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STRESS-STRAIN RESPONSE OF AN UNSATURATED VOLCANIC ASH SOIL FROM COLOMBIA

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Abstract

This study investigates the mechanical behavior of a volcanic ash-derived soil from Manizales, Colombia, focusing on the influence of water content variations and remolding processes on its stress-strain response. Characterized by high plasticity, high void ratios, and a unique mineralogy, these residual soils present significant geotechnical challenges, often leading to slope instability in populated Andean regions.To evaluate their stress-strain response, direct simple shear (DSS) tests were conducted on samples subjected to single and double compaction procedures. The specimens were evaluated under three initial hydraulic states (optimum water content, air-dried, and saturated) and applied vertical stresses of 50, 100, and 200 kPa. The results indicate that recompaction and higher compaction energy induce structural changes that increase the dry unit weight, effective cohesion, and friction angle. Furthermore, the study highlights the fundamental role of matric suction; although water content variations had a negligible effect at low confinement (50 kPa), a substantial increase in shear strength and shear modulus was observed at higher stress levels (100 and 200 kPa) as suction increased. These findings underscore the importance of considering the hydraulic state and compaction history in the stability analysis of earth structures using these materials.

Keywords: volcanic ash soils, unsaturated soils, direct simple shear (DSS), shear strength

List of notations

c' is the effective cohesion

ϕ' is the effective friction angle

G is the secant shear modulus

G_{max} is the small-strain shear modulus

G_s is the specific gravity

OCR is the Overconsolidation Ratio

PI is the Plasticity index

w_o is the Initial water content

w_{dry} is the Water content after three days of air-drying post-compaction

w_L is the liquid limit

w_{opt} is the optimum water content

w_p is the plastic limit

w_{sat} is the saturated water content post-compaction

γ_d is the maximum dry unit weight

σ'_n is the effective normal stress

1. Introduction

Volcanic ash-derived soils, often classified as Andisols, are residual materials formed by the weathering of tephra deposits (Herrera et al. 2007; Wesley 1973). These soils are distributed globally, with significant occurrences in Chile, Peru, Ecuador, Colombia, Central America, the United States, Kamchatka, Japan, the Philippines, Indonesia, New Zealand, among others (e.g., Bartoli et al. 2007; Galvis-Castro et al. 2022; Hernandez et al. 2018; Putra et al. 2020; Rao 1996; Shoji et al. 1993). Despite accounting for less than 1% of the Earth's soil cover, they represent approximately 12% of the land surface in Colombia (Herrera et al. 2007).Consequently, a substantial portion of Colombian urban settlements, industrial infrastructure, and government centers is situated on these deposits (Galvis-Castro et al. 2022; Mendoza et al. 2021).

Beyond their geographic distribution, these residual soil deposits exhibit physical properties and mineralogical compositions that differ substantially from those of sedimentary soils (Nanzyo 2002; Rao 1996). Characterizing these materials is particularly challenging, as their mechanical and dynamic behavior is governed by formation processes and climatic conditions, often leading to slope instability, high sensitivity, and cracking (Hernandez et al. 2018; Verdugo 2008). In a geotechnical context, these soils are typically characterized by high water retention capacity, extremely high liquid limits, low in-situ densities, poor workability due to excessive water content, low shear wave velocities and very soft consistencies (Betancur Guirales et al. 2013; Bommer et al. 2002; Hernandez et al. 2018; Herrera et al. 2007; Terlien 1997; Vásquez-Varela and Mendoza 2021).

The unique nature of these soils is largely due to minerals such as allophane and imogolite. In terms of compressibility, the overconsolidation ratio (OCR) is not solely a function of stress history; instead, it is governed by a yield stress originating from the soil's structure, chemical bonding, and cementation (Galvis-Castro et al. 2022; Wesley 2003). Regarding shear strength, these soils exhibit high friction angles (ϕ') ranging from 30° to 43°, despite their characteristically high plasticity and porosity (Verdugo 2008; Wesley 2003). Furthermore, index properties and mechanical response undergo irreversible changes upon drying relative to their natural state, as the material aggregates into larger particles, thereby altering the original mechanical behavior (Romero-Mancilla et al. 2021). Similarly, variations in the small-strain shear modulus (G_{max}) are controlled by the micro-fabric and component interactions, including the presence of aggregates, pores and minerals like allophane and imogolite, which collectively dictate the mechanical response (Gobin et al. 2023).

In addition to these intrinsic factors, the behavior of volcanic ash-derived soils varies significantly with wetting and drying processes (Hernandez et al. 2018). Experimental research has demonstrated that suction and cementation play a pivotal role in soil behavior, both of which contribute to an increase in shear strength (Caicedo et al. 2014; Delage and Cui 1996; Pereira et al. 2005). The study of water content fluctuations and their subsequent effect on suction levels is particularly critical in tropical environments. A reduction in suction can lead to a decrease in apparent cohesion, thereby compromising soil stability and potentially triggering mudflows (Betancur Guirales et al. 2013;

Bommer et al. 2002). Despite recent advancements in the characterization of these materials, a knowledge gap remains regarding how water content variations influence the stress-strain response, especially when considering the effects of remolding. This study evaluates the impact of water content variation on the shear strength parameters, c' and φ', and the shear modulus, G, of a volcanic-ash derived soil from Colombia by employing direct simple shear (DSS) test.

2. Materials and methods

2.1 Soil properties

The soil used in this research is a remolded volcanic ash-derived soil collected in Manizales, Colombia (South America), at a depth of 1.5 m. the sampling site is located at coordinates 5°03'25.5"N 75°28'49.9"W. These deposits originated from eruptions of the Ruiz-Tolima volcanic complex during the Holocene and Pleistocene epochs over the last 20,000 years of the Quaternary period (Herrera et al., 2007). In Colombia, volcanic ash-derived soils cover approximately 11.6% of the national territory, primarily across the departments of Caldas, Risaralda, and Quindío, a region inhabited by approximately 2.5 million people (Herrera et al. 2007).

