied. Table 3 show a summary of such test trials in natural stage samples.

Table 3. Trials on original state samples

Trial	Norm	Number of trials by soil sample
Original sample moisture	I.N.V.E – 122	2
In-situ CBR trial	I.N.V.E – 169	2
In-situ CBR trial with immersion.	I.N.V.E – 169	2
N-state unconfined compression trial	I.N.V.E – 152	3-5
Permeability trial	I.N.V.E – 151	2
Determination of consistency limits.	I.N.V.E – 126 I.N.V.E – 127 I.N.V.E – 125	2
Determination of especific gravity	I.N.V.E – 128	1
Granulometry for 200 flow and 200 hold	I.N.V.E – 123 I.N.V.E – 106	1
Compactation trial	I.N.V.E – 141	1
Trial for simple compression to remodeled sample without cement	I.N.V.E – 152	2

Trial for samples with cement stabilization

Table 4 shows the used regulations for the test and methods followed to select the appropriate cement content.

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Table 4. Foreign Regulations used to trial stabilization and trials to stabilized samples

Regulation	Description
D 558 – 96	Standard Tests Methods for Moisture-Density Relations of Soil-Cement Mixtures
PCA	Soil-Cement Laboratory Handbook

To develop the experimental method, Portland Type 1 (28) or Type UG (general use) cement was used. The cement percentage selection to study was based on ASSHTO classification (American Association of State Highway and Transportation Officials) (28), and on the Portland Cement Association (29) requirements. Followed, the properties for compaction cement-soil mixture were established, to which max dry density and optimal moist content was calculated for each location to achieve an appropriate trial samples work.

Once the modeling was finished, samples were subjected to cure in a control room for 7 days with a relative moisture of no less than 96%, to later go through a wet and dry procedures. Samples were submerged in water during 6 hours and then dried in oven at 71°C (160 °F) for 42 hours, and finally removed to proceed to unconfined compression and durability testing.

Results

Samples characterization in original state

In total there where 5 soils samples taken from the urban area of Popayan as shown in table 5 and figure 1.

Table 5. Soil description

Location	Color	Depth	Description
University	Red brown	(0.5m-1m)	Very dry soil and quite hard to the touch
Campestre Club	Mauve brown streaks	(0.5m-1m)	Soil with high content of organic matter
Coconuco	Dark brown	(0.5m-1m)	Soft soil, with plasticity
Quarry	Light brown	(0.5m-1m)	Very heterogeneous soil, texture, color and hardness changes
Power Plant	Dark brown	(0.5m-1m)	Soil with a variety of streaks meaning different components.

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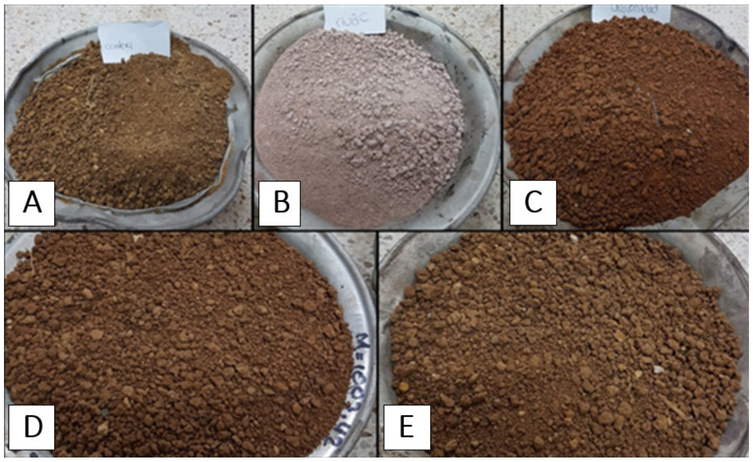

Figure 1. Soil specimens: A) Quarry; B) Campestre Club; C) University; D) Coconuco; E) Power Plant.
Source: authors

Specific Gravity (Gs)

Results gathered from the three trials made for each soil sample along its statistical analysis is exhibited in Table 6.

Table 6. Results for specific Gravity test for different specimens

	University	Club	Coconuco	Quarry	Power Plant
Specific Gravity	2.794	2.668	2.776	2.784	2.780

It is visible a small difference between the observed results regarding the specific gravity test, then the confidence grade is high, and results are an accurate representation of the studied property. In general, the variance presents a minimal difference between the factor studied for each type of soil in Popayan: with a standard deviation of 0.0464 and a variance coefficient of 1.6798. Such result could mean the similar mineral composition because the pedogenetic evolution conditions are alike for the region ground.

Natural moisture (w %)

Results presented in Table 7 , show a high percentage of natural water regarding the mixture water formation, which indirectly proves the high-water retention in clay soils and invites to consider water as an element that could affect the satisfactory resistance of soil-cement samples.

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Table 7. Moisture average for each specimen

	University	Club	Coconuco	Quarry	Power Plant
Moisture (%)	63.08	32.81	52.52	54.33	55.91

Soil CBR (California Bearing Ratio) in-situ trial and mass unity (bulk density)

CBR measures the ground response as a whole according to external forces. However, this test also serves as an indirect way to calculate some other properties that contribute to understand its bearing capacity as for unit mass and shearing. Table 8.

Table 8. Obtained results for the CBR test in natural state with statistics analysis (Unit masses)

	University	Club	Coconuco	Quartry	Power Plant
Mass Unit (in-field) [kg/m³]	1.470	1.631	1.714	1.616	1.592
Mass Unit (dry) [kg/m³]	0.901	1.228	1.156	1.048	1.021

Figure 2 presents de CBR variation between test location. It is possible to differentiate that Club and Coconuco have the highest bearing values close to 20% and 15% accordingly. However, when subjected to saturation, they lose their structural properties therefore its resistance, allowing to be classified as highly sensitive to moisture changes. On the opposite side, the Quarry soil is the one with less resistance values of CBR (close to 5%), although with high stability against changes in its structure due to moisture changes. Finally, soils of the University and the Power-plant present bearing properties moderately favorable when compared to other soils as they respond very well to moisture changes.

Gravimetrical and volumetric ratios

Relation between the different constitutive phases (solid, liquid and gas), allows to consider the arrangement, size and distribution of particles, quantity or water distribution, in general about the structural capacity of the soil. Table 9.

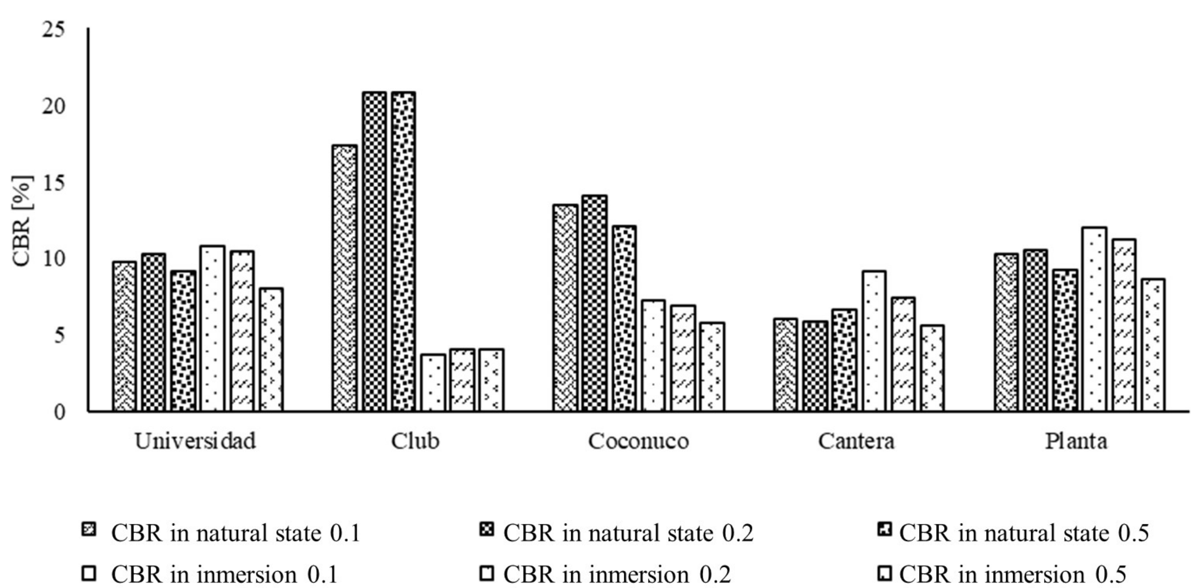

Figure 2. Values for CBR in natural state and CBR in immersion in testing sites

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Table 9. Main volumetric and gravimetric calculated for different sites

