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The influence of secondary mineralogy on the mechanical behavior of a granitic residual soil in the semiarid region of Brazil

Influência da mineralogia secundária no comportamento mecânico de um solo residual granítico no semiárido brasileiro

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Abstract: The external geological processes that form soils play a crucial role in their behavior. In the specific case of mature residual soils, cementation rather than stress history plays a fundamental role in their mechanical behavior. The aim of this work is to assess the influence of mineralogy on the mechanical behavior of a granite alteration profile in the Brazilian semiarid region, specifically in terms of direct shear. The study was carried out on the topsoil of granitic rocks. Disturbed and undisturbed samples were taken at three points. XRD analyses were carried out on the sand and fines fractions for mineralogical characterization and XRF analyses for chemical characterization of the points studied. Geotechnical characterization tests included granulometric analysis and consistency limits. Direct shear tests were carried out to study the mechanical behavior. The results showed that the mineralogical composition, the soil structure, and the cementing role of iron minerals are the main factors causing the mechanical behavior of the soil studied. Local variations in the drainage capacity and the degree of soil weathering explain the presence of secondary minerals and the differential mechanical behavior of the samples studied.

Keywords: Secondary minerals; mechanical behavior; granitic residual soil.

Resumo: Os processos geológicos externos de formação de solos têm um papel crucial no comportamento dos mesmos. No caso especifico dos solos residuais, a cimentação e não o histórico de tensões tem papel fundamental no seu comportamento mecânico. Este trabalho tem por objetivo avaliar a influência da mineralogia presente em um perfil de alteração granítico no semiárido brasileiro, no comportamento mecânico do mesmo, especificamente quanto ao cisalhamento direto. O estudo foi realizado no solo de cobertura de afloramento de rochas graníticas. Realizou-se a coleta de amostras deformadas e indeformadas em três pontos. Foram realizadas análises de DRX nas frações de areia e finos para a caracterização mineralógica e análises de FRX para caracterização química dos pontos estudados. Os ensaios de caracterização geotécnica incluíram: análise granulométrica e limites de consistência. Para o estudo do comportamento mecânico realizaram-se ensaios de cisalhamento direto. Os resultados obtidos mostraram que, a composição mineralógica, a estrutura do solo e o papel cimentante dos minerais de ferro se configuram como os principais fatores causadores do comportamento mecânico do solo estudado. Variações locais quanto à capacidade de drenagem e ao grau de intemperismo do solo explicam a presença dos minerais secundários e o comportamento mecânico diferencial das amostras estudadas.

Palavras-chave: Mineralogia secundária; comportamento mecânico; solo residual granítico.

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1. Introduction

External geological processes of soil formation play a crucial role in their behavior. Soils resulting from the weathering process, referred to as residual soils, exhibit peculiar behavior from a geotechnical standpoint that sometimes deviates from traditional considerations regarding soil behavior. The majority of findings in soil mechanics come from research on sedimentary soils, created by erosion, transport, and deposition processes. Thus, the behavior of residual soils has been highlighted in the specialized literature, emphasizing that there is no single behavior pattern and that said behavior is influenced by several factors, such as the rock of origin, the degree of weathering, the local environment, and the climate, among others. In this sense, the influence of the mineralogical composition of granitic residual soil on its mechanical behavior has been proven (FONSECA et al., 2006; SAMAR, 2022; SUN et al., 2023).

Likewise, structural aspects, specifically the presence of aggregates (KÜHN et al., 2022), and textural aspects, such as porosity (DELCOURT, 2022), are fundamental to understanding the mechanical behavior of soils.

Finally, in granite rock alteration profiles, the type and degree of weathering are fundamental in defining the secondary minerals present and the specific behavior of the soil (DOLUI et al., 2016; FANG, 2019; MENUNIER AND VELDE, 1979). Kaolinite is the main secondary mineral resulting from alteration in granites, but the specific mineralogical composition of each soil varies depending on the aforementioned factors.

Chemically, iron plays a very important role in soil behavior, mainly due to its cementing function (MAHALINGA-IYER AND WILLIAMS, 1991; SAMAR et al., 2022; SHUI-SHENG et al., 2016), which explains soil aggregation and microstructure (ZHANG, 2022). More specifically, Lade and Overton (1989) proved that an increase in the cement content in soils produces an increase in cohesion and tensile strength, as well as an increase in the angle of friction at low confinement pressures.

