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Geotechnical behavior of a tropical residual soil contaminated with soap solution

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Abstract
Tropical soils are soils that exhibit physical, chemical, mineralogical and mechanical characteristics that differ from those of temperate zone soils as a result of factors such as weather, humidity and other conditions of the tropics. These characteristics and the anthropogenic contamination of the environment are the subject of the present study, which aims to analyze a soil of tropical residual origin located in the municipality of Guarne – Antioquia (Colombia). Laboratory tests, some of which are more adequate to characterize this type of soil than classical methods (miniature compacted tropical classification, suction, the pinhole test, breakdown, the collapse index, X-ray diffraction, scanning electron microscopy) are performed on samples in their natural state and samples contaminated with a soap solution to establish the differences between the geotechnical characteristics of this soil under both conditions. Subsequently, the influence of the contaminant on the soil's properties is discussed.

Keywords: Tropical residual soil, Lateritic soil, Contamination with soap, Soap solution, Antioquia batholith.

Comportamiento geotécnico de un suelo residual tropical contaminado con solución de jabón

Resumen
Los suelos tropicales son aquellos que debido a factores como el clima, la humedad y otras condiciones propias del trópico, poseen características físicas, químicas, mineralógicas y mecánicas diferentes a los suelos de las zonas templadas. Dichas particularidades y la acción contaminante en el medio producida por el hombre, son la motivación del presente artículo, el cual pretende analizar un suelo de origen residual tropical ubicado en el municipio de Guarne – Antioquia (Colombia), mediante la realización de ensayos de laboratorio, algunos de los cuales son más adecuados para caracterizar este tipo de suelos (Clasificación Miniatura Compactado Tropical, Succión, Pinhole Test, Desagregación, Índice de Colapso, Difracción de rayos "X", Microscopía Electrónica de Barrido), a muestras tanto en estado natural como contaminadas con una solución jabonosa, para establecer las diferencias entre las características geotécnicas de dicho suelo en ambas condiciones y posteriormente, discutir la influencia que tiene el contaminante en sus propiedades.

Palabras clave: Suelo residual tropical, Suelo laterítico, Contaminación con jabón, Solución jabonosa, Batolito Antioqueño.

1. Introduction

The existing studies on soil behavior are extensive. However, the information available on soils that are affected by anthropic processes is relatively scarce. Generally, it is of special geotechnical interest when the soil mass interacts with substances that can alter its properties. In this paper, the effect of a soap solution is evaluated that is highly likely

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to be found deposited in the soils of regions that do not possess an appropriate wastewater disposal system.

In this study, a series of laboratory tests were performed to compare a residual soil sample from the Antioquia batholith in a natural state, with a sample of the same type that was contaminated with a soap solution. For this purpose, in addition to the classical soil mechanics tests (natural humidity, the specific gravity of solids, granulometry by mesh and hydrometer, consistency limits, the direct consolidated drained (CD) shear strength test), tests that accurately describe the characteristics of the studied soil type soils were performed (miniature compacted tropical (MCT) rapid classification, suction by filter paper, the pinhole test, disaggregation, consolidation, double-edometric assays, X-ray diffraction (XRD), scanning electron microscopy (SEM)).

2. Study area

The study soil is located in the municipality of Guarne-Antioquia (6°17´55´´N and 75°24´20´´W). It has a surface of 151 km^2 and is located in eastern Antioquia Department on the Medellín-Bogotá highway 25 km from the city of Medellín. The municipal capital is located at approximately 2,150 m.a.s.l. with heights that range from 2,100 to 2,400 m.a.s.l. The average temperature is 19°C, the average relative humidity is 80% and the average annual rainfall is between 1,900 and 2400 mm. In the region, two climatic periods are presented, which correspond to the rainy seasons (April to March and August to November) and the dry seasons (June to July and December to March) [1].

2.1. General aspects of the geology and geomorphology of the study area

In the study area, an igneous-metamorphic core is geologically distinguished, which is located on the east slope of the Cordillera Central and corresponds to the igneous intrusion of the Antioquia batholith in the Medellín Amphibolite. The Antioquia batholith has a granitic composition with compositional variations that range from quartz-diorites to tonalities and with minerals such as, primarily, plagioclase, quartz, hornblende and biotite [2].