Specimen	University	Club	Coconuco	Quarry	Power-Plant
Specific Gravity [-]	2.794	2.668	2.776	2.784	2.780
Moisture [%]	63.083	32.806	52.524	54.329	55.906
Mass Unit humid [kg/m³]	1.470	1.631	1.714	1.616	1.592
Mass Unit dry [kg/m³]	0.901	1.228	1.124	1.047	1.021
Porosity [-]	0.677	0.540	0.595	0.624	0.633
Void ratio [-]	2.099	1.173	1.470	1.659	1.722
Saturation ratio [-]	0.840	0.746	0.992	0.912	0.902

Porousness depends on various factors like bulk density, particles size distribution, particle shape and cementation, being this last one, the most frequently studied within this research goals (30). Richard et al (31) present that the increment of soil resistance is due to the reduction of the porosity spaces increment the contact points of the aggregates or soil particles.

This may allow to attribute high resistance to those soils from Club and Coconuco to its low porosity in relation to presented information on figure 3. However, this fact makes them easy to saturate with less water volumes, therefore prone to moisture. This might be the reason that this to samples result affected after the immersion test.

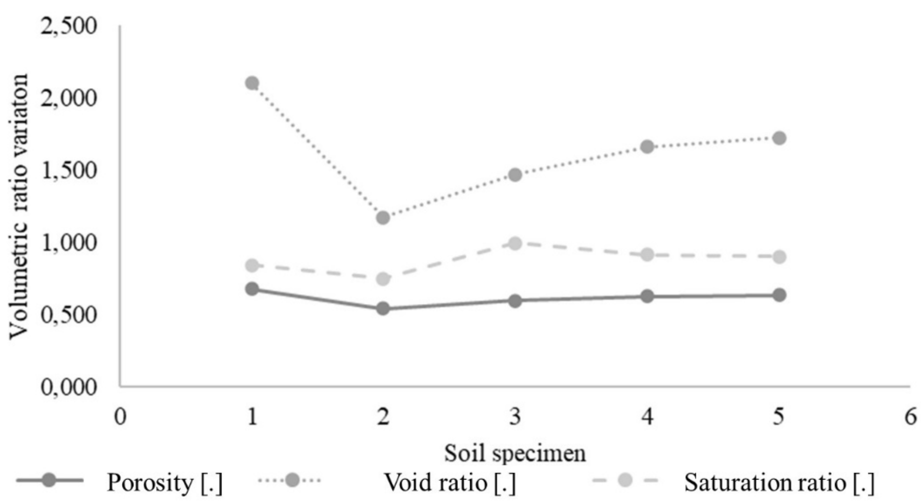

Figure 3. Volumetric ratio variation on 5 types of soil 1) University. 2) Club. 3) Coconuco. 4) Quarry. 5) Power Plant

Compaction Test

Compression is a procedure applied to soil, after a remodeling process in which soil loses its original structure and cementation on a macro scale. Compaction, as a mechanical process, reduces the empty spaces on remodeled soil, but does not restore neither the lose structure nor the cementation. Many authors agreed that, on remodeled soils, lesser gap ratios occur due to a high internal friction angles and higher dilatation, therefore a greater resistance to cutting (32). However, such behavior, is not visible on SDCV, because most of its resistance to shear is given by the cement properties, then, when remolding, the resistance increment -due to the contact with its aggregates-, is diminished by the cement action. Figure 4.

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Regarding the compaction trial, the lab test can be carried on with different levels of compressing energy, highlighting 2 of the most common ones: Normal Energy Proctor and Modified Energy Proctor. Figure 4 shows how its deformation can change by the function of the used compression energy. To greater compress energy, greater resistance with less deformations and vice versa.

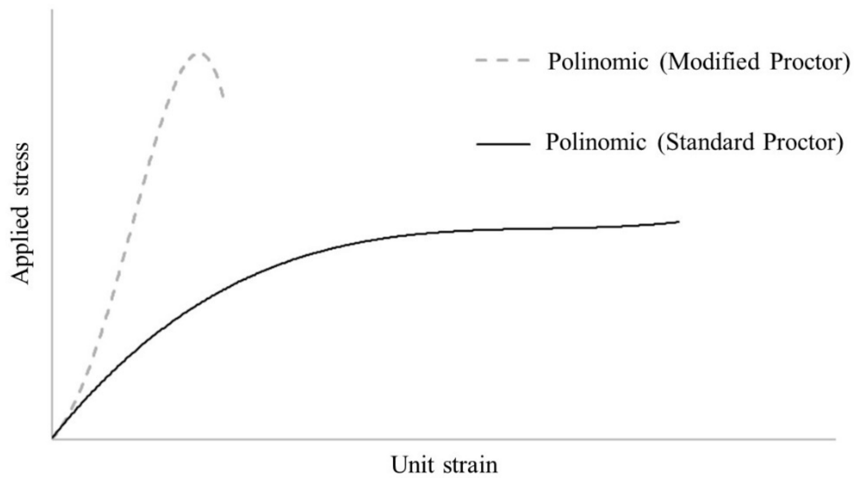

Figure 4. Soil resistance behavior with different compression energy. Mohd Yusoff et al. (33)

Choosing the compress energy for present research test was based on two theories. Firstly, the one proposed by Viveros (34) in which an excessive energy is applied. The original structure of the material can be broken therefore water contained in pores is freed, incrementing the amount of free water within and transforming the material into a viscous mass. The second theory refers to the demands in which the ground is exposed to, as in slope conditions of the studied soils that require to prioritize the resistance lose with greater deformations over the high resistance on small deformations.

According to that, the test that would allow to evaluate the most representative conditions for present research were Proctor standard (Table 10).

Table 10. Maximum density and optimal moisture for studied specimen

	(1)	(2)	(3)	(4)	(5)
Max dry mass [g/cm3]	1.015	1.31	1.237	1.083	1.115
Optimal moisture [%]	57.1	33.1	39	49.3	49.2

(1) University; (2) Campestre Club; (3) Coconuco; (4) Quarry; (5) Power Plant.

Figure 5 shows a slight to almost none diminishing of the empty spaces and consequently an increment in the soil density after compacting with Proctor Standard energy.

According to Melentijević et al. (4) volcanic ashes behave in an unusual manner, showing softening during energy input. Therefore, observed values might confirm that hypothesis as the level of improvement of the bulk density in connection of the empty spaces between stages is minimum.