Geologically, the study area is located within the so-called Dona Inês Intrusive Suite, which, according to CPRM (2016), consists of medium-grained to fine-grained leucocratic hornblende-biotite granites. These are isolated plutonic bodies that, when subjected to weathering, result in residual profiles with thicknesses not exceeding 1 meter (XAVIER, 2021).

This work aims to evaluate the influence of the mineralogy present in a granitic alteration profile on its mechanical behavior, specifically in terms of direct shear.

2. Materials and Methods

The study was conducted on soil covering granite rock topsoil. These are shallow soils with a maximum thickness of 1.5 meters (Figure 1).

Figure 1 – Granite rock topsoil with alteration profile.
Source: Authors *(2024).*

The collection of disturbed and undisturbed samples (Figures 2 and 3) was carried out at three points (P1, P2, P3) corresponding to profiles of alteration of granitic rocks, 400 m apart.

For mineralogical characterization, XRD was performed on the sand and fine fractions (passing through sieve #200) at the three points studied. For chemical characterization, FRX was performed on the soil sample at the three collection points.

The geotechnical characterization tests included: granulometric analysis and consistency limits. Lastly, for the study of mechanical behavior, direct shear tests were performed (Figures 4 and 5).

Figure 2 – Collection (a) and preparation of undeformed samples (b, c, d).
Source: Authors *(2024).*

The preparation of samples for characterization tests followed the procedure recommended by standard NBR 6457/2016. The tests followed the standards indicated below:

a) Granulometric analysis: NBR 7181/2016
b) Consistency limits: NBR 6459/2016 and NBR 7186/2016

Figure 3 – Preparation of the chemical and mineralogical characterization of the disturbed samples.
Source: Authors (2024).

Direct shear tests were conducted under flooded conditions in accordance with the procedures recommended by ASTM D3080-04. The samples were carved from the undeformed blocks and placed in the shear box. Then, the normal stress predicted for each test specimen was applied. Tests were performed on each sample with normal stresses of 50, 100, and 200 kPa.

Figure 4 – Preparation of the test specimen for the direct shear test (a); and determination of soil moisture prior to testing (b, c, d). Source: Authors (2024).

Figure 5 – Direct shear tests: images of the test specimens after shearing.
Source: Authors (2024).

3. Results and discussion

3.1 Chemical and mineralogical characterization of the soil

Table 1 shows the different element contents in the form of oxides at the three points studied. Figures 6 to 8 show the mineralogical composition of the three points studied for two fractions: fine fraction (passing through sieve #200) and sandy fraction.

Chemically, the samples studied are composed mainly of silicon, aluminum, and iron as the main elements. The three points studied show little incidence or absence of more mobile elements such as Na, Ca, K, and Mg. This fact indicates good lixiviation conditions. On the other hand, the points studied show variations in the relative proportions of some elements such as iron, zirconium, and titanium. These variations in the points studied can be explained by the irregular distribution of primary minerals in the original rock body.

Table 1 – Chemical composition (FRX) of the samples studied

Oxides (%)	Sample 1	Sample 2	Sample 3
SiO2	40,257	34,409	36,581
Al2O3	34,939	31,849	31,257
Fe2O3	16,133	28,942	28,066
ZrO2	4,855	1,360	1,925
TiO2	3,244	1,314	1,877
SrO	0,179	0,421	0,168
Ga2O3	0,130	0,058	-
Cr2O3	0,108	0,075	0,082
CuO	0,101	-	-
SO3	0,053	0,076	-
MgO	-	0,894	-
K2O	-	0,602	
CaO			0,045
TOTAL	100	100	100

Source: Authors (2024).

Mineralogically, the process of monosialization stands out, a common process in granite rock alteration profiles constituting relatively superficial profiles (Fang et al, 2019), explained by the climatic conditions and good drainage of the study site. Thus, the mineralogical phases present in the diffractograms reflect the original composition of the bedrock, in terms of inherited primary minerals, such as quartz, and accessory minerals, such as rutile and magnetite; and secondary minerals produced by rock alteration processes and leaching of mobile soil elements (K, Na, Ca, and Mg), such as kaolinite—originated from the alteration of feldspars: microclines and plagioclases—and iron oxyhydroxides, such as goethite and hematite—originated from the alteration of ferrous or ferromagnesian minerals such as magnetite and hornblende. Although not identifiable in the diffractograms, zirconium was attributed to the incidence of zircon, commonly found as an accessory mineral in igneous rocks, either alone or as inclusions in minerals such as hornblende.