This soil is classified according to the Unified Soil Classification System (USCS) as a high-plasticity silt (MH). The obtained Atterberg limits and the resulting classification (Table 1) are consistent with values reported in the literature for soils whose mineralogical composition is primarily characterized by halloysite-type minerals (Hernandez et al. 2018).

Table 1. Properties of the volcanic ash-derived soil collected in Manizales, Colombia.

Property	Value	Unit
Liquid limit, w_L	74	%
Plastic limit, w_p	37	%
Plasticity index, PI	37	%
Specific gravity, G_s	2.67	-

2.2 Experimental setup

Direct simple shear (DSS) tests were conducted using the Direct Shear Test Track II apparatus at the Pontificia Universidad Javeriana, Bogotá. Samples were prepared following two distinct preparation procedures. The first procedure, for samples designated as Single Compaction (SC), consisted of air-drying the material to a water content of approximately 13%, followed by manual disaggregation. The soil was then compacted by wetting the material until reaching the optimum water content according to the Standard Proctor compaction method ASTM D698-12 (2021). The second procedure, for samples designated as Double Compaction (DC), involved manually crushing a previously compacted sample until the material was disaggregated. Subsequently, the material was air-dried and finally re-compacted following the same Standard Proctor method (ASTM D698) by wetting the soil back to the target water content.

A total of 12 tests were performed, varying the applied vertical stress (50 kPa, 100 kPa, and 200 kPa), the preparation procedure (SC or DC), and the water content. The water content conditions included: optimum water content w_{opt}, water content after three days of air-drying post-compaction w_{dry}, and saturated water content post-compaction, w_{sat} (see Table 2). The tests were conducted at a constant displacement rate of 0.009 mm/min. The tested specimens were circular, with a diameter of 63.5 mm and a height of 29.3 mm.

Table 2: Experimental program and testing conditions for Direct Simple Shear (DSS) tests.

Test ID	Sample state	Effective normal stress σ'_n (kPa)	Initial water content w_0 (%)	Water content condition
DO-50	Double Compaction	50	37.5	Optimum
DO-100	Double Compaction	100	38.1	Optimum
DO-200	Double Compaction	200	37.4	Optimum
SO-50	Single Compaction	50	36.9	Optimum

SO-100	Single Compaction	100	38.5	Optimum
SO-200	Single Compaction	200	37.6	Optimum
SS-50	Single Compaction	50	47.1	Saturated
SS-100	Single Compaction	100	47.9	Saturated
SS-200	Single Compaction	200	47.0	Saturated
SW-50	Single Compaction	50	24.1	Air-dried (3 days)
SW-100	Single Compaction	100	30.5	Air-dried (3 days)
SW-200	Single Compaction	200	24.6	Air-dried (3 days)

3 Results and discussion

3.1 Characterization of the volcanic ash soil

3.1.1. Mineralogical, chemical composition and classification

Figure 1 shows a comparison of the positions of various soils from the central Andean region of Colombia on the Casagrande plasticity chart. This dataset includes information from the Geotechnical Microzonation of Manizales (CIMOC & CEDERI 2002; Hernandez et al. 2018), and the present study. The results indicate that the majority of the data points lie below the "A-line" (90% of the results) and only 16% exhibiting liquid limits below 50%. According to the classification criteria proposed by (Wesley 1973), these findings confirm that most of these soils are volcanic ash-derived.

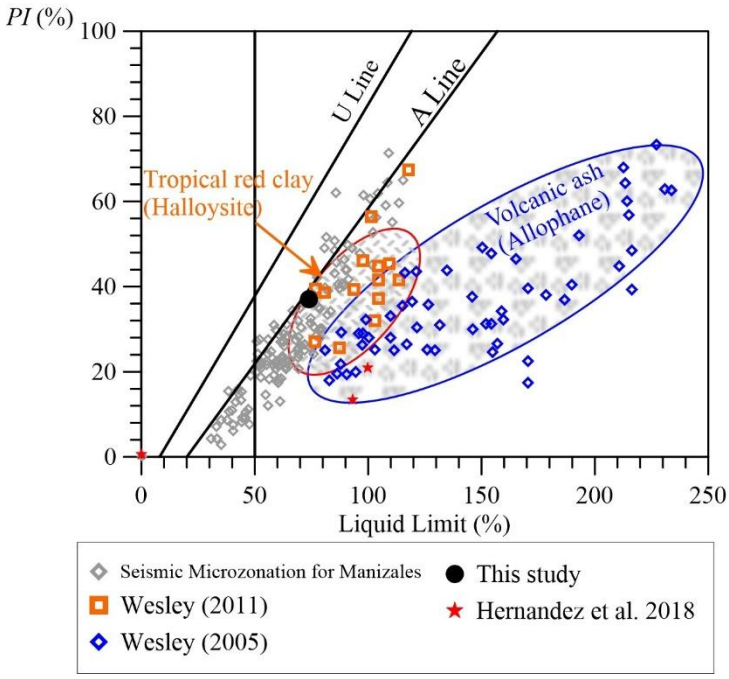


Figure 1. Summary of plasticity indices and liquid limits of soils derived from volcanic ash found in the literature, represented in the Casagrande plasticity chart.

Numerous tests demonstrate that positions below the A-line, coupled with high liquid limits, indicate the presence of allophanic clays (Wesley 1973, 2011). This is further corroborated by the trend line established by (Mendoza et al. 2021), which relates liquid limit and plasticity index values falling below the A-line. Additionally, the consistency indices of these residual volcanic ash soils in their natural state are very close to zero due to their high natural water content, which typically ranges from 40% to 200%.