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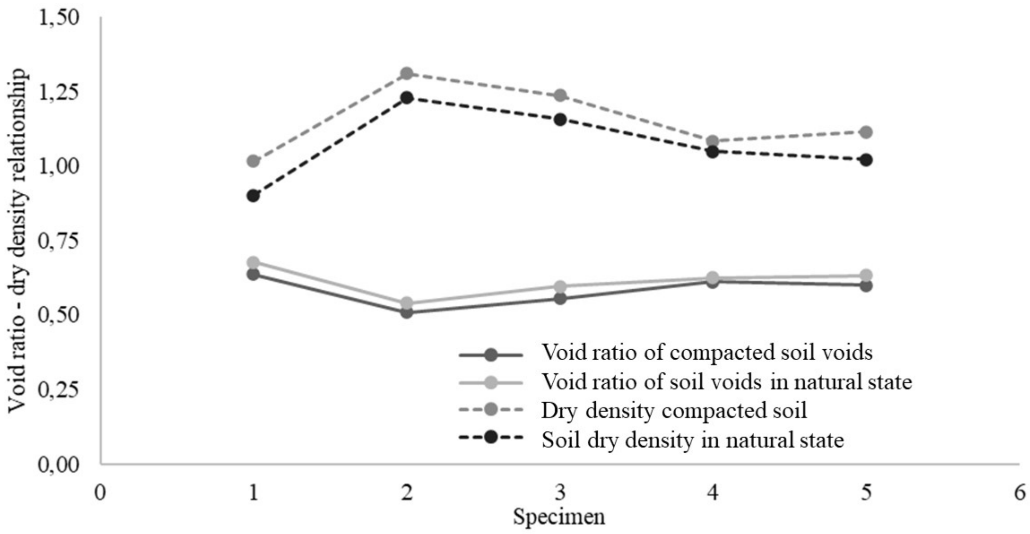

Figure 5. Comparisson between void ratio and dry density [kg/cm3] of soil on compacted and original state. 1) University 2)Campestre club 3) Coconuco 4) Quarry 5) Power plant

Resistance test to compress unconfined of soil samples in natural and remolded state

In regard of present research, resistance test to single compression fills this main purposes: As a way to offer an approximate value of ground cutting resistance, as it will be the main available parameter of mechanical influence; to provide a standard to evaluate the improvement level of ground resistance to its natural stage, remodel and cement remodel; and to achieve mechanical resistance and related properties of SDCV and compare to other types of soils.

When loads are applied and inside the ground cutting effort is produced, cementing absorbs most of them and produces a noticeable increment of ground resistance. According to Herrera (8), SDCV are characterized by its high cementation due to clay minerals present. Therefore, it can be attributed to the resistance developed by ground to self-cementation in studied soils. Figure 6 .
It can also be observed a typical behavior of plastic and fragile materials. Soils like Campestre Club and University that had developed greater resistance values, having the tendency to failure with less deformations (3% and 4%) respectively. This means: having less deformation capacity makes them more fragile. However, soils like Coconuco and Quarry, have lesser resistance but bigger unit deformations (10% and 11%). These means that in soils highly ductile is expected that cutting resistance lowers with the water matter and vice versa. This assumption agreed with previous research made by (35), who found that the increase of soil saturation caused considerable resistance capacity. Pande et al. (36), mentions that such condition is the result of clay materials that are compacted or had moisture under the dry layer, acting as a thicker way due to its particles bonding.

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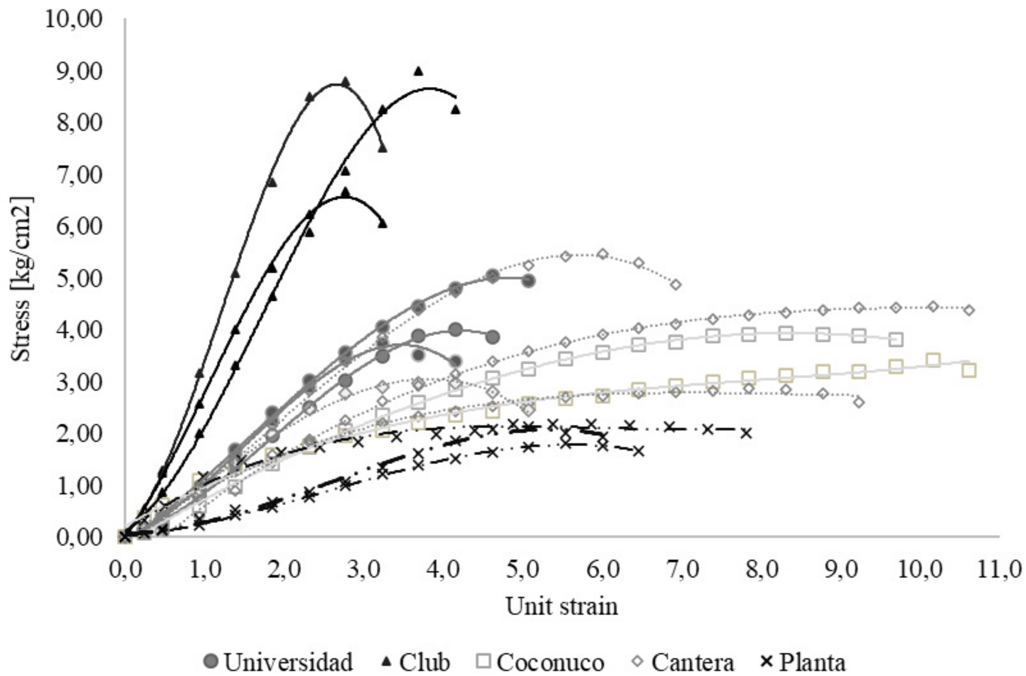

Figura 6. Effort-Deformation curves obtained for each compression test

Like that, the reduction of the water amount results in a bigger friction angle since individual grains become aggregates with greater dimensions, as it is known, the friction angle is proportional to the size of it.

Figure 7 shows the resistance variation to compression of specimens in relation to the natural moisture matter. It can be observed that a lowering tendency slightly marked, that is, if the amount of water in soil is high, resistance to cutting will diminish, which is consistent to findings.

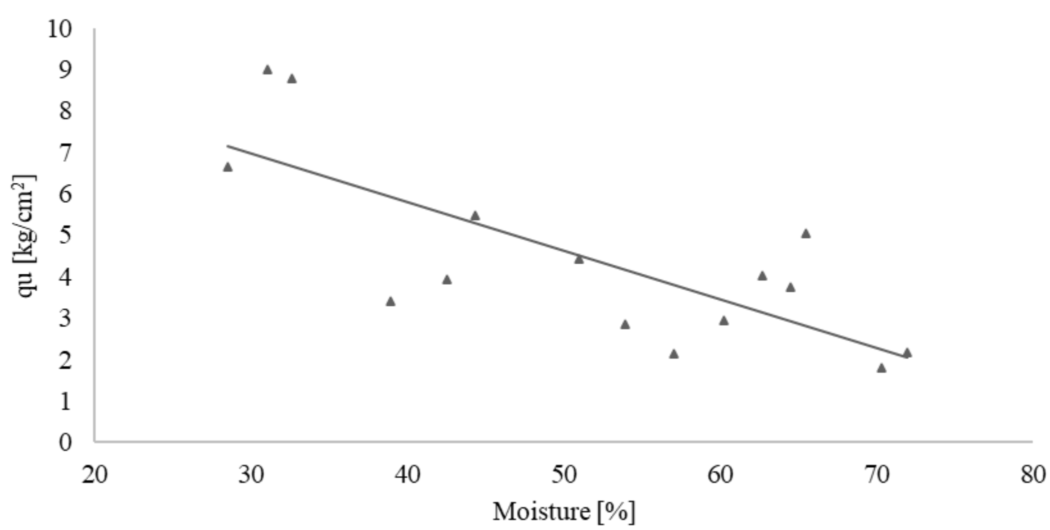

Figure 7. Relation between the moisture content and unconfined compression test.