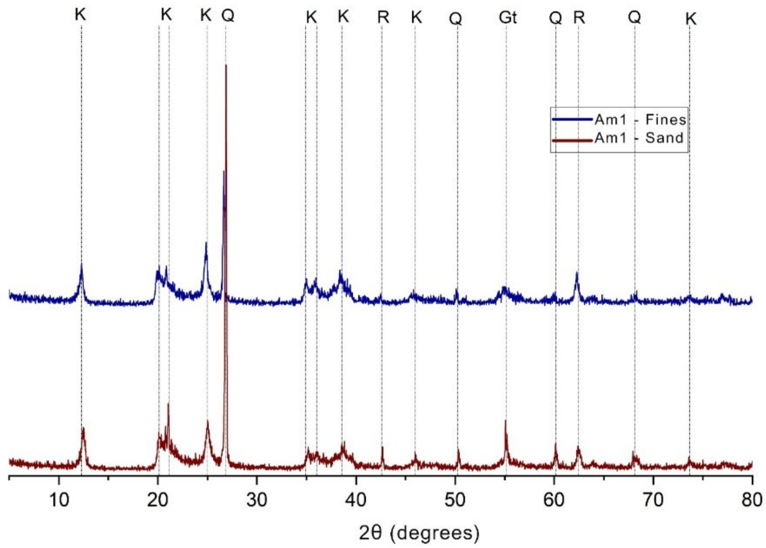

Figure 6 – XRD sample 1: fines and sand. Legend: K=kaolinite; Q=quartz; R=rutile; Gt=goethite. Source: Authors (2024).

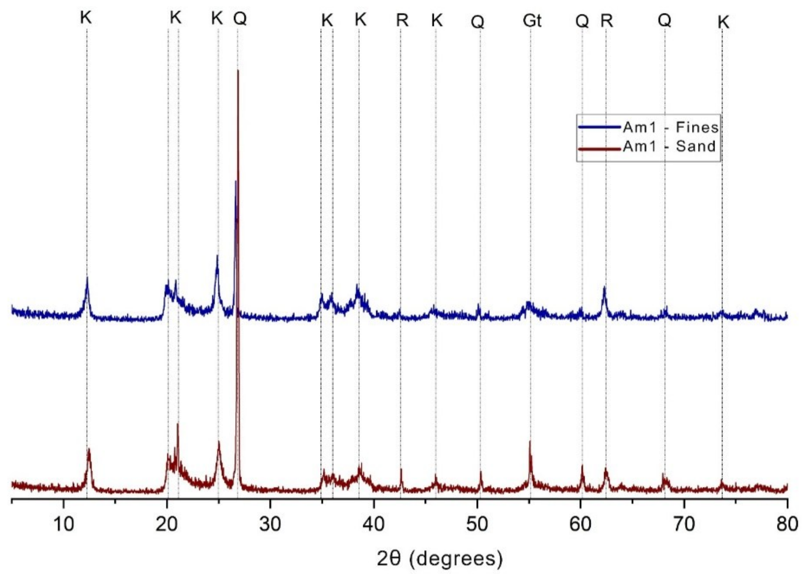

Figure 7 – XRD sample 2: fines and sand. Legend: K=kaolinite; Q=quartz; R=rutile; H=hematite; M=magnetite. Source: Authors (2024).