The Scanning Electron Microscopy (SEM) micrograph in Figure 2 display the cylindrical tubular morphology characteristic of halloysite, a mineral formed by the weathering of volcanic ash. Furthermore, the presence of allophane can be inferred based on the mineral's evolutionary sequence (Verdugo 2008; Wesley 1973, 2003). Diaz and Villada (2002) also confirmed the coexistence of allophane, imogolite, and halloysite in samples from Manizales, Colombia, using X-ray diffraction (XRD) and SEM. These results are consistent with the research on typical volcanic clays conducted by (Wesley 2011).

The average chemical composition obtained from five Energy Dispersive Spectroscopy (EDS) spectra is: C 39.97 ± 0.79 %, O 41.03 ± 0.66 %, Al 7.36 ± 0.18 %, Si 6.52 ± 0.17 %, Fe 5.12 ± 0.56

% and Ti 0.26 ± 0.98 (see Table 3). The average molar Al/Si ratio is approximately 1.17. While this value is near the theoretical 1:1 for halloysite, the higher ratios observed in specific spectra suggest the presence of aluminum rich amorphous phases (Baumgarten et al. 2013).

Table 3. Elemental chemical composition and molar ratios from EDS analysis.

	Spectrum 1 (%)	Spectrum 2 (%)	Spectrum 3 (%)	Spectrum 4 (%)	Spectrum 5 (%)
C	32.03 ± 0.71	32.77 ± 0.7	38.61 ± 0.73	47.18 ± 0.79	49.27 ± 1.04
O	46.32 ± 0.65	50.38 ± 0.63	44.3 ± 0.6	35.95 ± 0.65	28.18 ± 0.77
Al	6.37 ± 0.15	8.84 ± 0.18	9.04 ± 0.19	6.05 ± 0.17	6.49 ± 0.21
Si	4.39 ± 0.13	5.67 ± 0.14	8.06 ± 0.18	7.39 ± 0.19	7.1 ± 0.22
Fe	10.88 ± 0.72	2.34 ± 0.54	-	3.43 ± 0.72	8.96 ± 0.25
Ti	-		-	-	1.04 ± 0.98
Al/Si ratio	1.51	1.62	1.17	0.85	0.95

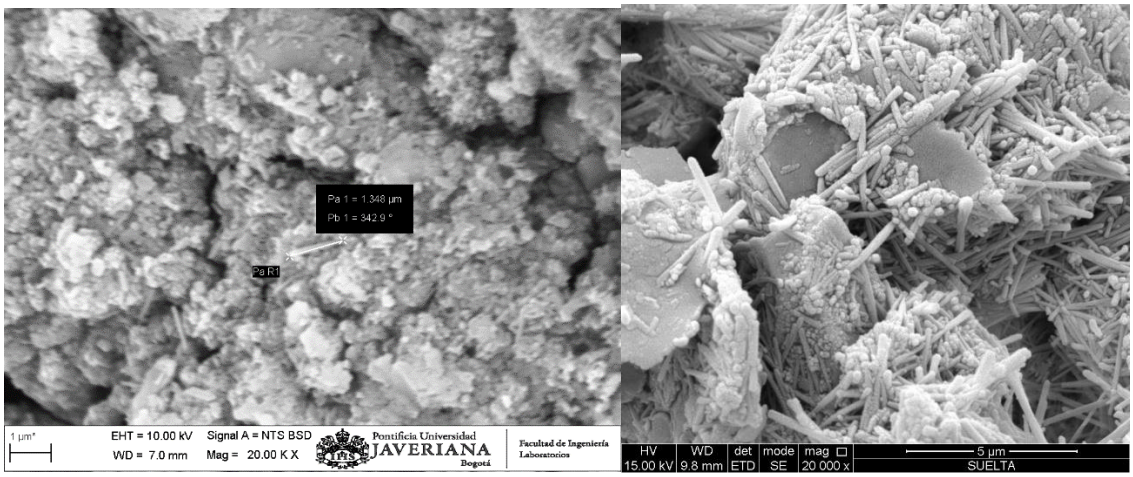


Figure 2. SEM micrographs of the volcanic ash soil from Manizales, Colombia.

3.1.2. Particle size distribution

Particle size distribution was determined using a Mastersizer 3000 laser diffraction system, as shown by the solid red lines in Figure 3. The laser diffraction method automatically measures particle size distribution by analyzing light scattering. For the tests, the material was gradually introduced into deionized water, which served as the dispersing agent. The results obtained with laser diffraction

method show the cumulative volume passing for each particle size, the soil sample was prepared under natural water content condition, this figure also includes the grain size distribution curve obtained via the hydrometer method, using sodium hexametaphosphate as a dispersant agent.

It is observed that the curve obtained using the hydrometer method shows smaller particle sizes, which is attributed to the disaggregation of soil particles by the dispersing agent; conversely, the curve obtained with the laser diffraction method shows an aggregated particle size distribution. Similar results have been found in research on volcanic ash-derived soils in Japan (Gobin et al. 2023).

The particle size distribution curves obtained by both methods fall within the ranges previously reported for volcanic ash-derived soils in the city of Manizales (Herrera et al. 2007; Vásquez-Varela and Mendoza 2021) and Popayán, Colombia (Hernandez et al. 2018).

Regarding the effect of drying on the grain size distribution, the results demonstrate that the drying process induces a shift of the curve to the right, resulting in larger apparent particle sizes. This phenomenon is caused by a change in soil structure, where primary particles aggregate into stable, coarser clusters.