It can also be observed that a total porosity value (0.6 to 0.65), common for SDCV. Lince and Khalajabadi (37), found similar values to this type of soils in a Colombian coffee grow area, with variations of (0.50 a 0.69) in a sampling depth of 0.1 m to 0.3 m (Figure 8).
Table 11 represents the unconfined compression test results performed on a remodel sample. Even though it is about remodel specimens with a certain level of homogenization due to lab handling,

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University and Power-plant show high variation coefficient. This means the high complexity of the composition and behavior of soils, and that is why they become good candidates to proposed improvement using cement (Figure 8).

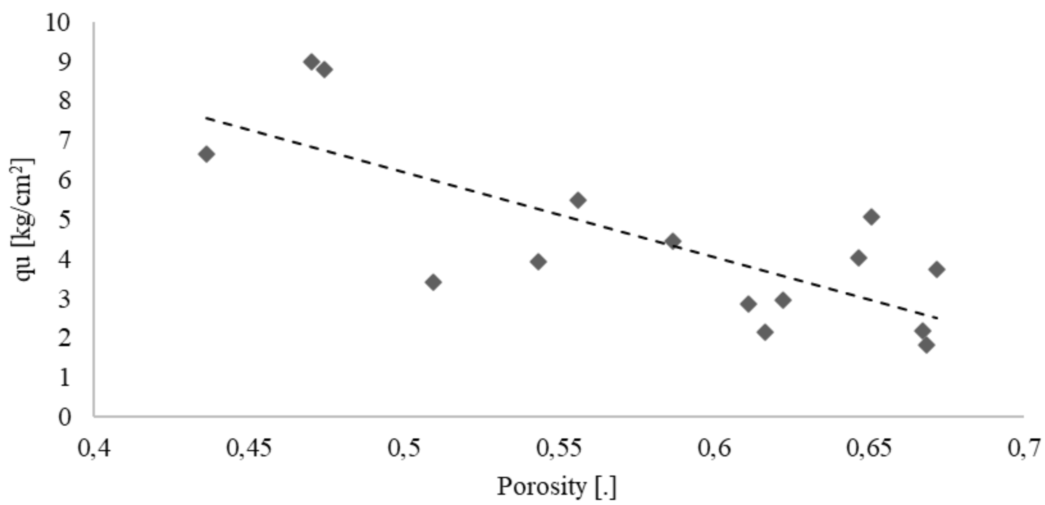

Figure 8. Porosity and final resistance of samples on unconfined compression test

Table 11. Final resistance to compression of remodel samples

	(1)	**(2)**	**(3)**	**(4)**	**(5)**
qu1 [kg/cm²]	2.92	3.22	1.45	2.79	3.99
qu2 [kg/cm²]	2.43	3.05	1.40	2.88	3.20
Media [kg/cm²]	2.67	3.13	1.42	2.83	3.59
Cv [%]	13	3.70	2.40	2.30	15.5

1) University 2) Campestre club 3) Coconuco 4) Quarry 5) Power plant

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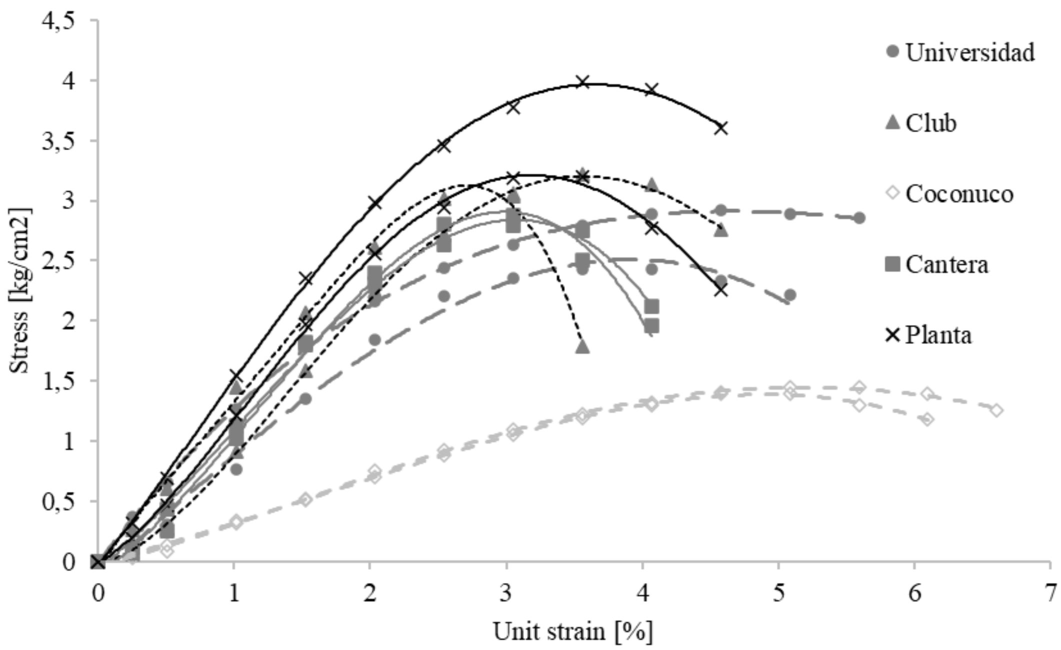

Figure 9. Deformation effort curve obtained in the single compression on remodeled samples

One of the most interesting quality that shows the SDCV characteristics, is regarding the loss of resistance after remodeling even whit its natural moisture. Such resistance is the measure of a parameter named sensitivity, defined as the relationship between the compression resistance of the unaltered sample (qui), and the compression resistance of the remodeled sample at same moisture (qur). Sensitivity values show the affectation levels of the remodeled soil, therefore, the low sensitivity values represent that the soil is not being effected by remodel, moreover, might mean an improvement when values are less than 1.0. In contrast, high values result in desaturation of the soil due to remodeling important diminishing of resistance. Values on table 12 exhibit the sensitivity levels that clay soils can have, and figure 10 exhibit the diagram of the sensitivity of compared soils.

Table 12. Classic sensitivity values on clay soils

Sensitivity	Description
>1	Insensitive
1-2	Low sensitive
2-4	Medium sensitive
4-8	Sensitive
8-16	Extra sensitive
>16	Quick

Modified from Das (2019). Classification of clays based on sensitivity (38)

In general, it can be inferred that the studied soils had low to medium sensitive values (St < 3), loosing half or almost three times its resistance to compression, which is consistent to a low and mid sensitivity (1.89 – 2.98) reported by Colmenares et al. (23) in Galicia (Pereira municipality). On the other hand, the soil tested in the Power-Plant shows a typical value mostly due to its strong changes in hardness, color, texture and, overall, to its different properties among samples taken.

