Implications of physical and chemical changes in volcanic ash soils related to road construction

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Abstract. Soils derived from weathered pyroclastic material in a humid tropical environment, known as volcanic ash soils, cover a low portion of the Earth's surface. However, its unique characteristics, such as high porosity, low unit weight, high water content, and susceptibility to change in properties by drying and remolding, justify its study due to the impact of these characteristics in the construction of embankments and road subgrades, particularly on the compaction characteristics. The urban settlements located in the tropical zone, close to areas of volcanic activity, develop their road infrastructure on this type of soil. Under laboratory conditions, the soils' chemical and physical changes, particularly on the particle arrangement or fabric, create a gap between their expected and actual behavior at the construction site. This article presents some problems in road construction related to these unique features and how to deal with them on the construction site, applying conventional classification and compaction tests in the lab and construction site. The particularities of the soils in these conditions are explained using unconventional tests to assess the microscopic effects of compaction on the soil fabric.

1. Introduction
Volcanic ash soils are less than 1% of the Earth's continental surface [1]. However, the effect of its genesis on its geotechnical behavior [2] and the subsequent impact on infrastructure justifies the study of these soils, particularly in those aspects in which they differ from the expected behavior of the sedimentary soils covered in traditional soil mechanics.

This work presents some problems in road construction on and with soils weathered from volcanic ash in a hot-humid tropical environment. Several researchers studied the characteristics of this type of soil. Numerous works emphasize the difficulties of classifying soils due to their change in properties because of the standard laboratory handling processes [3-8]. Other authors investigated the mechanical properties of these soils to establish their stability in slopes and foundations [6,9-11]. Also, the seismic response of these soils has been investigated [12,13].

The authors review some experiences on road construction issues related to the classification of volcanic ash soils and the obtaining of relationships between dry unit weight and moisture in road construction quality assurance and control. A single physical parameter, dry unit weight, is key to quality assurance and construction control; however, due to chemical and physical changes of volcanic ash soil under drying, this value must be assessed under controlled conditions to avoid unrepresentative results.
2. Background

As previously stated, residual soil deposits from weathered volcanic ash are a small fraction of the world's soils [1,14]. Although less studied than sedimentary soils, volcanic ash soils present problems such as cracking, high water retention capacities, workability problems due to excessive moisture, and very soft consistencies that justify its study [1,2,10,15-17]. In addition, the properties of these soils vary depending on the wetting or drying path [2,18-19]. These problems imply challenges in constructing embankments and road subgrades on these soils, particularly with the compaction characteristics used in earthworks quality assurance and quality control.

Figure 1(a) shows that soil deposits weathered from volcanic ash occupy approximately 11.6% of Colombia's territory on the three branches (Cordilleras) of the Andes [1]. This region comprises a vast majority of the economic activities and infrastructure development.

Figure 1(b) and Figure 1(c) show the formation and transformation of andesitic volcanic ash into soil. First, smaller than 2 mm ash particles are expelled by the volcanic eruption and transported by the wind. In Colombia, volcanic ash soil originated from the Ruiz, Tolima volcano complex eruptions in the last 20 thousand years of the Holocene and Pleistocene epochs of the Quaternary [8]. Once deposited, the volcanic ash suffers a transformation or diagenesis phase into volcanic ash soil. The mineralogy of these soils contains unusual clay minerals and amorphous materials, such as allophane, which are products of very rapid cooling that inhibit the development of a crystalline structure.