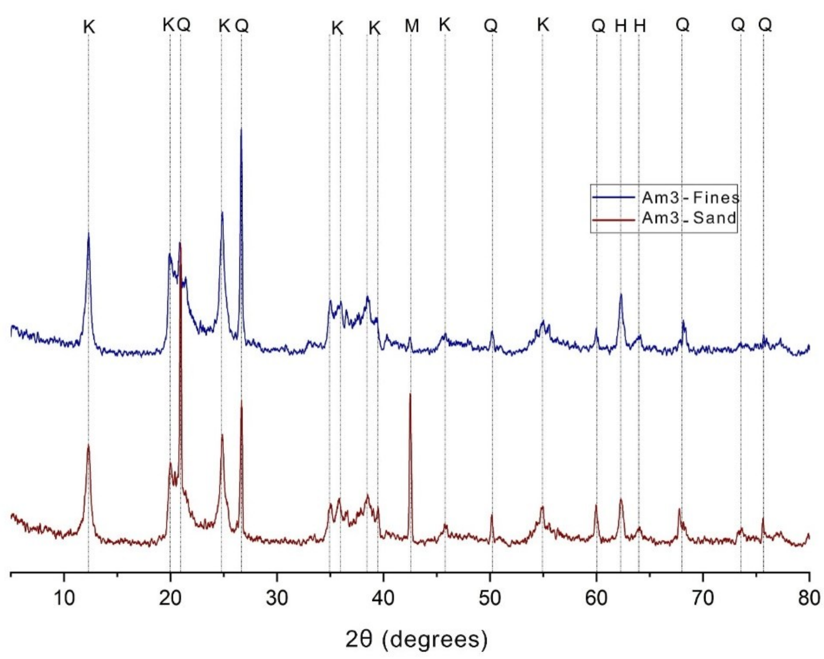

Figure 8 – XRD sample 3: fines and sand. Legend: K = kaolinite; Q = quartz; H = hematite; M = magnetite. Source: Authors (2024).

3.2 Physical characterization

The results of the granulometry tests are shown in Figures 9 to 11, in terms of granulometric curves, and in Table 2, which presents the various fractions that make up the soils of the studied samples. Tables 3 and 4 show, respectively, the consistency indices and the values of clay activity and plasticity of the soils studied.

Table 2 – Granulometric fractions of the soils studied.

Sample	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
01	14,25	14,43	12,93	23,79	8,56	26,04
02	2,72	8,43	7,26	13,46	8,04	60,09
03	10,35	6,96	11,35	25,91	7,49	37,94

Source: Authors (2024).

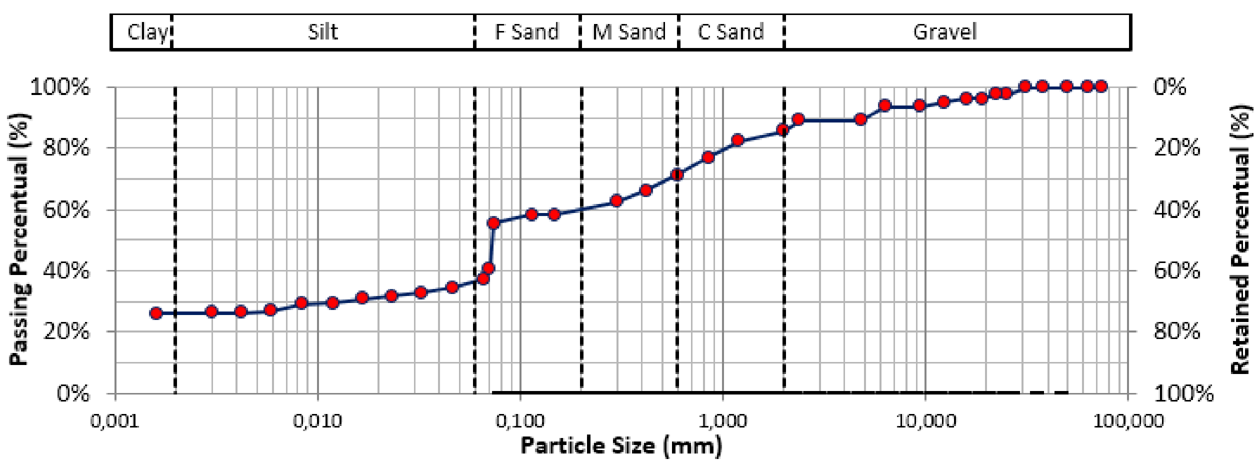

Figure 9 – Grain size curve of Sample 1.
Source: Authors (2024).

