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Influence of the compaction process in the shear strength of a volcanic soil

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Abstract. This study contains experimental results on the influence of the compaction process over the shear strength of a soil derived from volcanic ash. The tested soil comes from the area of Palestina, located in the department of Caldas in the center of Colombia. This research includes the use of both basic and advanced experimental techniques: dynamic and static compaction methods that allow to estimate the impact of the applied compaction energy on the material; and the technique of the filter paper that enables to evaluate the characteristics of water retention in statically compacted samples for different compaction conditions. The experimental results led to observe the behavior of the soil in terms of its density and water content at compaction, also considering the suction characteristics. Different types of soil fabric generated as a result of the nature and magnitude of the compaction energy were found; on the other hand, the variation of some soil properties, such as water retention, shear strength and soil stiffness, was observed. The extended Mohr-Coulomb failure criterion [1] accurately represented the final stress conditions at failure.

Keywords. Shear Strength, compacted soil, unsaturated soil, volcanic soil.

Introduction

In several countries it has been seen that the use of volcanic soils, as building material, seems to be inconvenient for the performance of the geotechnical structures, in terms of their volumetric performance and shear strength. According to [2] and [3], these problems have been related mainly with the compaction process during the construction. (e.g. in Colombia, Costa Rica, New Zealand, India, Japón and Indonesia). The control of the compaction process in engineering practice is generally developed by following the classic methods such as the one proposed by Proctor in 1930, which determines the optimum water content for a specific compaction energy that produces the maximum dry density: given that, in the majority of soils there is a unequivocal relationship between the density and the shear strength. The method also has been used very often with the volcanic soils. According to [4], as a result of the compaction in the field and the control by the Proctor methodology, there is evidence that the material after compacting presents very low resistance to the shear. The hypothesis that supports this outcome is that, the energy provided towards the soil can be excessive, therefore, the soil micro-structure breaks and consequently, the water contained into the pores is released, increasing the quantity of free water and converting the material in a viscose mass.

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The influence of the compaction process on the shear strength of volcanic soils was studied through the design and execution of an experimental program using a volcanic ash-derived soil.

1. Properties of the soil studied.

The soil in this study has its origin in the physical and chemical alteration of the volcanic ashes deposits (dissolution, lixiviation and precipitation of composite). These processes transform the minerals, the shape, the size of the particles, the fabric and the porosity. Their influence is controlled by the climatic conditions and the time. The climatic conditions (precipitation, temperature, humidity and air) determine the presence of available fluids for the chemical reactions, the rate at which such reactions occur, the migration of composite and the erosion, among other processes [5]. The time, on the other hand, dominate the sequence of the synthesis of secondary minerals and the distribution of the different particle sizes. Volcanic ashes confer quite definite properties to the soils (Andosols and Andic soils). One of the main characteristics that the soils inherit from the original material is the Allophane, an amorphous aluminium silicate (particular characteristics of the soils rich in these minerals are recognized worldwide). An experimental program, that included the required tests in order to know the specific properties of the volcanic ash-derived soil, was performed. The soil used corresponds to the most superficial layer of a representative zone of the typical soil of the Palestina area. Particular recommendations for the characterization of tropical residual soils were taken into account [6]. The index properties and the gradation curve of the material of study are shown in table 1 and figure 1.

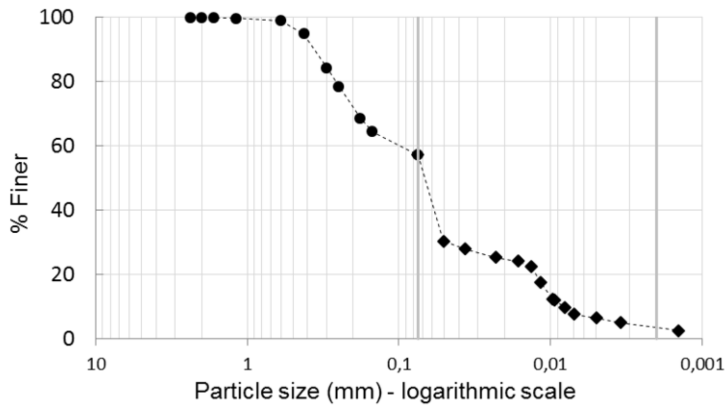

Figure 1. Particle size distribution of the soil studied.

Table 1. Properties of the soil studied.

Visual Description	USCS Group	LL (%)	PL (%)	PI (%)	Gs	e Natural Sample
Silt with sand and clay (LAA)	ML	58,7	37	21,7	2,63	1,7

2. Experimental techniques

2.1. Compaction characteristics

Static and dynamic compaction tests were performed with the aim of representing and investigating the different states of compacted soils and the interdependence between the dry density (ρd) and the water content (ω) under different compaction energy.