The municipality of Guarne is characterized by three geomorphological units associated with the Antioquia batholith: moderated to steep slopes, valleys associated with the La Mosca creek and ridges characteristic of regions of low hills with medium slopes and that are located between the valleys and the mountain units [3].

2.2. Description of the weathering profile

The weathering profile of the region is described as follows. In Horizon 1, volcanic ash from the Ruíz – Tolima complex is found [4], which is highly weathered. Horizon 2 is primarily sandy loam with a high content of quartz and biotite. In this horizon, because of the characteristics of its location and the horizon's strong reddish color, soils with signs of lateralization can be expected. Therefore, this study was performed on this horizon. In Horizon 3, no structures inherited from the parent rock are observed. This horizon is predominantly sandy and primarily composed of quartz and plagioclases altered to clay minerals. Horizon 4 has a saprolitic soil in which several discontinuities inherited from the parent rock can be observed. These discontinuities are filled with organic matter with a spacing of approximately 5 mm. Finally, in Horizon 5, a sign of the intrusion of the Antioquia batholith over the Amphibolite of Medellín is found, which is described in [5] as *"Hanging-wall amphibolite assemblages over the Antioquia Batholith"*.

3. Method

Initially, using the soil samples collected in the study area, both altered (packed in bags) and unaltered (drawer type), the contamination of the material with the soap solution was performed in the Laboratory of Geotechnics and Pavement of the National University of Colombia, Medellín. For this purpose, it was determined that the humidity of the sample after contamination should exhibit approximately the same value as the soil natural humidity (27%-29%). Accordingly, a volumetric analysis was performed, which established the humidity to which the sample had to be decreased (15%) so that 40% of the initial void ratio (e) would be generated (Table 1) and to which the sufficient amount of soap solution in a concentration of 10% was then added to ensure the same initial humidity of the soil after contamination. Once the sample was contaminated with the soap solution, it was carefully sealed so the humidity would remain constant. The described process was performed to control at least one variable in the soil's behavior. To obtain a proper infiltration of the solution and to facilitate a significant effect on the soil properties, the soap solution was allowed to act on the soil for 10 days before the respective tests were begun.

For the case of uncontaminated soil, which facilitated the respective comparisons, the results of the study [6] were used.

3.1. Physical characterization

- Natural humidity content [7].
- Specific gravity of solids [8].
- Granulometry by mesh and hydrometer, with and without deflocculant [9].
- Consistency limits [10].
- MCT rapid classification [11]. This procedure enables the classification of the study soil using the method proposed by [11].

3.2. Mineralogical characterization

- XRD [12].
- SEM [12].

3.3. Chemical characterization

- Measurement of pH in H2O and KCl [13]. According to [14], as cited by [15], if the difference between the measured values of pH (KCl) and pH (H2O) is positive, this outcome indicates the predominance of oxides and hydroxides of iron and aluminum in the soil. A negative value is negative indicates the predominance of clay minerals.

3.4. Mechanical characterization

- CD shear strength test [16].
- Double edometry [17], [18]. This approach consists of the simultaneous execution of two single-edometric tests, one in natural humidity conditions and the other in saturated conditions, from which two compressibility curves of the soil are generated. Based on the differences between the void ratios, the collapse index is calculated.
- Disaggregation. This test aims to examine the stability of an undisturbed soil sample immersed in distilled water, which can be associated with phases of the erosion process [19].
- Pinhole test [20]: This test attempts to simulate the piping effect in the soil [19].
- Suction test by filter paper, mixed trajectory. This test enables the measurement of the matric and the total suction [21].

4. Analysis of results

4.1. Index properties

Initially, classification tests were performed following the methods of the Unified Soil Classification System (USCS) and the MCT classification. These tests were performed on the sample in a natural state and after contamination with the soap solution on specimens with a natural humidity content and air-dried samples. Table 1 summarizes some of the index properties.

In the case of samples in a humid state, both natural and contaminated, the limits do not vary significantly. Additionally, although in the case of samples in a dry state (0% moisture) the plasticity index decreased, which indicated that the drying process aggregates the particles, the classification of the material is not affected in any of the cases and remains a high-compressibility slime (MH).