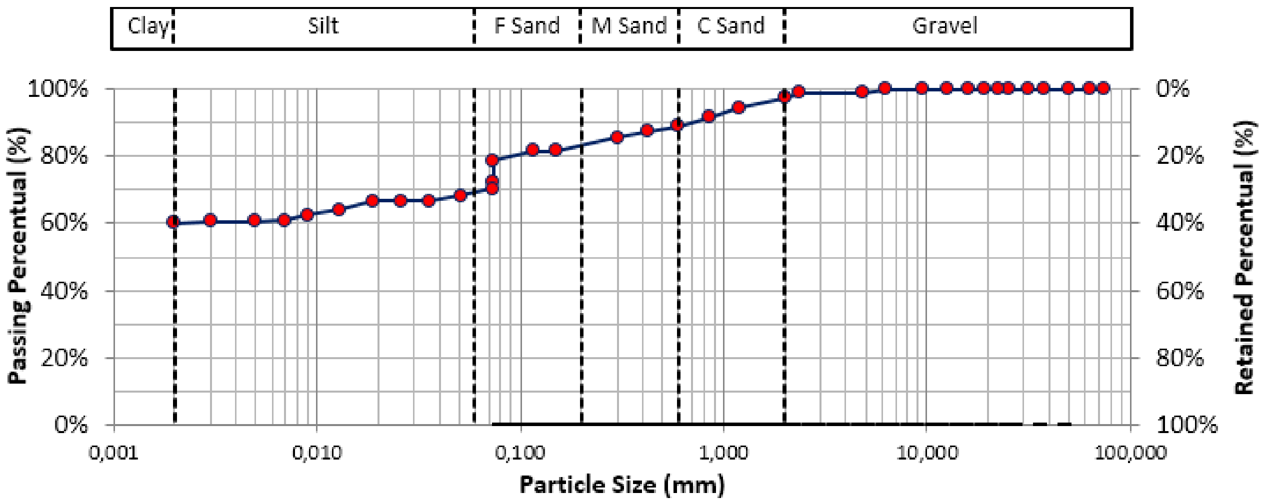

Figure 10 – Grain size curve of Sample 2.
Source: Authors (2024).

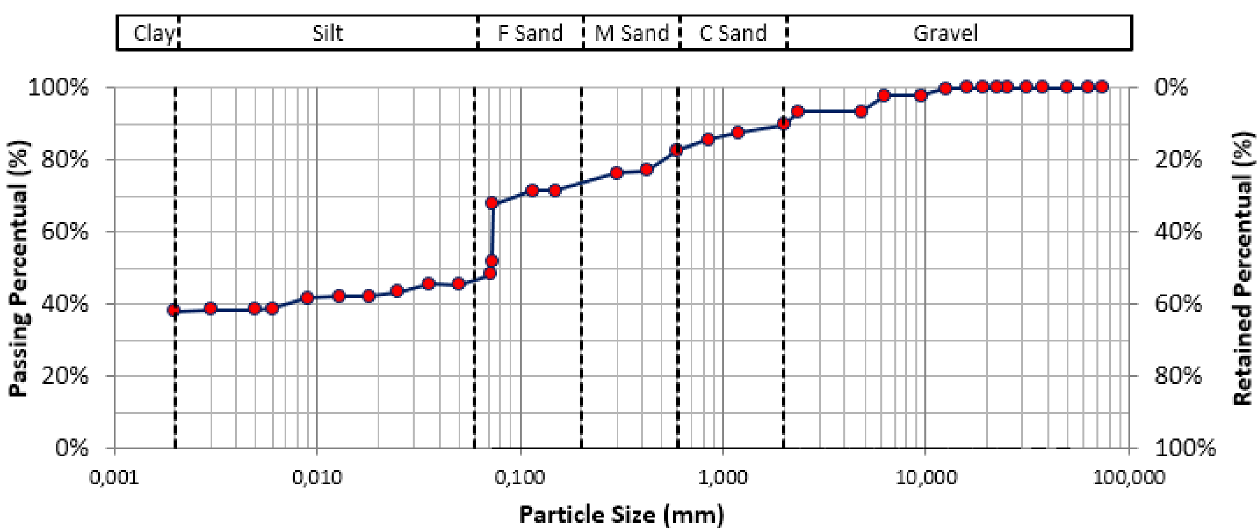

Figure 11 – Grain size curve of Sample 3.
Source: Authors (2024).

Table 3 – Consistency Indices of the samples.

Indices	Sample 1	Sample 2	Sample 3
LL (%)	38,5	51,5	43,9
LP (%)	24,3	25,9	21,7
IP (%)	14,2	25,6	22,2

Source: Authors (2024).

Table 4 – Evaluation of the plasticity of the soils studied.

Samples	Activity of clay	Das e Sohan (2014)	Caputo (2017)
1	0,55	Medium Plasticity	Moderately Plastic
2	0,43	High Plasticity	Highly Plastic
3	0,59	High Plasticity	Highly Plastic

Source: Authors (2024).

The results regarding clay plasticity and activity are consistent with the soil mineralogy. That is, the soils are essentially kaolinitic, plastic, and with low clay activity. Table 5 shows the geotechnical classification of the three samples studied.

Table 5 – Geotechnical classification of the soils studied.