2.2. Dynamic compaction

To determine the compaction characteristics of the soil under study, Proctor type tests were performed by applying different compaction energies. The methodology for the Proctor test corresponds to the standard ASTM [7] and a variation is done in the number of blows for every layer during the test, aiming to achieve different values of applied energy, which are defined in table 2. In figure 2, the dynamic compaction curves of the studied soil are presented.

Table No 2. Relation Energy - No. of blows. Type Proctor test

Blows	Energy (kN*m/m3)
15	354.8
25	591.3
35	827.8

The following observations are presented. They display differences with the typical performance of soils in this test:

- As the compaction energy increases, the maximum dry density increases.
- As the compaction energy increases, the optimum water content increases.
- The maximum dry densities occur to saturation degrees close to 91%

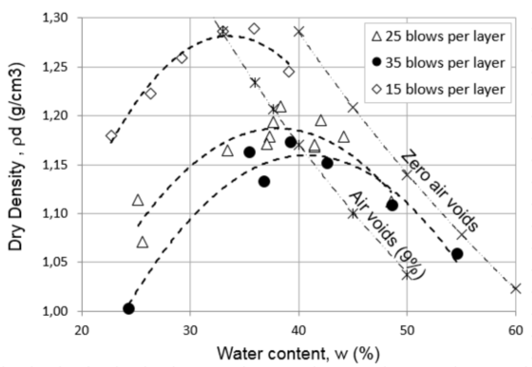

Figure 2. Proctor test for different compacting energies.

2.3. Static compaction

A variable peak stress compaction procedure, with variable final deformation, was executed: a process in which the curves (Load-displacement) were monitored in order to measure the compaction energy. Curves of Iso-energy were evaluated and the results are represented in the Proctor plot. The compaction characteristics (ρd, ω) for the static compaction are presented in Figure 3, in continuous lines.

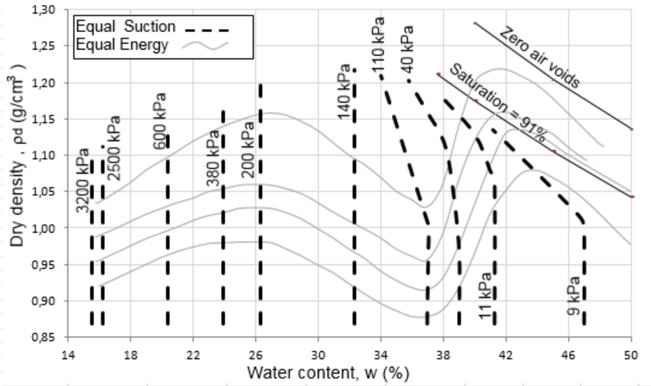

Figure 3. Compaction curves of the studied soil with suction constant suction lines.

3. Measurement of the matric suction

The water suction associated to each compaction state is additional information of big interest to understand the soil performance. Authors such as [8] and [9] have shown iso-suction lines in compacted soils over the curves in the compaction diagram. Figure 3 presents also the values of the matric suction measured for the statically compacted samples. The Filter paper technique was used for suction measurement. The matric suction increases as the compaction water content reduces and when the degree of saturation increases. Curves of equal suction tend to be vertical lines and for high degrees of saturation (about 80%) the bend to the left following the lines with equal degree of saturation. For low water contents, the suction is controlled apparently only by the water content, with no influence of the dry density.

3.1. Soil - Water retention Curves

The relationship between the pore water suction and the water content is represented in the denominated soil.-water characteristic curve, or soil - water retention curve. This is one of the fundamental relations used to describe the performance of a partly saturated soil. The suction is inversely proportional to the water content in a soil and its value increases while the soil loses saturation. In this study, the water retention curve was found for both, the soil in natural condition and for the statically compacted soil with initial conditions of water content and density similar to the ones the natural material. The experimental work was developed taking into account that the construction process that is applied for the compaction of volcanic ash-derived soils is based in the criterion of compacting the material simulating the in situ soil density for the natural water content [3]. Figure 4 presents Soil- water retention curve of the soil used in this study (in natural condition), and typical curves according to the type of soil[10]. In this figure, it is observed that the curve corresponding to the Silt with sand and clay (LAA) is similar with the curve of soil studied. They also have similarities in particle size distribution.