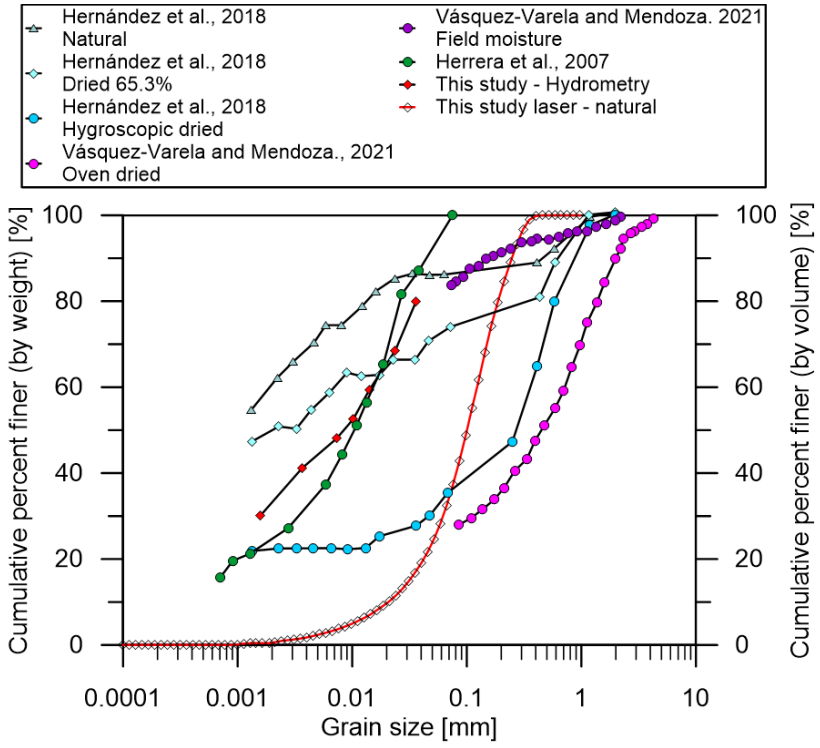


Figure 3. Particle size distribution curves of volcanic ash soils in Colombia.

3.1.3. Compaction characteristics

Low maximum dry unit weights in the natural state of volcanic ash-derived soils have been reported by several authors, including (Hernandez et al. 2018; Vásquez-Varela and Mendoza 2021; Verdugo 2008). Researchers such as (Hernandez et al. 2018; Herrera et al. 2007; Romero-Mancilla et al. 2021; Verdugo 2008; Wesley 2003) have demonstrated that drying volcanic ash-derived soils prior to compaction testing significantly affects the resulting maximum dry density. These authors found higher maximum dry unit weights in air-dried or oven-dried samples compared to natural (undried) samples, with oven-drying having a more pronounced effect on the increase of the maximum unit weight (see Figure 4). The susceptibility of these samples to drying is attributed to the collapse of allophane spheres and imogolite tubes, which causes the release of adsorbed water without any subsequent recovery to the mineral's original morphology (Mackenzie et al. 1989).

Two material preparation procedures were conducted in this study, as described in the previous chapter. For the samples compacted using the procedure designated as SC, an optimum water content w_{opt} of 43.9% and a maximum dry unit weight γ_d of 10.5 kN/m^3 were obtained. For the samples compacted following the DC procedure (pre-compacted samples), the results showed an optimum water content w_{opt} of 42.3% and a maximum dry unit weight γ_d of 11.4 kN/m^3. These results are presented in Figure 4. It is evident that the samples subjected to a double compaction process exhibit higher dry unit weights than those that underwent only a single compaction stage. This behavior is attributed to structural changes in the material resulting from the air-drying process and the compaction energy applied during compaction process.

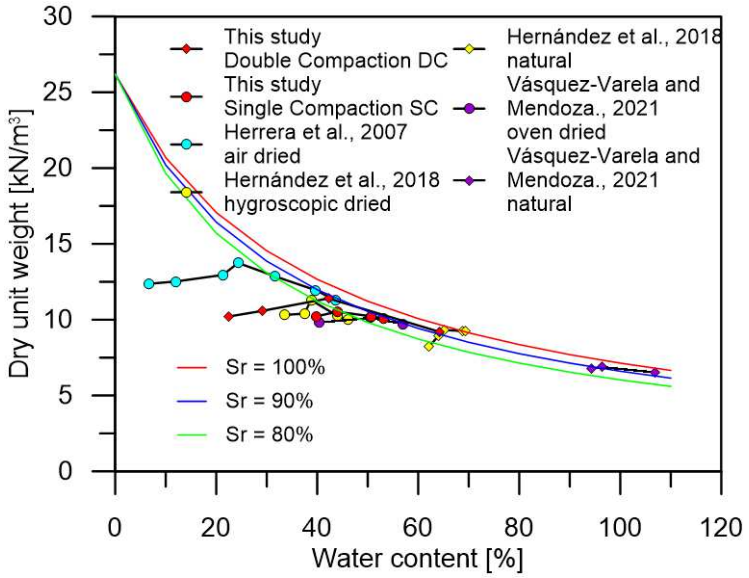


Figure 4. Standard Proctor test results for volcanic ash soils in Colombia.

3.1.4. Soil water retention courve

The soil water retention curve was determined using a WP4 device and is represented by the red line in Figure 5. The curve was established for a drying path, with the sample prepared at the optimum characteristics derived from the compaction test. The gravimetric retention curve was fitted using the RETC software (van Genuchten et al. 1991) according to the Van Genuchten-Mualem model (Mualem 1976; van Genuchten 1980). The figure also includes drying path water retention curves reported in the literature for volcanic ash-derived soil samples in Colombia. A strong similarity is observed in the reported water content ranges and suction levels (Hernandez et al. 2018; Herrera et al. 2007).