Sample	SUCS Classification	H.R.B Classification
01	CL – Sandy Lean Clay	A-6 – Clayey soils
02	CH– Fat Clay with Sand	A-7-6 – Clayey soils
03	CL – Sandy Lean Clay	A-7-6 – Clayey soils

Source: Authors (2024).

3.3 Mechanical characterization

Figures 12 to 14 show the mechanical behavior of the samples studied. Table 6 summarizes the direct shear test values obtained.

The data from the direct shear test of Sample 1 resulted in a curved rupture envelope, possible for residual soil conditions, in which the stress history does not play a fundamental role in its behavior, with cementation acquiring this function. Using linear regression to obtain a straight envelope, the R^2 index was only 0.794, which indicates a low representativeness of the actual behavior of the material studied. By drawing the envelope by hand, a cohesive intercept of approximately 19 kPa can be obtained, consistent with the lower percentage of the clay fraction. For confining stresses of 50 kPa and 100 kPa, the test specimens underwent compression and subsequent expansion, exhibiting overconsolidated soil behavior. For the stress of 200 kPa, since there was only compression of the sample, the material exhibited normally compacted soil behavior. For samples 2 and 3, it was possible to obtain a linear rupture envelope with a good fit (R^2 = 0.9987 and R^2 = 0.9973, respectively).

In the case of Sample 2, which is more plastic and has a higher percentage of clay fraction, the friction angle and cohesive intercept parameters were lower than those of Sample 3. Based on the equations obtained from the envelope lines, Sample 3 has greater shear strength than Sample 2. Regarding volumetric variation, Sample 2 showed compression for the three stresses studied, demonstrating normally compacted soil behavior. Sample 3, on the other hand, showed expansion for the confining stress of 50 kPa, exhibiting overconsolidated soil behavior, and compression for stresses of 100 kPa and 200 kPa, typical of normally consolidated soil.