D: Dry
H: Humid
LL: Liquid Limit
PI: Plasticity Index
Wnat: Natural humidity content
Gs: Specific Gravity

Table 1.
Summary of physical properties

SAMPLE		LL (%)	PI (%)	w_{nat} (%)	G_s	e	S (%)	USCS	MCT
Natural	D	54	18	28	2.8	1.2	68	MH	LA'-LG'
	H	58	20						
Soap	D	51	7	27	2.8	1	73	MH	LA'-LG'
	H	54	17						

Source: The authors

e: Void ratio
S: Saturation
USCS: Unified Soil Classification System
MCT: Miniature Compacted Tropical

The soap solution influenced the increase in intermediate size pores and the decrease in the proportion of macropores in the soil. However, as shown in the characteristic curve, the void ratio did not change significantly.

4.2. Granulometry

The results for the natural and the contaminated samples are shown in Figure . It can be observed that the percentages of fines is very similar for both cases, which indicates that the contaminant does not affect the predominant size of the soil particles. However, the granulometry by hydrometer of both specimens was performed with (WD) and without deflocculant (FD) to identify the aggregations present in the soil before and after contamination. The expression used to determine the stability of the aggregates is defined according to [22], as cited by [12]: Total aggregates (TA) = % of clay with deflocculant - % of clay without deflocculant, particles with diameter less than 0.002 mm. The soil sample contaminated with soap presents stronger aggregation than the sample in the natural state (contaminated TA, 12%; natural TA, 4%). However, these aggregations are weaker and more unstable (higher TA indicates less stability, curves with and without deflocculant being more separated).

4.3. MCT rapid classification

The MCT classification is a method primarily developed for tropical soils that enables the to be sorted into two main groups: lateritic (L) and non-lateritic soils (N) [11]. Additionally, these groups are divided into subgroups according to their granulometric characteristics.

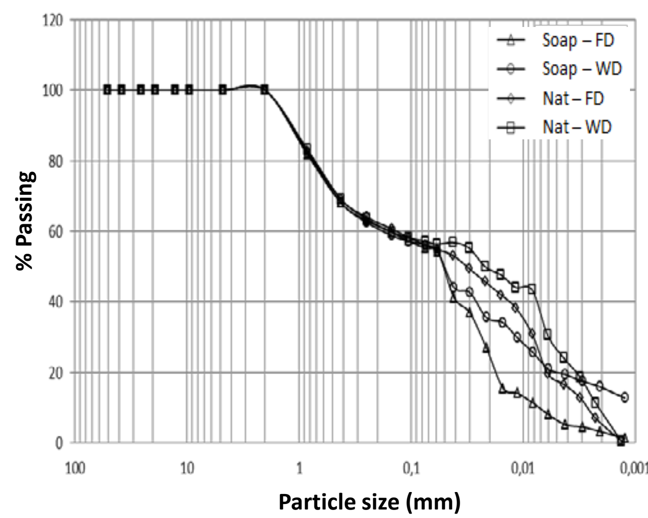


Figure 1. Granulometric curve of the soil
Source: The authors

The test was performed on the soil in the natural state and the soil contaminated with soap solution and determined that the soil under both conditions presents the characteristics of a tropical soil of subgroups LA' – LG'. Considering the intrinsic characteristics of these soils, there is a direct relationship to the characteristics of the study area, specifically for the case of LG', which presents soils of reddish color, with organic matter at the superficial level and the presence of sesquioxides. In addition, the soils are resistant to hydraulic erosion when properly compacted. However, in the natural state, they can collapse by immersion in water [11] and are susceptible to superficial erosion when unprotected.

In addition, the relation between previous results and those obtained using the USCS classification, in which an MH soil was obtained [11], could be verified.

The results obtained in the present test are not decisive in themselves and must be complemented with other tests, such as pH measurement, suction, SEM and XRD, which enable establishing if the soil is lateritic or under laterization process.

When these results are compared with those obtained for the natural sample, it is observed that the contamination of the soil did not affect the MCT classification because it did not present any variation in the results.