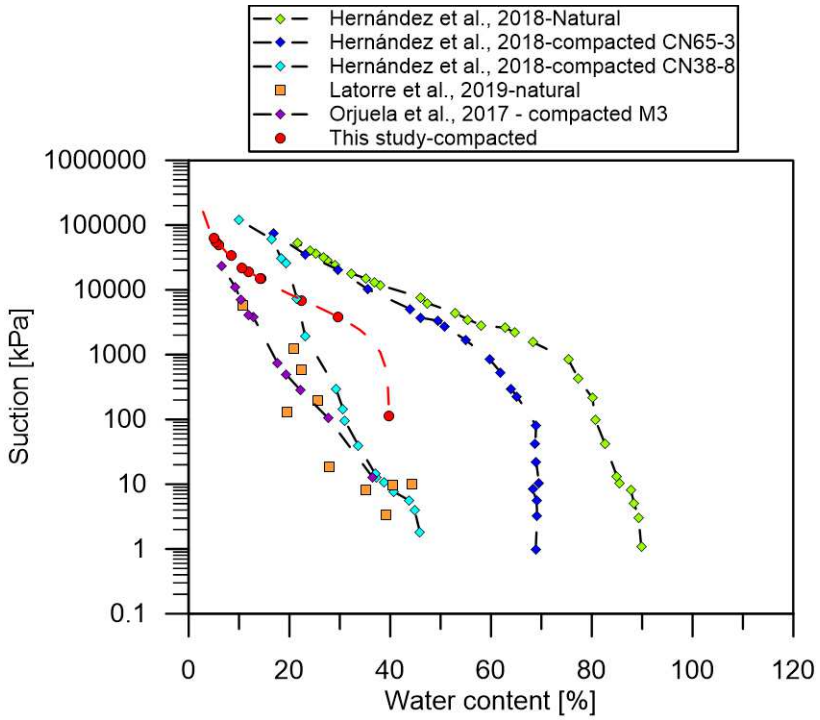


Figure 5. Soil water retention curve for volcanic ash soils in Colombia.

3.2. Effect of Recompaction on Soil Shear Strength

To study the effect of recompaction in a direct simple shear test, tests were conducted at vertical stresses of 50, 100, and 200 kPa on samples subjected to two preparation processes, SC and DC, as explained in the Materials and methods section. The shear stress vs. shear strain and axial strain vs. shear strain behaviors obtained from these tests are presented in Figure 6. Figure 6a shows that samples subjected to the mechanical compaction effort twice (DC process) exhibit higher shear strength than those compacted only once (SC process). This increase in strength can be attributed to enhanced particle aggregation, which leads to structural changes and higher resistance. In volcanic ash soils, this process is particularly significant as mechanical reworking alters the natural fabric and pore distribution, resulting in a more stable, overconsolidated-like structure. Consequently, the SC samples exhibit axial compression during the shearing phase at vertical stresses of 50 and 200 kPa (Figure 6b). In contrast, the SC sample under a vertical stress of 100 kPa and the recompacted DC samples display dilative behavior, characterized by axial expansion during the shearing phase. Therefore, recompacted samples tend to exhibit behavior more characteristic of overconsolidated

soils due to the higher compaction energy. This is consistent with the findings of (Cordão Neto et al. 2018; Fleureau and Kheirbek-Saoud 1992) who demonstrate that the yield stress is a function of compaction energy.

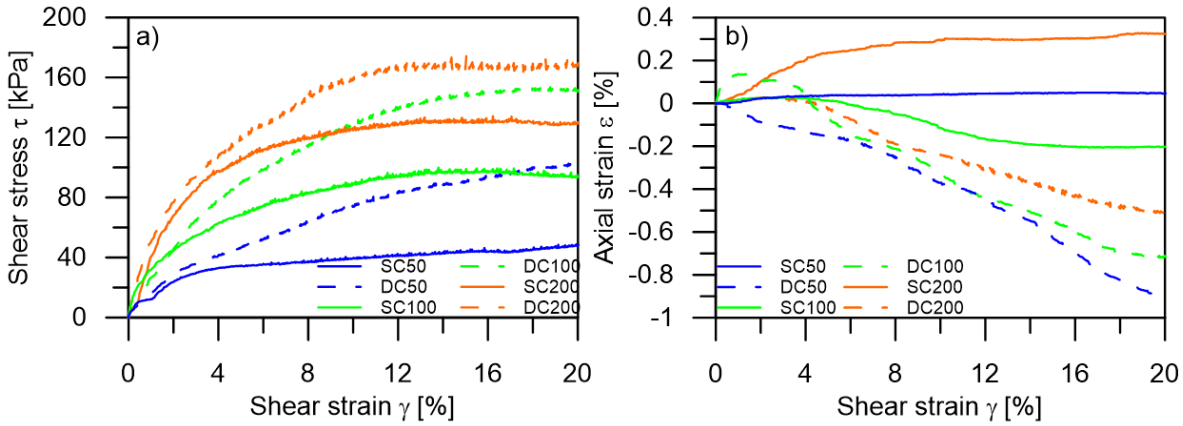


Figure 6. Shear response of single-compacted (SC) and double-compacted (DC) samples: a) shear stress vs. shear strain, and b) axial strain vs. shear strain.

Figure 7 shows the secant shear modulus G obtained at different shear strain percentages for the single-compacted (SC) and double-compacted (DC) samples. The results indicate that the shear moduli decrease as shear strain increases, with higher values observed in the DC samples compared to the SC samples across all three applied vertical stresses. Furthermore, a clear relationship exists between the vertical stress and the initial secant modulus, which degrades as shear strain increases, consistent with the findings reported by (Soga et al. 2007).