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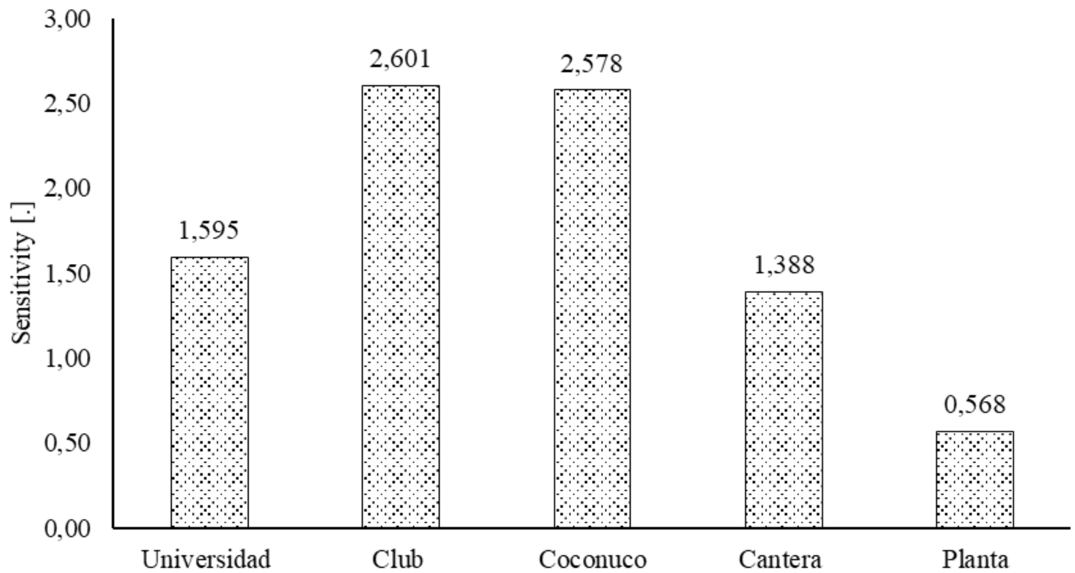

Figure 10. Sensitivity to remolding of samples.

Permeability Test (k)

Determination of permeability in soils is studied indirectly through consolidation test. Table 13 exhibits the obtained result for each soil tested.

Tabla 13. Table consolidated of permeability after statistic data

Sample	**Permeability - k**			
	M1 [cm/s]	M2 [cm/s]	Media [cm/s]	Cv [%]
University	1.40E-08	4.56E-08	2.98E-08	75.2
Club	9.23E-08	7.17E-08	8.20E-08	17.8
Coconuco	1.77E-07	2.17E-07	1.97E-07	14.7
Quarry	9.43E-08	3.24E-08	6.34E-08	69.1
Power -Plant	1.69E-07	1.37E-07	1.53E-07	14.8

M1: Cast 1, M2: Cast Coefficient variance values proceed through de sample formula.

Considering the coefficient variance values suggest a great unpredictability around the permeability, such properties range within the normal value for loamy and clay soils.

Fine soil particles size test (granulometry trial)

Soil structure refers to the disposition, bundling, size and shape of single particles. Grabulometry might be one of the most basic tests but not less important. Its goal is to determine the distribution of particles in a sample. It is based on two standardized test by INVIAS regulations. First stage looks for a correct preparation of the samples (I.N.V.E-106). Second stage is developed by 2 procedures that allow the approximate granulometric distribution of particles bigger or smaller than 75µm (#200).

Figure 11, exhibits that the University, Club Campestre and Cononuco show a high content of clay in its compositions (D< 0.002); while the samples from Power-plant and Quarry have lower levels. This might be linked to the depth where the samples were taken therefore, to the level exposure to

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weathering and metheorization, suggesting a lower metheorization and higher size particles directly link to depth.

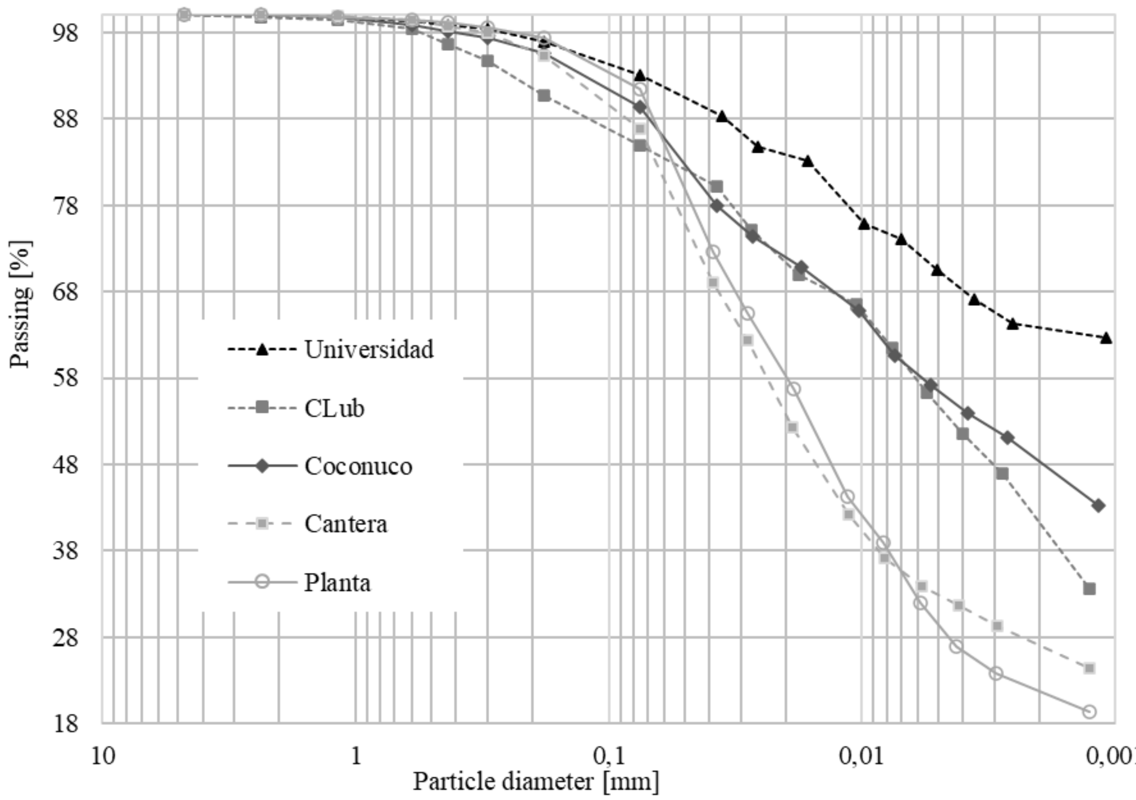

Figure 11. The granulometric curve showing the distribution of particles in each tested soil

Soil consistency (Atterberg Limits calculation)

Soil consistency refers to its adhesion and cohesion forces acting upon it according to different moisture and applied forces. Its definition highlights the importance of water within, because is the element in charge of changing the soils firmness. In fine soils, adhesion strength and cohesion allow particles to stay attached when applying a given force acting as the resistance offer by the soil when reshaped or kneaded. Table 14 present the results for the Atterberg limits and Table 15 soils consistency index.

Table 14. Atterberg Limits test results

[%]	University	Club	Coconuco	Quarry	Power-plant
Liquid Limit	100	55	89	94	86
Plastic Limit	56	34	41	48	48
Contractión Limit	31	30	28	31	33

Table 15 Soil consistency index

[%]	University	Club	Coconuco	Quarry	Power-plant
Plasticity index	44.11	20.25	47.94	46.04	38.28
Flow index	-30.59	-18.67	-30.32	-42.51	-18.02
Toughness index	-1.50	-1.30	-2.45	-1.25	-2.51
Contraction index	25.41	4.59	12.89	17.01	15.12

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Previous table shows that the lowest value for plasticity belongs to the Club location. Such behavior means that a small change in the amount of moisture in the soil can produce big changes in its consistency, moving rapidly from a semi-solid to semi-liquid. Table 16 suggests that most of the studied soils present a soft consistency in natural state, typical in soils with a plasticity interval, excepting the Club sample, which has a hard consistency, meaning that it ranges between semi-solid to solid. The relation between the consistency and mechanical resistance of soils can be proven on the resistance and confined compression test, where soils ranging on the plasticity values had a more ductile behavior when submitted to vertical load than the sample from Club location, which had higher resistance but less plasticity. It is also visible how Coconuco, Quarry and Power-plant had higher values with clay activity, which means a higher capacity of water retention.