![Figure 1. Volcanic ash soils in Colombia: (a) geographical distribution, (b) to (d) formation process; adapted from [1,20].](image)

Allophane consists of hollow spheres that measure approximately 5 nm in diameter with 3.8 nm internal diameters and holes of about 0.3 nm [21]. These allophane spheres are mixed with imogolite, which consists of fine thread-like fibers. Weathering of allophane produces halloysite, which also has unusual properties. Additional weathering transforms halloysite into kaolinite [2]. These minerals are obtained by physical and chemical processes, including dissolution, leaching, and precipitation of the initial volcanic ash. In general, the ash minerals are light (Gs < 2.8), and the soils have high void ratios, porosities, and liquid limits. Also, a brittle structure is formed that changes in the compaction process leading to a change in behavior [2]. This behavior change is different depending on the wetting or drying path.
Figure 2 was taken by authors' request at the Instituto de Investigaciones en Estratigrafía (IIES) at Universidad de Caldas, Colombia, using scanning electron microscopy (SEM) for an undisturbed sample, and a compacted sample of volcanic ash soil from Manizales, Colombia, obtained at geographical coordinates 5°03'25.5" N / 75°28'49.9" W and three meters depth.

Regarding mechanical properties of volcanic ash soils, results showed by Hernández, et al. [2], Herrera, et al. [8], Arango [9], Forero-Dueñas, et al. [11], Yamin, et al. [12], Wesley [22], and Moroto [23] report peak effective friction angle of residual soils derived from volcanic ash in a range from 25 to 43 degrees, which increases with the compaction process [2]. Herrera, et al. [8] and Wesley [22] report residual friction angles with lower values. Lizcano, et al. [1] made vane tests on volcanic ash soil surface samples and measured peak resistance between 70 kPa to 195 kPa. The residual resistance found for those samples varied between 38 kPa to 170 kPa, with a sensitivity ranging from 1 to 3. The void ratios of these soils vary from 1.0 to 8.0, while their coefficients of compressibility (Cc) vary from 0.1 to 0.8. Regarding the compaction process, Hernández, et al. [2] report values of 65% optimum moisture and a dry unit weight of 9.6 kN/m³ in the drying path and 38% optimum moisture and a dry unit weight of 11.4 kN/m³ in the wetting path.

![Figure 2. SEM images of volcanic ash soil: (a) undisturbed, (b) compacted.](image)

3. Discussion

Based on the previous physical characteristics, a discussion of this type of soil in road construction is raised. This discussion was presented from the physical properties of these soils and their application to road engineering regarding soil classification and compaction properties and quality assurance and control.

3.1. Soil classification

Soils from weathered volcanic ash in a hot-humid tropical environment are susceptible to changes in their properties because of remolding or oven drying procedures in the laboratory [3-5,7,22]. An erroneous soil classification may impact the appropriate definition of pavement design units or even imply unreal liquefaction susceptibility when silts or clays are classified as sands.

Figure 3, obtained by the authors, shows the change in grain size distribution caused by oven drying on volcanic ash soil from Manizales, Colombia. Based on the oven-dried sample, the soil would be classified as sand with some material finer than the 0.075 mm sieve. The actual soil should be classified as silt or clay, based on the laboratory's grain size analysis on samples without oven drying. Hernández, et al. [2] stated that volcanic ash soils have the characteristic that when clayey soils are hygroscopically dried and re-saturated, they are transformed into sandy soils.
Figure 3. Comparison of grain-size analysis of a volcanic ash soil with and without oven drying from Manizales, Colombia.

Figure 4 shows the position in Casagrande's chart of several soils from the central Andean region of Colombia, including the city of Manizales, with data from [5] and [24]. All tests were performed on undried samples [25], and their approximate mineralogy corresponds to allophane or halloysite according to an approximate zonation of mineral composition presented in Wesley [17] and Fourie, et al. [26]. Diaz and Villada confirmed the presence of allophane, imogolite, and halloysite in the samples labeled as Manizales, Colombia, with X-Ray diffraction (XRD) and SEM [24].

Figure 4. Position in Casagrande's chart of volcanic ash soils from the central Andean region in Colombia.