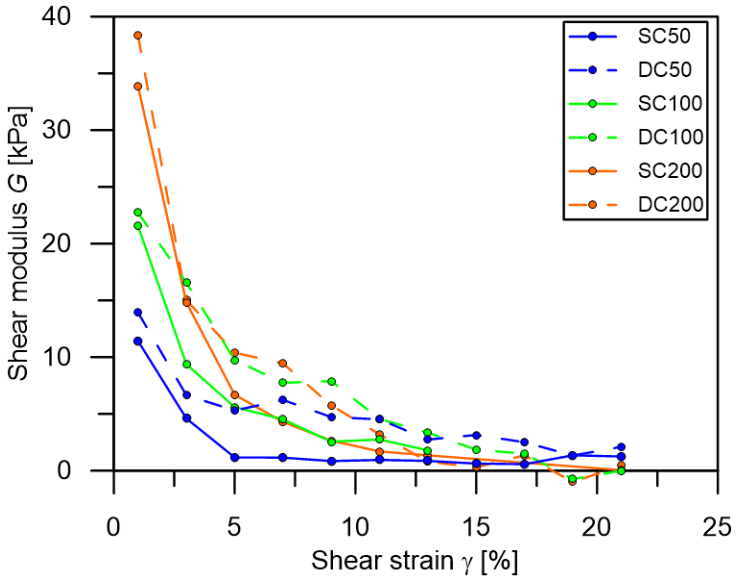


Figure 7. Shear modulus variation for single-compacted (SC) and double-compacted (DC) samples.

Figure 8a presents the Mohr-Coulomb failure envelopes at different shear strain levels for the single-compacted (SC) and double-compacted (DC) samples. Figure 8b shows the failure envelope at a shear strain of 16% for both compaction processes. As evidenced in Figure 8b, there is a clear increase in shear strength parameters: the cohesion c' increases from 37.2 to 73.4 kPa, and the friction angle ϕ' rises from 25.7° to 30.6° for the SC and DC samples, respectively. The occurrence of such substantial strength parameters aligns with observations by (Wesley 2003) in volcanic ash-derived soils in Indonesia and New Zealand, where friction angles can reach 40° and cohesion values exceed 20 kPa.

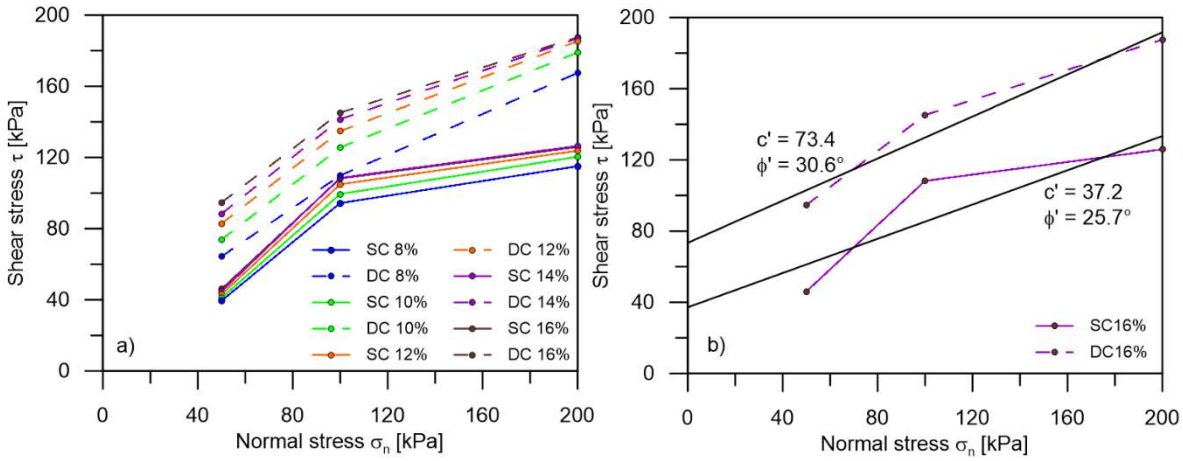


Figure 8. Mohr-Coulomb failure envelopes for single-compacted (SC) and double-compacted (DC) samples: a) envelopes at different shear strain levels, and b) envelopes at 16% shear strain.

3.3. Influence of water content on soil shear strength

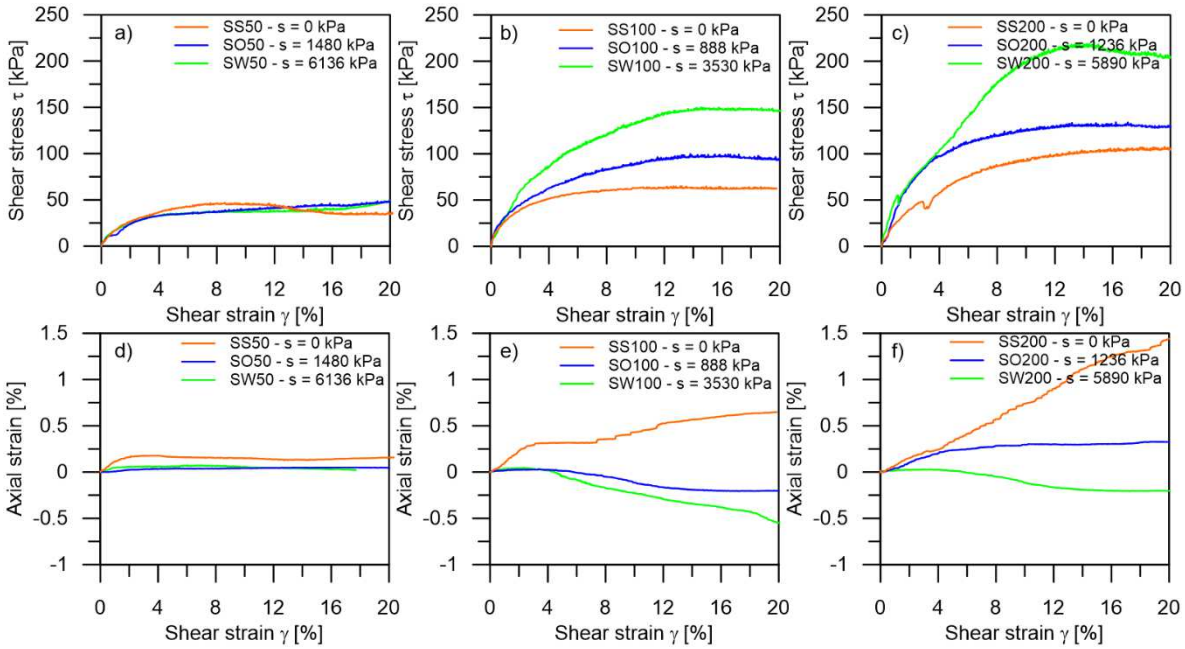
Figure 9 presents the direct simple shear DSS test results for samples prepared at different initial water contents. All specimens were initially compacted at the optimum water content, following the procedure for single-compacted (SC) samples described in the Materials and Methods section. Subsequently, three different hydraulic states were evaluated: as-compacted at optimum water content w_{opt} (SO samples), air-dried for three days after compaction w_{dry} (SW samples), and saturated after compaction w_{sat} (SS samples).