Table 16. Consistency determination and clay activity in studied soils

Sample		University	Club	Coconuco	Quarry	Power-plant
Liquidity Index	Value [%]	0.164	-0.07	0.25	0.14	0.22
	Assesment	Plastic range	Solid semi-solid range	Plastic range	Plastic range	Plastic range
Concistency index	Value [%]	0.84	1.07	0.75	0.86	0.78
	Assesment	Plastic range	Solid to semi-sólido range	Plastic range	Plastic range	Plastic range
Activity	Value [%]	0.69	0.50	1.02	1.71	1.80
	Assesment	Inactive clay	Inactive clay	Normal Active	Activa clay	Active clay

Figure 12 and Table 17, show the classification of soils by the two most recognized international systems. According to SUCS, the total of soils from locations are loamy with high plasticity (MH). However, as AASTHO classification, is closer to define them as loam-clayey part of the group A-7-5.

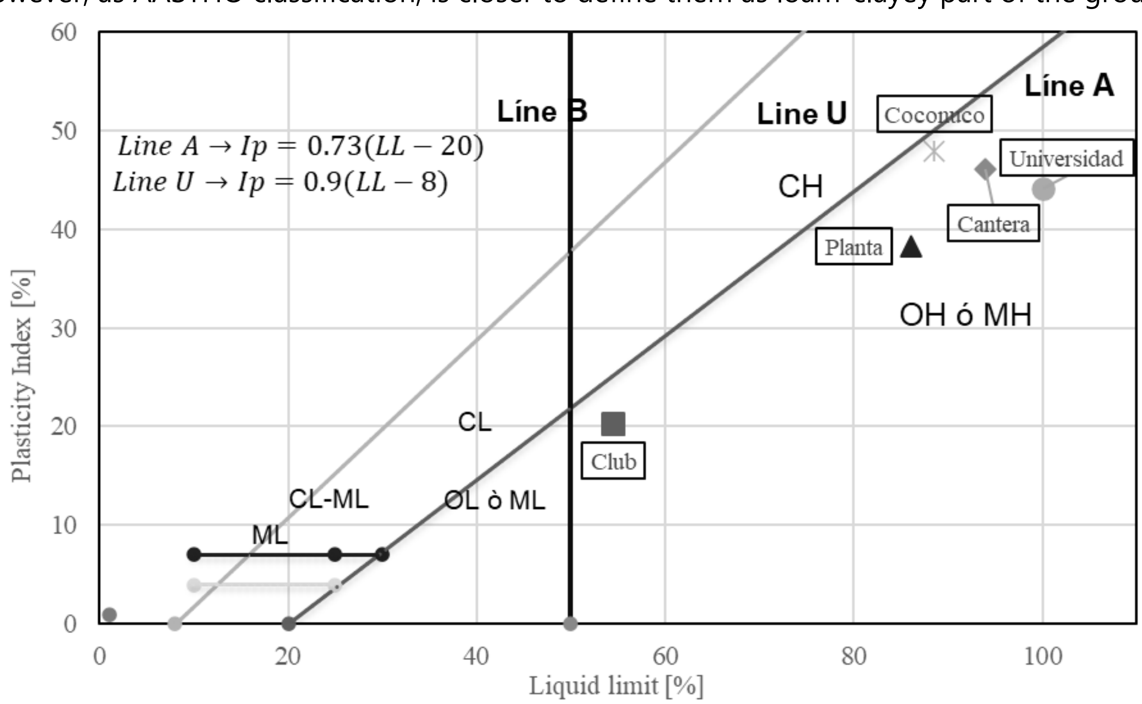

Figure 12. Casagrande method soil clasification

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Table 17. SUCS and AASTHO international method soil classification

Sample	System	SUCS	AASHTO
University	Nomenclature	MH u OH	A-7-5(20)
	Description	High plasticity loamy or High plasticity organic Loamy	Loam-clay
Club	Nomenclature	MH u OH	A-7-5(15)
	Description	High plasticity loamy or High plasticity organic Loamy	Loam-clay
Coconuco	Nomenclature	MH u OH	A-7-5(20)
	Description	High plasticity loamy or High plasticity organic Loamy	Loam-clay
Quarry	Nomenclature	MH u OH	A-7-5(20)
	Description	High plasticity loamy or High plasticity organic Loamy	Loam-clay
Power-plant	Nomenclature	MH u OH	A-7-5(20)
	Description	High plasticity loamy or High plasticity organic Loamy	Loam-clay

Sample stabilization with cement admixture

After samples characterization in their original state, Club, University and Quarry were the ones selected, considering the results on table 18. To achieve valid comparative results, percentages of cement where set (Table 19) .

Tabla 18. Valuated cirteria for estándar sample selection

Sample	Plasticity Level (%)	Single compression. Original state sample (kPa)	Single compression. Remodeled sample (kPa)
Club	34	799.634	307.438
University	56	418.450	262.034
Quarry	48	486.802	277.920

Table 19. Cement percentages for stabilization

Sample to be stabilized	ASSHTO classification	Cement Porcentajes under study (%)
Club	A-7-5 (15)	8, 11, 12, 13, 15
University	A-7-5 (20)	8, 11, 12, 13, 15
Quarry	A-7-5 (20)	8, 11, 12, 13, 15

Obtained results from normal compaction test when adding different percentages of cement show that the soils from Quarry and University, which contain a plasticity limit of 48% and 56% accordingly, showed very closed values to optimal moisture between [45% -51%] and maximun density range of [1.10-1.13] g/cm^3. On the other hand, tested sample of Club with a plasticity limit of 34%, lower than obtained results, showed an average result of 34% optimal moisture and density of 1.34 g/cm^3 (Table 20) .

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Table 20. Relationship between moisture-density on samples

Soil: Club					
Cement [%]	8	11	12	13	15
Optimal moisture [%]	33.3	33.1	33	33.7	34
Max density [g/cm³]	1.33	1.34	1.34	1.34	1.34
Soil: University					
Cement [%]	8	11	12	13	15
Optimal moisture [%]	48.5	50.6	45.7	45.6	45.7
Max density [g/cm³]	1.1	1.13	1.13	1.13	1.13
Soil: Quarry					
Cemento [%]	8	11	12	13	15
Optimal moisture [%]	48.7	50.4	50.9	44.7	44.8
Max density [g/cm³]	1.11	1.13	1.09	1.12	1.15

Table 21 Show the number of specimens tested by soil sample. The method used was based on regulation INV E-152-13 (27). For the durability test, a brushed technique was applied on all samples: Their properties after cement were determined by the amount of weight loss and/or decurrant when applying wet and dry cycles resistance Figure 13.

Table 21. Sampled test performed on each type of soil to be treated

Sample	**Cement [%]**					**Total / sample**
	8	11	12	13	15	
Unconfined resistance	13	13	13	13	13	65
Durability	2	2	2	2	2	10

In the moisture and drying process would have the involvement of properties of durability and resistance. The main factors affecting the structural integrity of soil are the environmental conditions (temperature and moisture variations) and the imposed demands, that end up weakening it (39).