3.2. Compaction properties and quality assurance and control
Volcanic ash soils present two main challenges for compaction as a road construction material: first, as subgrade in cuts, the structure of the soil forbids the conventional compaction procedures with the sheep-roller compactor and other devices that cause large strains in the soil mass; second, in embankments, the compaction procedures require the use of low-pressure equipment (i.e., wide-rail tractor selected by trial and error) and minimum handling from the borrow area to the extension and compaction at the construction site to avoid the disintegration of the soil.

The use of undisturbed samples is mandatory for assessing resistance in this type of soil. Thin-walled tubes provide appropriate samples for stability and deformation analysis; the in-situ sampling of California bearing ratio (CBR) mold [27] allows an approximate "undisturbed" technique for volcanic
ash soils. The dynamic cone penetrometer (DCP) test [28] evaluates the undrained shear resistance of the subgrade with known correlations with the CBR and resilient modulus for subgrade evaluation [29-31]; for earthwork quality control construction, care must be taken in the laboratory estimation of compaction requirements based on the standard procedures to evaluate the unit weight-moisture-resistance relationships [32]. Figure 5 shows compaction curves for volcanic ash soils from two roads near Pereira, Colombia's central Andean region; both curves were obtained on samples with and without oven drying before the compaction in the laboratory.

In Figure 5(a), the in-situ condition (red diamond) corresponds to high moisture (95%) and a low dry unit-weight (6.835 kN/m³), which contrast with the characteristics of the oven-dried samples with a maximum dry unit weight of 10.2 kN/m³ and optimum moisture of 47%. Any attempt to construct an embankment based on the oven-dried compaction curve will require an impractical reduction of up to 50% of gravimetric moisture (several tons of water per truckload of borrowed soil) and an improbable increase of 146% in the dry unit weight. Figure 5(b) shows similar behavior; both cases show a clear difference between the optimum compaction moistures and the maximum dry unit weights of oven-dried and undried volcanic ash soils. Reference [4] reports the same behavior at Juan Santa María Airport construction in San José, Costa Rica, on residual tropical soils. Failure to identify the change in volcanic ash behavior due to laboratory practices as oven drying will cause a wrong assessment of the unit weight-moisture relationship. Such error will significantly impact construction activities as the quality control will be based on unrepresentative results. Any attempt to satisfy the low optimum moisture will require the setting-up of industrial drying installations with the associated costs, that is, to carry the alteration process from the small-scale samples in the lab to the whole earthwork construction at the field.

![Figure 5. Compaction curves with oven-dried and undried samples obtained from (a) Pereira, Marsella, Colombia, K10+400 and (b) Pereira, Cerritos, Colombia, K1+700.](image)

4. Conclusions
This study presents an understanding of the physical behavior of volcanic ash soils applied to engineering; volcanic ash soils formed in the hot-humid tropical environment have physical features that may be changed compared to the other soil in the world, these changes impact road construction activities. For example, the soil has a low density but stability in slopes with high angles. The compaction behavior changes with the wetting or drying path; these soils' unique behavior has been explained by their chemical composition, especially by the presence of minerals such as allophane, halloysite, and imogolite, which are susceptible to irreversible transformations in routine laboratory processes that were primarily conceived for sedimentary soils.
Two main aspects can impact the construction of roads in soils derived from volcanic ash in a tropical environment: the first is the error in classifying the soil as sand when it is silt or clay, which affects the definition of pavement design units and could even produce wrong conclusions about the susceptibility of the deposit to the liquefaction phenomena; the second impact compromises the validity of the reference tests for the quality control of the compaction of embankments, which represent unrealistic conditions in the field that will lead to the systematic rejection of batches, waste of resources, and delays because of the inadequate soil characterization. Since the design of embankments requires the definition of flow, deformation, and resistance parameters of the soil for stability and settlement analysis, the inadequate characterization of the compacted state also represents a risk for the users of such earth structures. These situations can be avoided with simple and inexpensive procedures for characterizing soil samples suspected of having these characteristics by comparing test results with drying and without prior drying of the samples before classification, resistance, and compaction testing in the laboratory.

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