4.4. Mineralogical and structural analysis of the soil

4.4.1. X-ray diffraction (XRD)

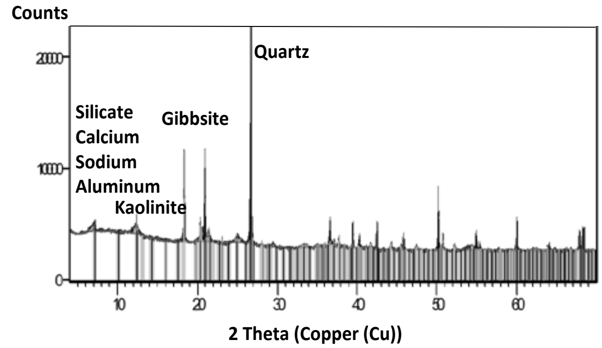
Based on the XRD test results (**Error! Reference source not found.**2), in the analyzed soil (in the natural state and contaminated with soap), there is a predominance of primary minerals (quartz, plagioclase, biotite). Additionally, as product of the alteration of these soils, clay minerals (primarily kaolinites) appear. The presence of iron and aluminum sesquioxides (gibbsite and hematite in a smaller proportion) was also observed. Regarding the proportions between the sesquioxides and clay minerals, the first are low, which enables the inference that the soil is under an initial laterization process.

As expected, the mineralogy of the two samples did not vary (the differences found are the result of the sampling and the heterogeneity of the soil). The time of exposure to the contaminant was too short to produce a mineralogical change in the soil.

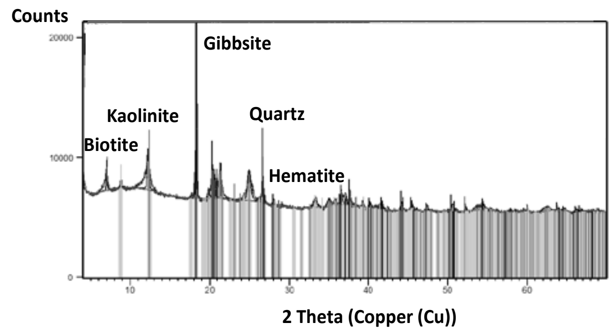
4.4.2. Scanning Electron Microscopy (SEM)

From this test, images were obtained in which the structural arrangement of the soil controlled by its mineralogy can be observed (Fig. 3).

In the case of the natural soil (Fig. 3a), a homogeneous and more compact structure can be observed with laminar minerals that possibly conform to the presence of minerals from the micas group (biotite). Fig. 3b shows a more dispersed structure of the soil grains, with a greater presence of medium size pores and micropores (as it will be observed in the characteristic curve). The difference between the two images can be associated with the alteration caused by the soap solution in the soil, which generated agglomeration between the grains. The agglomeration is unstable, as can be observed in the double edometric test.

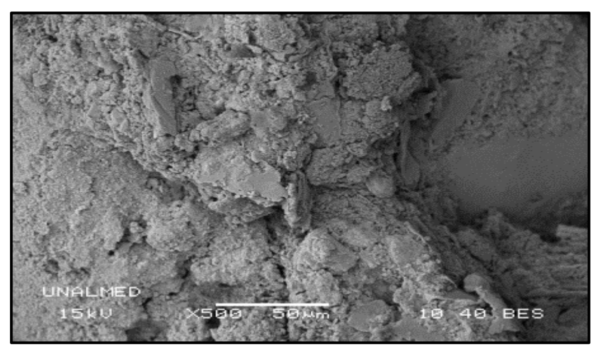


a. Natural soil XRD

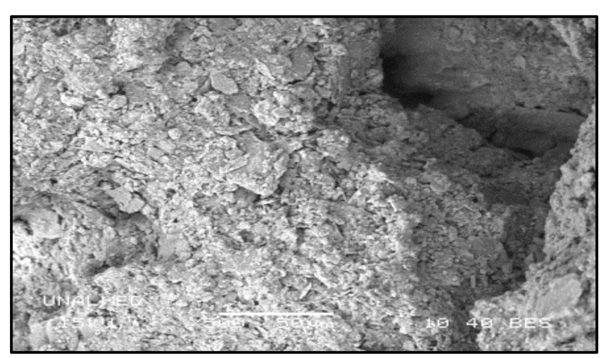


b. Soil contaminated with soap XRD

Figure 2. XRD results
Source: The authors



a. Natural soil



b. Soil contaminated with soap solution

Figure 3. SEM a. Natural soil b. Soil contaminated with soap (×500 magnification)
Source: The authors

Figs. 3a and 3b show small accumulations of material that can possibly correspond to aggregations caused by iron (Fe) or aluminum (Al) oxides and hydroxides. These aggregations could indicate the presence of minerals produced by the initial laterization in the soil of the study slope. This indication is corroborated by the XRD analysis and with the classification obtained by the MCT test.