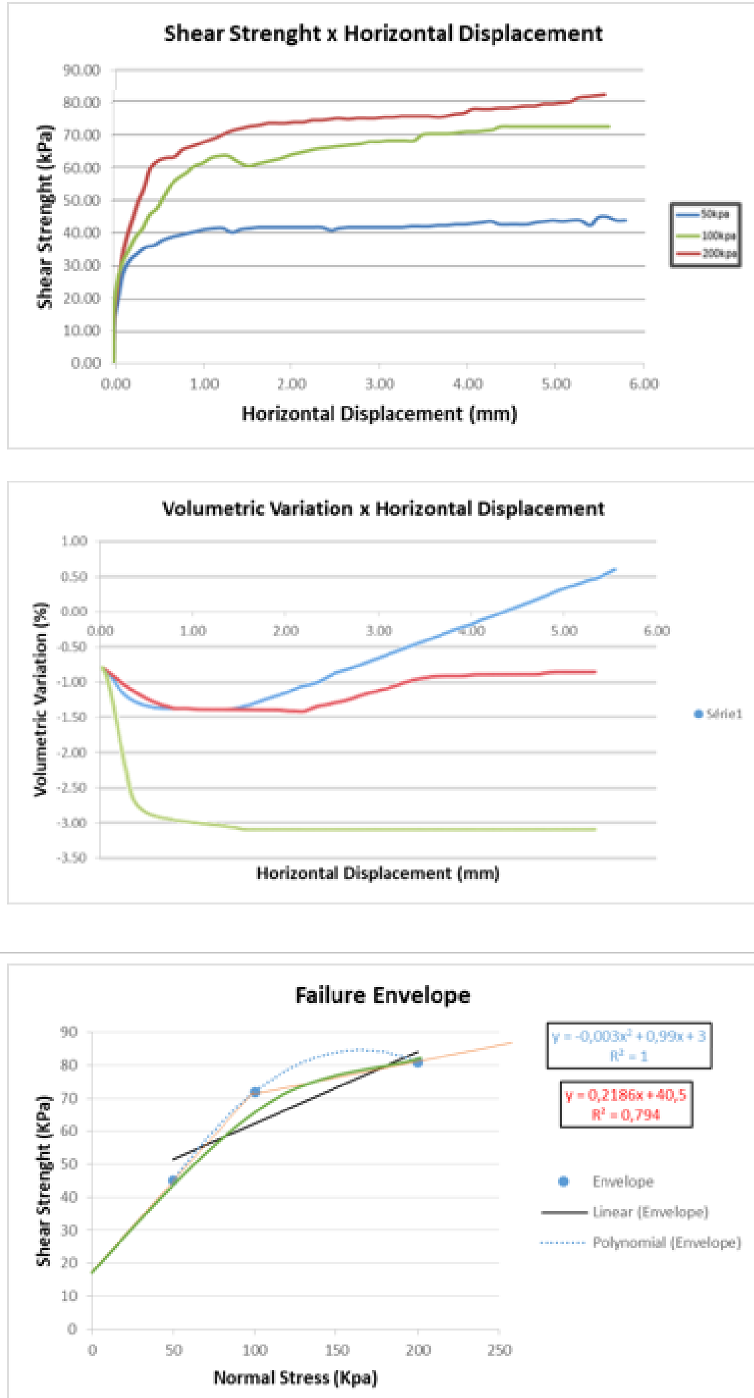

Figure 12 – Results of the direct shear test of Sample 1.
Source: Authors (2024).

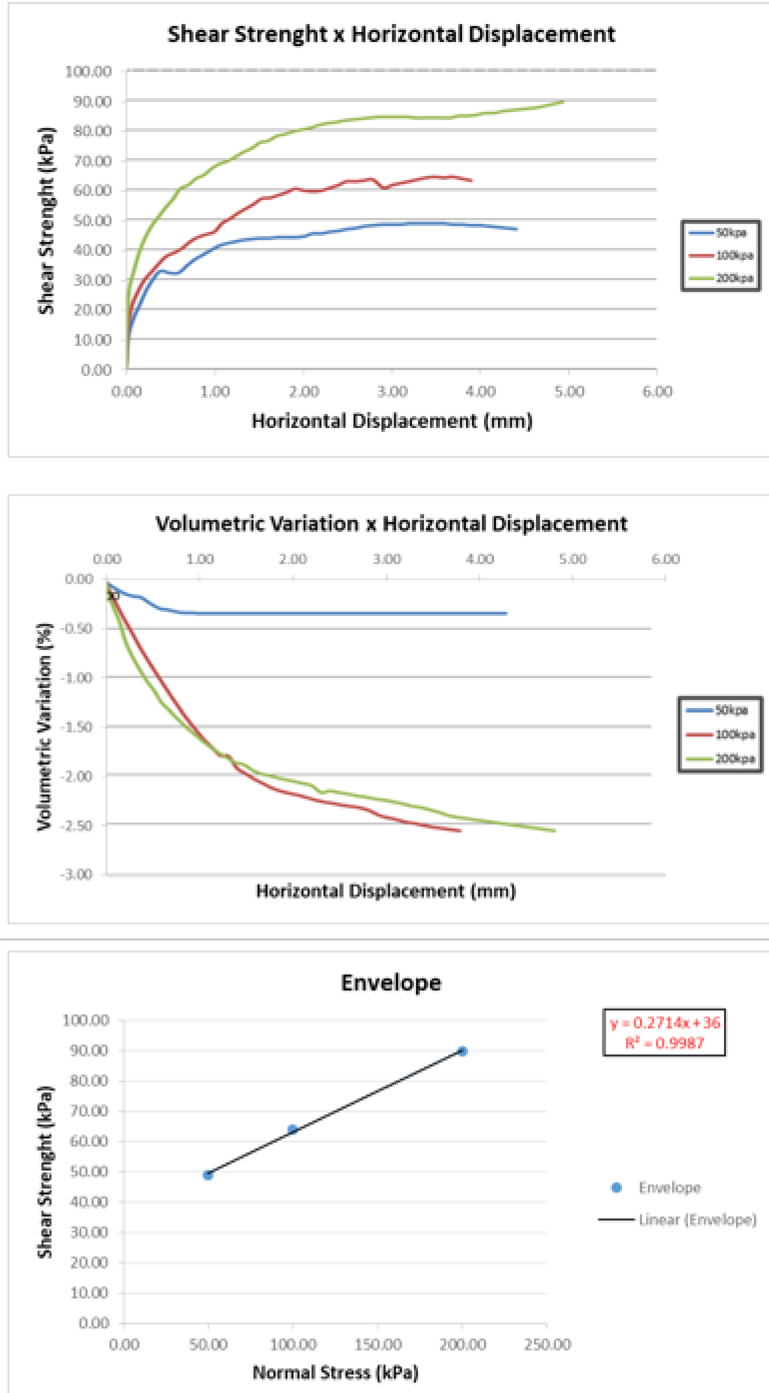

Figure 13 – Results of the direct shear test of Sample 2.
Source: Authors (2024).