The average water content at the start of testing was 37.6% for samples at optimum conditions, 26.4% for those air-dried over three days, and 47.3% for saturated specimens. Based on the soil-wter retention curve (SWR) showin in Figure 5, these water content stated correspond to average suction levels of 3799 kPa, 7020 kPa, and 0 kPa, respectively. These values highlight the significant influence of hydraulic state on the initial stress conditions of the soil.

Figures 9a to 9c illustrate an increase in shear strength as vertical stress rises across all testing conditions. At vertical stress of 50 kPa, the influence of water content on shear strength was negligible. However, at higher stress levels (100 kPa and 200 kPa), shear strength increased as water content decreased. This behaviour is attributed to the contribution of matric suction to the soil's shear strength, as suction acts as a fundamental state variable in unsaturated soil mechanics (Fredlund et al. 2011; Fredlund and Morgenstern, 1977). According to Bommer et al 2002, combination of suction and inter-particle bonding might explain the existence of steep slopes formed in this materials.

Figures 9d-f illustrate the evolution of axial strain as a function of shear strain. A consistent contractive response is observed in the saturated SS samples across all vertical stress levels. In contrast, for the as-compacted SO and air-dried SW samples under a vertical stress of 50 kPa, the magnitude of compression is significantly lower than that of the SS specimens. Notably, a transition to dilatant behavior occurs for the SO and SW samples at a vertical stress of 100 kPa; a similar dilative trend is maintained for the SW sample at 200 kPa. Conversely, the SO sample exhibits a shift back to compressive behavior under a vertical stress of 200 kPa. This response in the unsaturated samples is attributed to suction, which enhances shear strength and induces greater material stiffness due to internal capillary forces. As vertical stress increases, this dilative tendency is suppressed by the confinement hindering soil expansion. Consequently, the saturated samples do not exhibit this behavior, closely resembling the response of a normally consolidated soil.

(Verdugo 2008) indicates that samples consolidated below the yield pressure show a moderate contractive response with some dilation at large strain, whereas the samples consolidated at higher pressure drastically change to a fully contractive response. This response is similar to that observed in common mechanically preconsolidated sedimentary fine-grained soils.



328

329 Figure 9: Direct simple shear response for samples at different initial water contents (SO, SS, and
330 SW): shear stress versus shear strain at vertical stresses of (a) 50 kPa, (b) 100 kPa, and (c) 200
331 kPa; and axial strain versus shear strain at vertical stresses of (d) 50 kPa, (e) 100 kPa, and (f) 200
332 kPa.

333

334 The Mohr-Coulomb failure envelopes obtained for the samples analyzed at different matric suction
335 levels are presented in Figure 10a. This figure demonstrates that the soil's shear strength increases
336 as suction rises (see Figure 10b). This effect is explained by the extended Mohr-Coulomb failure
337 criterion, which accounts for the influence of suction on the shear strength of unsaturated soils
338 (Vanapalli et al. 1996). Within this framework, an additional axis representing matric suction is
339 introduced. The data points located in the space of normal stress, suction, and ultimate strength lie
340 on a failure envelope that can be defined in terms of either total or effective stresses (Vanapalli et al.
341 1996). It should be noted that, due to the limitations of conventional DSS testing, suction is not
342 controlled during the shearing phase. Consequently, this figure represents the initial suction level
343 derived from the SWCC.

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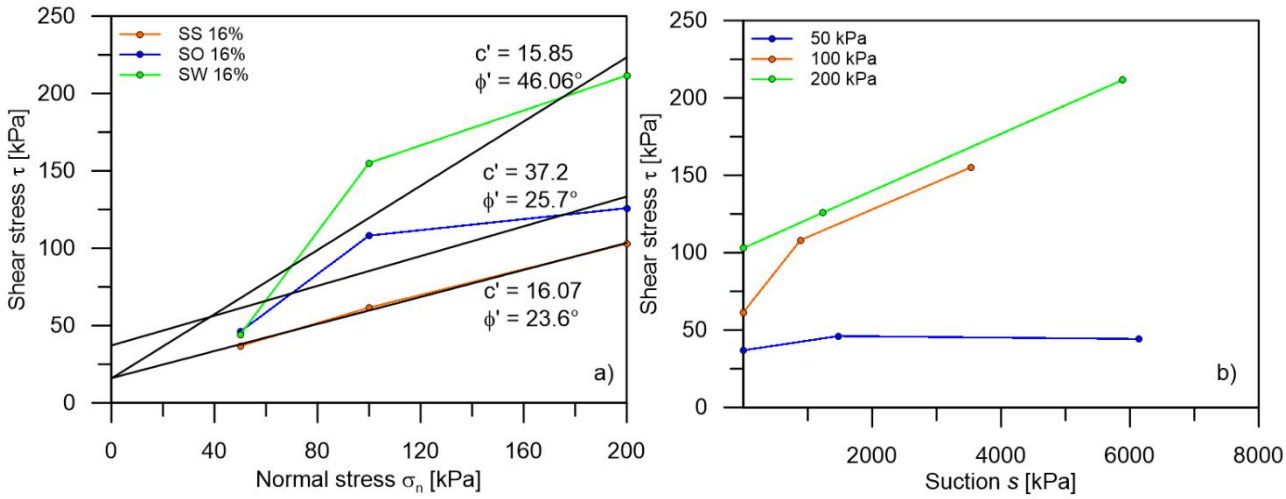