4.5. pH determination

Negative ΔpH values were obtained (-2.63 for the natural soil and -1.72 for the soil altered by the soap), which indicates the predominance of clay minerals [15] without emphasizing the presence of iron and aluminum sesquioxides, as was observed in the XRD test.

Regarding the sample altered with soap, the soap solution increases the soil acidity. Because the ΔpH remained negative, it was concluded that the time in which the soap solution was left to act was too short to expect a change in the soil mineralogy.

According to [23] and [15], in lateritic tropical residual soils, the acidity is associated with the presence of sesquioxides in large proportions, which produces aggregations between the particles and affects the structural distribution of the voids, regardless whether they are cemented by oxides or hydroxides of iron (Fe) and aluminum (Al). In this case, because the soil contaminated with soap solution presented on average an acidity increase (from 6.8 in the natural state to 5.7 when contaminated), the observed agglomerations (SEM, granulometry) and the presence of medium-size pores in the characteristic curve can be associated with this change in the soil's pH.

4.6. Consolidated drained (CD) shear strength test

The primary objective of this test is to determine the soil shear strength parameters. A CD shear test was performed. The behavior obtained is presented in Fig. 4.

Table 2 shows the shear strength parameters that correspond to the failure envelopes represented in the previous figure.

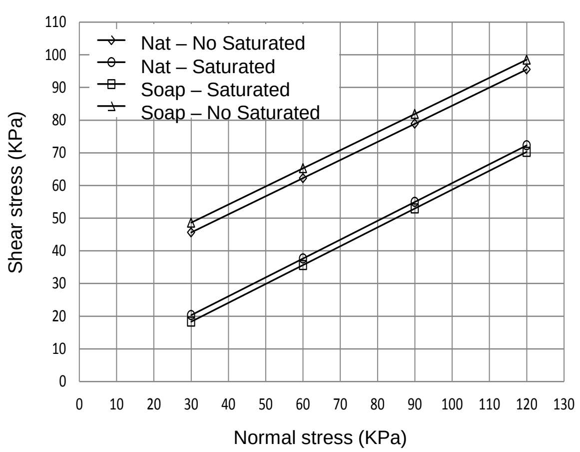


Figure 4. Shear strength of the natural sample and the sample contaminated with soap solution. τ (Shear strength) and σ (Normal load)
Source: The authors

Table 2.
Shear Strength parameters

Natural sample			Contaminated sample		
Moisture	c (kPa)	φ (°)	Moisture	c (kPa)	φ (°)
Unsaturated	29.0	29.0	Unsaturated	32.0	29.0
Saturated	3.0	30.0	Saturated	1.0	30.0

Source: The authors

The shear strength parameters obtained in the present test resemble the typical values of cohesion (c) and friction angle (φ) of the soils from the Antioquia batholith [24]. In addition, the data shown in Fig.e 4 and Table 2 demonstrate that the more significant changes in the shear strength parameters of the soil depend primarily on its saturation condition and to a lesser extent on whether the soil is natural or contaminated.

Regarding the presence or absence of the contaminant, it can be observed that the variation in the resistance is minimal. That is, the cohesion and the friction angle are not significantly influenced by the action of the soap solution.

In addition, the previous results are associated with the characteristic curve, in which for natural humidity the suction value in both samples is similar (Natural, 800 kPa; Contaminated, 1100 kPa). This outcome is reflected in the similarity of the shear strength parameters. For the saturated case, the suction in both cases decreases considerably, which affects those parameters.

4.7. Double edometric test

This test enables the determination of the collapse index, which is obtained after performing the test in saturated and unsaturated conditions. In this case, this test is developed for specimens in natural conditions and for specimens contaminated with a soap solution (Fig.e 5).
From the analysis of Fig.e 5 and the estimation of the collapse indexes by the method proposed by [25], the addition of the contaminating agent can activate the collapse potential of the soil. This statement is supported by comparing the values of the collapse index, which for the natural sample are below 3.0% (thus classifies as a *moderately collapsible soil*) and for the contaminated sample are above 5.0% for the last two load increments (400 and 800 kPa) (which groups the soil with *problematic collapsible soils*).