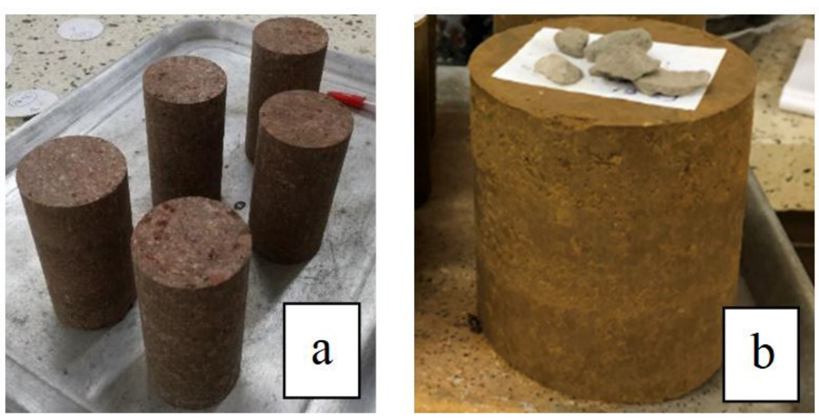

Figure 13. a) unconfined compression test compacted specimens b) durability specimen

In general, it can be observed that on the three stabilized soil, the compactation curves, after adding cement, experienced a reduction regarding the optimal moisture and an increment on its maximum density. This might be explained from the following to points of view: (i) bigger aggregates formation during the cement hydration, therefore lowering its specific surface hence its capacity to water absorption and retention. (ii) The increment of the density has to do with the

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dosage soil and cement, as the resultant material will have properties alike the initial materials, therefore, some properties like density will increment in a proportional rate to the amount of mixture Figure 14 and Figure 15 .

In relation to the other soils, University shows a significant variation regarding density and moist in the compaction curves. Such variation could be explain as: (i) soil granulometry suggested a high content in clay (>60%), meaning a high water retention in the specific surface and a matrix potential; (ii) with the added cement and the particles formed by bigger flocculate particles, soil experiments a dramatic change in its particles size, comparing with other two soils, less thin granulometry that was no affected by specific surface and water retention is reduced, along its capacity to hold it producing a behavior of soil similar to thicker ones (Figure 16).

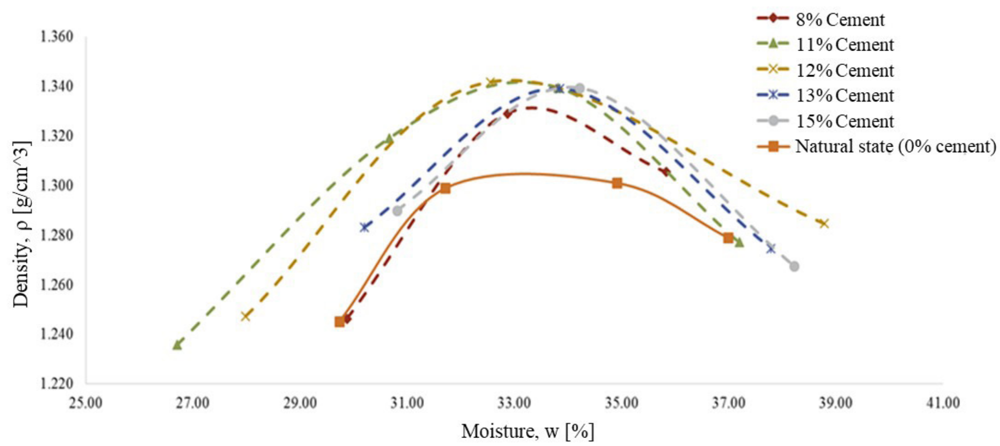

Figure 14. Natural compactation curve and cement compactation curve on Club Campestre sample

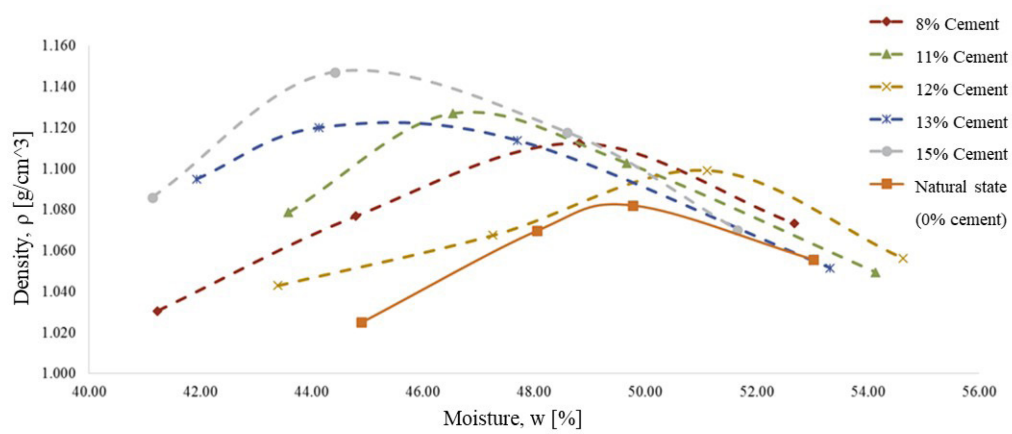

Figure 15. Natural compaction curve and cement compaction curve on Quarry sample

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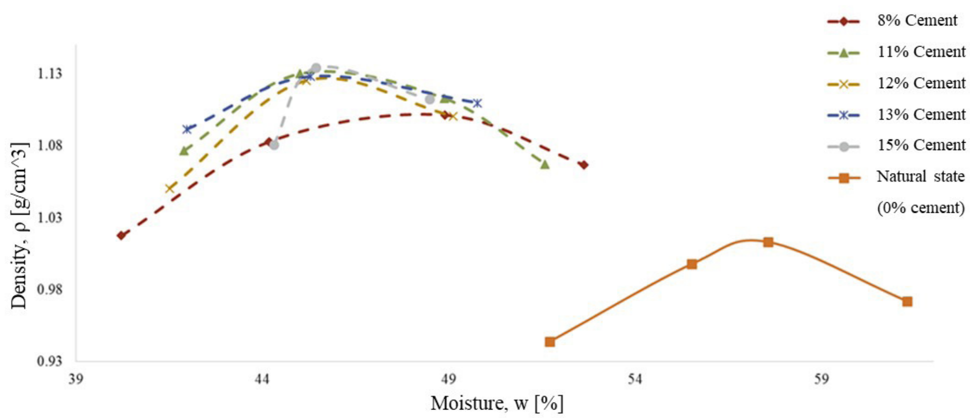

Figura 16. Natural compaction curve and cement compaction curve on University sample

Regarding the amount of water used for hydration of the cement-soil, some of it goes to cement hydration [Wd] and other evaporates leaving empty spaces that reduce its durability and resistance. Understanding that the reduction of the relations is positive for hardening mixture properties, as it increments its resistance, low relations [Wd/C] may be linked to greater resistance to unconfined compression. Like this, according to Figure 17, soil that has the lowest relations [Wd/C] is Club soil, and as expected, developed higher resistance to unconfined compression Figure 18.

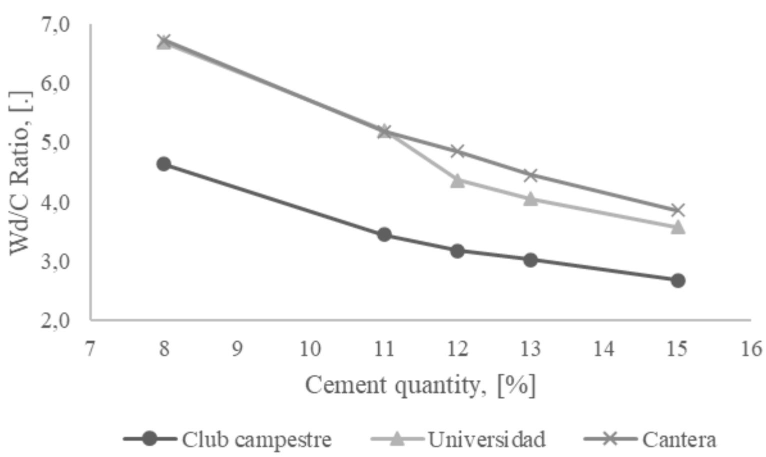

Figure 17. Wd/C Ratio behavior and cement amount

It may be possible to infer that obtained relations [Wd/C Ratio] in present research are high, and, if they were to decrease, an improvement of obtained resistance can be achieved. Therefore, it is proposed a soil structure resistance evaluation if submitted to higher compaction energy, which could show the reduction of water and an increment of the unconfined resistance. The proposed evaluation would suggest lowering the capacity of soil deformation towards a greater resistance, which according to the soil during service, would need to be analyzed and evaluated carefully. Finally, it is important to mention that the reduction of such amounts of cement generates economical benefits, due to less amount of it.