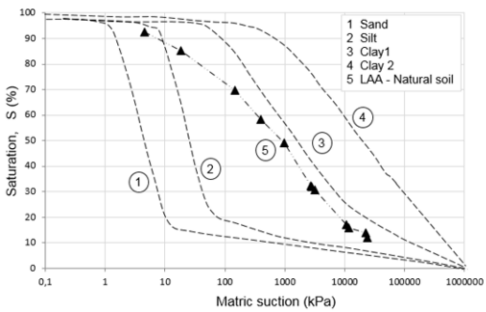

Figure 4. Typical Soil-water retention curves according to the type of soil. Adapted from Gitirana y Fredlund (2004).

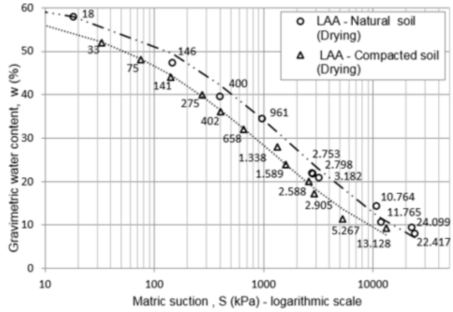

Figure 5. Soil-water retention of the natural Curves of natural and compacted samples.

Figure 5 presents the results of Soil-water retention curves for compacted and natural material. In both cases, drying curves are departing from similar initial dry density and water content (ρd, ω). The Soil-water retention curve of the compacted sample is displaced to the left from the one corresponding to the material in natural state. For constant water content values, the suction in the compacted material oscillates between the 59% and the 31% of the one corresponding to the natural material. This difference can be explained by the existence of different fabrics in both materials. It is inferred that the compaction energy provided to the compacted soil doesn't have enough magnitude to make up a fabric sufficiently closed that allows obtaining similar suction values in the residual water content. [11], found that, the bigger the compaction energy, the residual water content increases. According to the authors, the soil subjected to compaction forces lower than the standard Proctor test will have a high porosity and, therefore, the Soil-water retention curve will be displaced towards the left and down with respect to the retention curve of the soil in natural conditions. Images taken by the optical microscope from a natural sample and the statically compacted sample in similar conditions of dry density and water content are shown in Figure 6a and 6b. In both figures, it can be seen a modification in the structure of the compacted soil, mainly reflected in the loss of the cementation attributed to the iron oxides and the fabric condition, with a larger porosity than in the natural soil. In the natural sample, the accumulation of free water in the soil voids is observed. It is probably the cause of softening during the process of dynamic compaction. On the other hand, in the compacted sample, it is noted the agglomeration of small particles, creating arrangements of bigger size, allowing the generation of a more open fabric with a larger porosity. It is also observed that, the continuity of the pores produces "cracks" that might be the cause of the low stiffness and the low shear strength in the direct shear test in samples compacted by the wet side of the optimum water content.

4. Mechanic performance tests

The conventional Direct Shear equipment was used in order to evaluate the characteristics of shear strength of the compacted and natural material.

Several variables that might be involved in the process (dry density, water content, suction, saturation and normal vertical stress) were taken into account. The normal vertical stress was fixed to a constant value of (σn) 98.07kPa, for all the samples. It simulated an approximate vertical load of a 6m high embankment. The results from the shear tests are presented in the figures 7a. In general terms, when shearing is carried out in the dry side of the compaction optimum water content, (for a constant dry density), both the shear strength and the stiffness of the soil increase as the matric suction increases. It is inferred that, this result is directly caused by the increase in the capillary tensions. On the other hand, for samples compacted on the wet side (low matric suction), a ductile performance with low shear strength was observed. In the figure 7a is observed that the material presents softening by deformation for every density evaluated and for high levels of suction. In the specimens with low suction values, hardening by deformation appears for every assessed density. The latter means that, the density and the suction are important factors that influence the hardening or softening performance of unsaturated compacted soils.

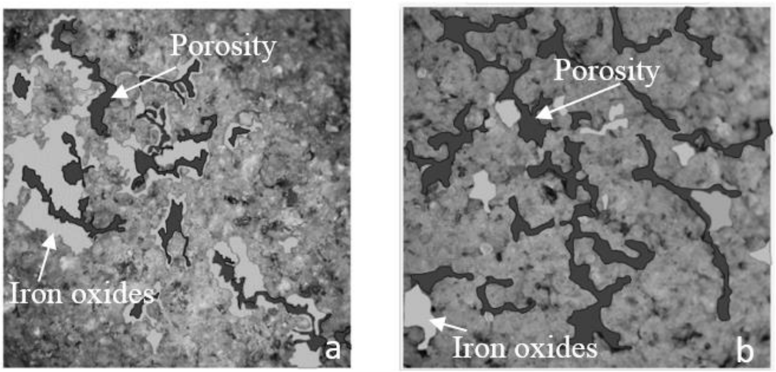

Figure 6. Fabric observation of the soil used: a) Natural Soil, b) Compacted Soil. In both cases. (ρd=0.96 g/cm3, w=58%)

Figure 7b, presents the relationship between horizontal displacement and vertical displacement for tests with different initial suction values and different values of dry density. Results show a dilatant behavior for high initial suction values at any tested dry density value. As the dry density increases, a larger dilatancy is observed. According to [12], this can be explained by the fact that the water content is reduced at high suctions and the soil particles can't move around each other, but they try to put themselves one over another when the shear is induced with reduced normal forces, which causes a bigger dilatancy. At lower suction values it is observed an effect of lowering of the volume for the tested densities. It can be inferred that the dilating or contracting performance of the compacted soil in this study depends mostly on the conditions of initial suction than on the dry density value.