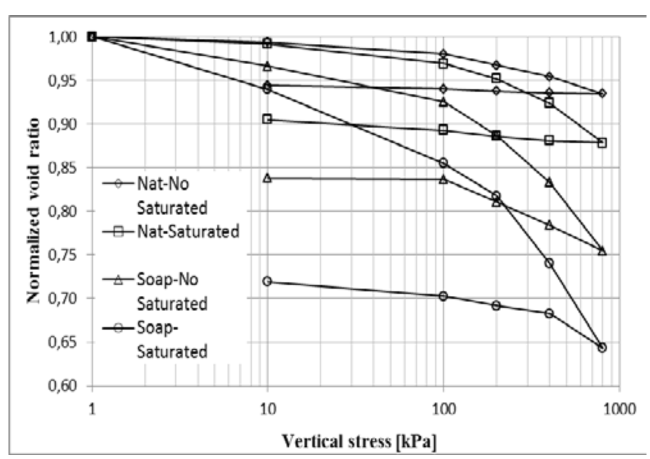


Figure 5. Result of the double-edometric test
Source: The authors

4.8. Erodibility test

During the visit to the study site, a series of erosion events that affected the soil were observed. These processes are superficial (grooves), which requires the performance of a series of tests that would allow establishing the degree of erodibility that the soil can present (disaggregation and the pinhole test).

The erodibility can be defined as the soil's capacity to resist erosion and depends not only on the soil's intrinsic characteristics (e.g., mineralogy, texture, structure) but also factors such as wetting and drying cycles and the chemical composition of the water that affects the soil [19].

4.8.1. Breakdown

The description of the soil responses for the breakdown test can be found in [19]. At the beginning of the test, for both samples, an immediate dispersion effect was observed, which can be associated with the difference in pressure that is generated in the interior of the sample when the water tries to enter a medium that contains soap solution. A second effect was a slight fracturing in the upper face of the soil cube, which can be associated with the osmotic expansion process generated by a chemical effect of the soap solution in the interior of the sample.

Finally, the process that characterized the test in both samples was the depletion indicated by the high degree of disintegration suffered by the samples (Fig. 6). This disintegration occurred because the aggregations or bonds formed by the soap solution were rapidly diluted when contact with the water was made. During the test, it was not necessary to complete the 24-hour observation period. The disaggregation effect was immediate for both samples.

4.8.1. Pinhole Test

Based on Fig.e 7, the natural soil does not present internal erodibility because the load and unload intervals exhibit a linear behavior. In the sample altered with the soap solution, a marked difference was observed between the loading and unloading intervals. In this case, the observed phenomenon was associated with detached particles caused by the flow of water and the subsequent plugging of the hole of these particles (unload interval below the load interval).

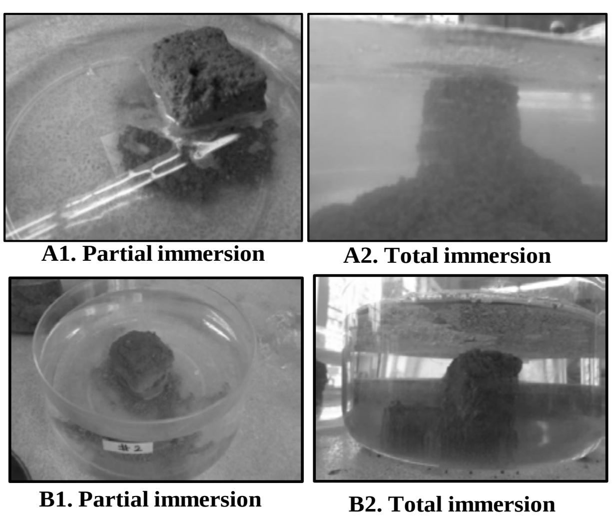


Figure 6. Breakdown test process. a. soil with soap b. Natural soil
Source: The authors