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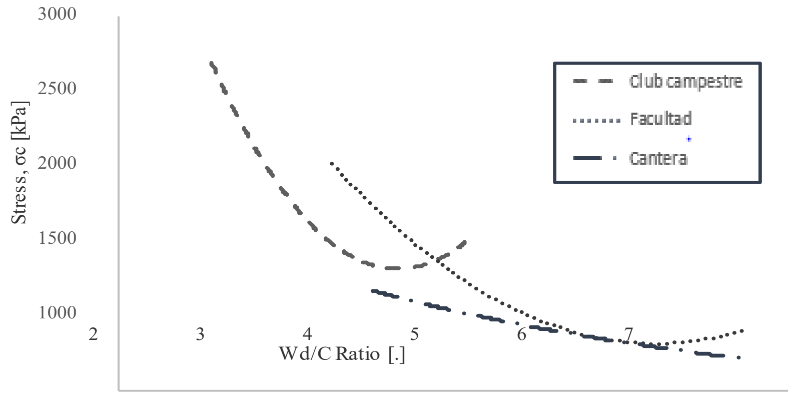

Figure 18. Unconfined compression resistance behavior with Wd/C ratio

On the other hand, having as a starting point the gathered results on the unconfined test on natural and remodeled state soils Table 22.

Table 22. Sensitivity values for non-stabilzed soils samples

Soil sample	Natural State Resistance [kPa]	Remodeled resistance [kPa]	Sensitivity (S)
Club campestre	815.40	313.47	2.601
University	426.64	267.52	1.595
Quarry	496.35	283.42	1.751

Due to this, it is recommended that during remodeling following factors should be taken into account to evaluate the soil improvement according to its original state. Firstly, when destroying the original soil structure by remodeling, its resistance reduces due to the cemented condition, then, from a chemical point of view, a breaking of the electrochemical bonding between particles happens as well as the redistribution of observed water becomes free water (author). Secondly, has to do with the soil compaction, according to the grade of imposed model during compression represented by the applied energy, the soil density and resistance properties risen producing a more homogeneous structure. Thirdly, related to the reduce of the resistance during the compaction process in a volcanic-ash soil when incrementing the amount to knocks.

The goal of three tested soils was to developed, inside the volcanic ashes, ranges with a low IP, and mid IP and a High IP. (Table 23).

Table 23. Summary of properties

Property	Campestre Club	University	Quarry
Clay [%]	69.9	83.5	52.2
Loam [%]	30.1	16.5	47.8
LL [%]	54	100	94
LP [%]	34	56	48
Moisture unit mass [kg/m³]	1.63	1.47	1.62
Specific Surface (Ss)	low	high	high
Dry unit mass [kg/m³]	1.22	0.901	1.05
Porosity, n nat [.]	0.54	0.67	0.62
Emptiness ratio, e nat [.]	1.17	2.09	1.66
W natural [%]	32.81	63.08	54.32
Gs	2.65	2.79	2.78

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K [cm/s]	8.2E-08	3.0E-08	6.3E-08
qu-natural [kPa]	815	426	496
Max dry unit mass. [kg/m³]	1.31	1.015	1.083
Wopt [kg/m³]	33.1	57.1	49.3
qu-remodeled [kPa]	313	267	283
Qu max cement estabilization	2755 Cement 15%	1483 Cement 13%	2151 Cement 15%
Classification SUCS	MH	MH	MH

Results referring to cement proportions, found that an optimal value is between 13 – 15 % on cement content, which is over the values found by Niu et al. (18), where they mention and optimal proportion of 10% cement. However, is important to clarify that research used 9% of stabilizing. For Rohmatun et al. (20), the optimal content is 7%, however, he also clarifies an aid to the filling of the UCS lowest value of UCS de 2353.60 kPa. Para Otilia et al. (17), the optimal content would be between 5-7%. However, let's remember that there is a paper that shows low cement content, explaining that among their conclusion, found that according to found parameter "would be viable for a embankments group, with a previous study of resistance to deformity and commissioning work", ruling out subgrade or embankment wreath. On the other hand, PCA (21) mentions that for A-7-5 soils, the optimal percentage of cement is normally between 10% to 16%, matching findings in present study.

Conclussions

The study of cement modified soil, stablishes a notorious difference between before-and-after of derivates of volcanic ashes soil like increment of resistance and a positive change on the physical characteristics like durability, becoming a contribution towards the advancement in Civil Engineering in Andean region in Colombia.

The development of the stabilization of the technicque with Portland cement presented physical satisfactorily results according to its durability behavior. In samples treated with 15% of cement, the loose mass valued show to be acceptable due that they offer a favorable resistance to weathering. The use of cement as an alternative technology has allowed to offer quick and efficient results regarding treatment of volcanic ashes derived soils. Results show that when using 13% and 15% it is possible to successfully avoid infrastructure slope flaking, offering an better affordable option than other stabilization systems, avoiding the stabilization superficial of cut or fill slopes in a road, which cause detriments or negative effects on road service, besides, the stabilization technique cement-soil does not require a permanent investment in cleaning of removed material.

Qualitative analysis of the fault presented in unconfined compression test show that most common ones on soils derived from volcanic ashes are from ductile and shear fragile extension

Stabilization guidelelines for design

The feasibility of three stabilization is strongly correlated with the specific surface (LL and Ss have an exponential proportional relation), due to soils with less liquid limit show a higher feasibility

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to be stabilized an improved with cement. (e.g., Club Campestre), which will be a fundamental information property to know regarding the cement expenditure in a future stabilization.

Likewise, high liquid levels are showing that is not possible, including improvement, to reach appropriate packaging (low void relations), then, this would be an important variable to consider when stabilizing with cement. This variable end up being very sensitive due to its exponential behavior (Ss vs. LL).

One of the relevant consideration is that the most important of liquid limit evaluation to the amount of clay as it was possible to see on Club Campestre and Quarry soil. Where Club has more clay, but less specific Surface, hence its most favorable behavior.

In general, the stabilization system using cement on soils derived from volcanic ashes might be refined to slope protection. It is effective because, in any amount of cement used, always the method showed improvement regarding greater resistance that the original sample, including stabilized ones on any cycle. Such, demonstrates that the systems might be used for stabilization on the flaking slopes effect.

Due to variability and mining characteristic of volcanic ashes, it would be necessary for each soil to develop an individual stabilization design.

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CRediT authorship contribution statement

Conceptualization - Ideas: Lucio G. Cruz-Velasco. Data Curation: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz. Formal analysis: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz. Acquisition of funding: Lucio G. Cruz-Velasco. Investigation: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz. Methodology: Lucio G. Cruz-Velasco. Project Management: Lucio G. Cruz-Velasco. Resources: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz. Supervision: Lucio G. Cruz-Velasco. Validation: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz. Visualization - Preparation: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz. Writing - original draft - Preparation: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz. Writing - revision and editing - Preparation: Lucio G. Cruz-Velasco , Sara M. Gómez-Rodríguez, Yeleman F. Valbuena-Muñoz.

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