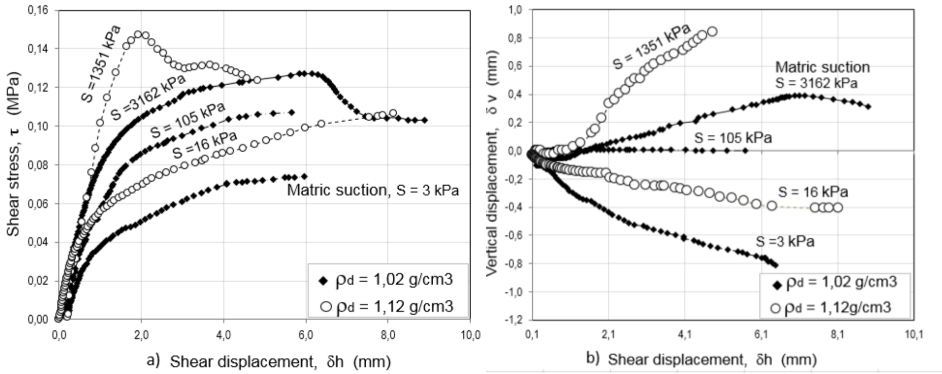

Figure 7. Response of soil to shearing as a function of the initial matric suction and the dry density

Figure 8 presents the variation of the shear strength with the initial suction and the dry density of the compacted samples, in tests of shear strength and using an initial normal stress σn of 98.07kPa. In the results it is observed that for lower suction values, S<105 kPa the shear strength decreases with suction at higher gradient than the one displayed in the suction range between 110 y 3200 kPa.

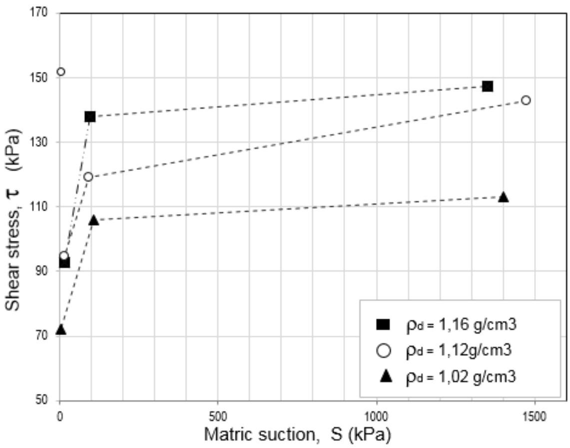

Figure 8. Shear strength based on the initial suction and the dry density.

The variation of shear strength of the material differs in the dry side and in the moist side of the compaction's optimum water content. On the wet side, it is evident that the suction and the dry density have strong influence on upon the shear strength. On the dry side, the effects in resistance increase because of the changes in suction are much lower than in the moist side, but it is observed that the dry density value has enough influence upon the shear strength.

5. CONCLUSIONS

Soils derived from volcanic ash, in its natural state, could be described as a cemented material. This cementation could be considered as quite light and it is characterized for the presence of iron oxides. The residual soil used for this study possesses properties that are susceptible to processes such as the drying and the remodeling, generating changes in the plasticity and deterioration of the natural structure. The obtained results in the dynamic compaction test with water content close to the natural in the studied material indicate that increasing the compaction energy results in softening of the soil, which in addition generates low values in the dry density. It is inferred that this outcome is consequence of the deterioration of the micro-structure of the soil. The static compaction process presents bimodal curves and it can be inferred that according to the compaction water content, the soil phases of water and air present different interaction phenomenon that generate loss or earning of efficiency in the process. The compacted soil has different structures according to three main factors: compaction water content, nature and quantity of compaction energy. The main tendencies found from the shear strength tests show that the resistance and stiffness are function of both the suction and the density. For the samples compacted at low water contents a fragile performance was experienced, with softening by deformation and volumetric change, characterized by the increased dilatancy when the dry density increases. In the specimens compacted with high water contents, low shear strength with ductile performance emerges, observing then hardening by deformation.

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