Figure 10. Shear strength variation at different suction levels: a) Mohr-Coulomb failure envelopes, and b) Shear stress as a function of matric suction.

3.4. Influence of water content on soil shear modulus

Figures 11a-c present the secant shear modulus, G, as a function of shear strain for the tested conditions. For samples subjected to a vertical stress of 50 kPa, the shear modulus whows neglible variations across different suction levels. However, at vertical stress of 100 kPa and 200 kPa, the shear modulus increases as suction rises. This behaviour is linked to the increase in effetive stresses contributed to the matric suction. In unsaturated volcanic ash soils, matric suction acts as a confining force that pulls particles together, increasing inter-particle contact areas and restraining particle rearrangement during small-strain shearing (Figure 11b-c). As the applied vertical stress increases, the soil skeleton becomes more constrained, allowing the matric suction to exert a more pronounced effect on the stiffness of the soil matrix. These results are consistent with the findings of Soga et al. (2007), who identified that both confining pressure and suction are primary variables governing the small-strain shear modulus in unsaturated residual soils.

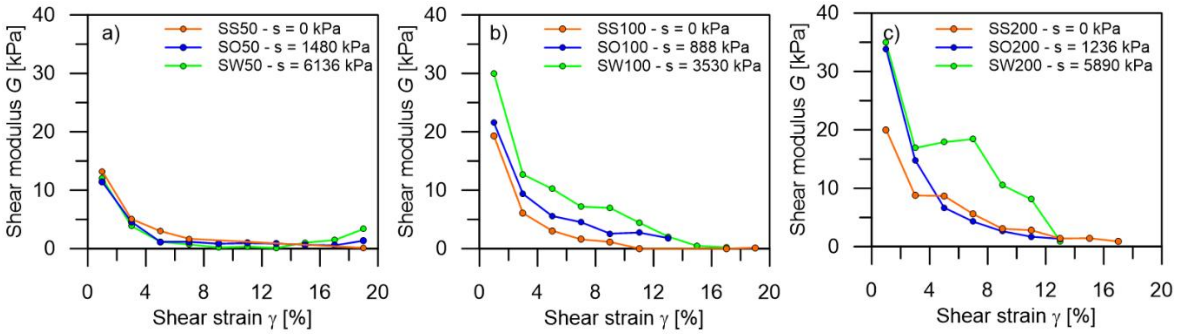


Figure 11. Variation of shear modulus for different initial water contents (SO, SS, and SW) at vertical stresses of: a) 50 kPa b) 100 kPa, and c) 200 kPa.

4 Conclusions

This study successfully determined the mineralogical characteristics, chemical composition, and geotechnical classification of a volcanic ash-derived soil from Manizales, Colombia, while evaluating the specific effect of recompaction on its stress-strain behavior and shear strength under the influence of initial water content states (air-dried, oven-dried, and natural), the following conclusions can be drawn:

- Drying induces irreversible aggregation of primary particles into stable clusters. Particle size determination is highly technique-sensitive: the hydrometer method disaggregates particles due to dispersing agents, whereas laser diffraction preserves natural clustering, yielding an aggregated distribution characteristic of these residual soils.
- Pre-drying irreversibly collapses the allophane and imogolite structure. Consequently, applying cumulative mechanical energy through a double compaction (DC process) resulted in a higher maximum dry unit weight γ_d of 11.4 kN/m³ and a lower optimum water content w_{opt} of 42.3% than a single compaction (SC process) (10.5 kN/m³ and 43.9%, respectively), confirming permanent structural changes.
- Compaction history governs the soil's mechanical behavior. DC specimens developed a stable fabric with dilative behavior typical of overconsolidated soils. This additional reworking

doubled the effective cohesion (from 37.2 to 73.4 kPa), increased the friction angle (25.7° to 30.6°), and produced notably higher initial secant shear moduli, G, compared to SC samples.

- The contribution of matric suction to the shear strength response and stiffness is confinement-dependent. While water content variations had a negligible effect at low confinement (50 kPa), higher stress levels (100 and 200 kPa) combined with lower water contents (higher suction) drastically enhanced shear strength and modulus, validating the extended Mohr-Coulomb framework.
- The initial hydraulic state dictates the volumetric response. Saturated specimens exhibited a contractive behavior resembling normally consolidated soils, whereas capillary forces in as-compacted and air-dried samples induced a dilative trend. Thus, rainfall-induced saturation eliminates suction, triggering sudden contraction and strength loss, a critical mechanism explaining the high susceptibility of these deposits to slope instability.

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Laboratory testing and data collection were performed by Esteban GUACANEME and Catalina LOZADA. Material acquisition was performed by Cristhian MENDOZA. Data analysis and interpretation were performed by Catalina LOZADA, Cristhian MENDOZA, and Hermes Ariel VACCA. The first draft of the manuscript was written by Catalina LOZADA, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during the current study are not publicly available, but are available from the corresponding author on reasonable request.

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