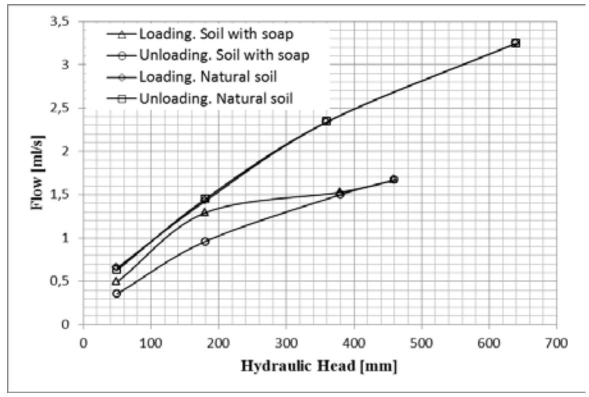


Figure 7. Pinhole test (natural sample and sample with soap).
Source: The authors

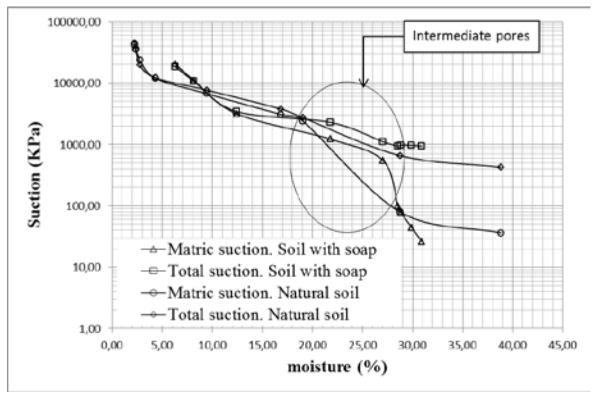


Figure 8. Characteristic curves of the natural soil and the soil contaminated with soap (matric and total suction)
Source: The authors

4.9. Characteristic curve

The results are presented in Fig.e 8. The curve that corresponds to the natural soil (matric suction) presents a soft slope, which is characteristic of a soil with homogenous structure, in agreement with the SEM analysis. In the curve that corresponds to the matric suction of the soil contaminated with soap, the presence of intermediate-size pores is observed (which were not so markedly present in the natural soil), as could be observed using SEM. The presence of intermediate-size pores can be explained by the agglomeration produced by the effect of the soap solution on the soil.

Regarding the total suction, generally, the suction values in the sample contaminated with soap are greater than the values for the natural sample, which is evidence of the osmotic effect produced by the soap solution because of the chemical components that are added to the medium.

5. Conclusions

The presence of a substance such as a soap solution in the soil is common in regions that lack sewerage systems.

Understanding the alterations caused by the percolation of these contaminating agents is important to improving the design of mitigation and improvement works and to determining areas a risk of disaster because they are exposed to such conditions.

Therefore, by studying in detail the results of the tests performed on samples in natural and contaminated states, is possible to describe the following tendencies: the physical characterization does not present significant changes, except for the granulometric analysis, in which unstable aggregations caused by the binding action of the soap are observed. The soil contaminated shows a more dispersed structure of the soil grains, with a greater presence of medium size pores and micropores. The difference between the two samples (natural and contaminated states) can be associated with the alteration caused by the soap solution in the soil, which generated agglomeration between the grains. The agglomeration is unstable, as can be observed in the double edometric test.

The presence of the soapy substance influenced the hydromechanical behavior of the soil because with respect to soil deformability the collapse phenomenon becomes critical: the soil passes from a problematic to a severe state. In addition, when evaluating the soil erodibility, both superficial and internal, deformability becomes a critical condition.

The composition of the fluid present in the interstices of a residual soil is decisive when estimating the geotechnical behavior, which occasionally cannot be fully appreciated using the classical methods of soil mechanics. Therefore, it is necessary to consider more specific tests that correspond to the properties that are induced in the soil mass by the presence of certain clay minerals and sesquioxides, which can easily be found at regional level from the weathering of the igneous rocks of the Antioquia batholith.

Finally, it should be noted that this study is a preliminary geotechnical analysis of a soil that has to be affected by a contaminant such as soap. However, research should be further into issues such as the use of other types of soil, another kind of soap, different concentrations and amounts of soap, and the time of exposure to the contaminant. This will allow to perform a statistical analysis of the data and determine a general trend of the effect of a soil contaminated with a soapy substance, to propose the recovery of these soils [26].

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