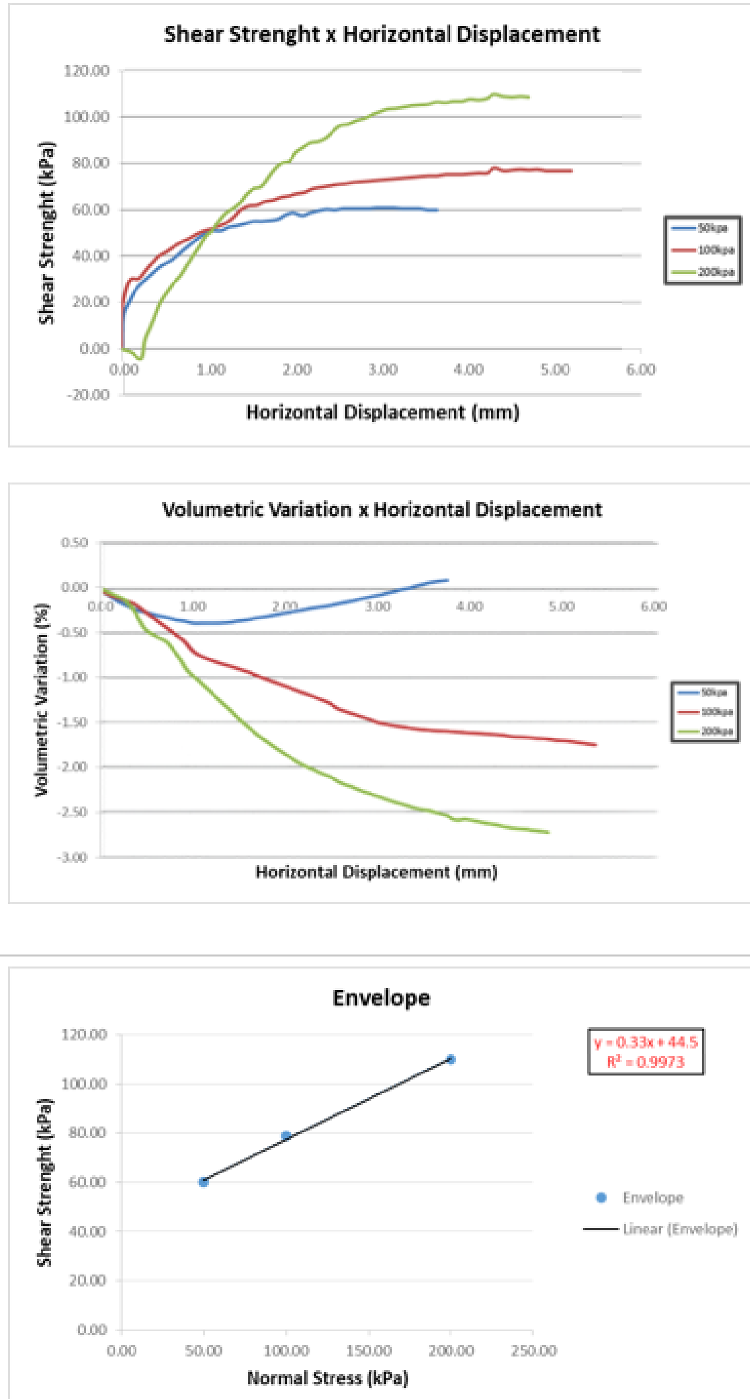

Figure 14 – Results of the direct shear test of Sample 3.
Source: Authors (2024).

Table 6 – Values of the direct shear test.

Sample 1		
Normal	Shear	T envelope
50	45	51,43
100	72	62,36
200	81	84,22
Sample 2		
Normal	Shear	T envelope
50	49	49,57
100	64	63,13
200	90	90,26
Sample 3		
Normal	Shear	T envelope
50	60	61,00
100	79	77,49
200	110	110,49

Source: Authors (2024).

The results of the direct shear test are consistent with what is expected for mature residual soils, in which the stress history does not play a fundamental role in their behavior, with this function being performed by cementation. In this sense, the mechanical behavior of the soil studied can be explained, essentially, by its structure, more specifically by the presence of clay aggregates (KUHN et al., 2022), coated with iron compounds, constituting a typical configuration for residual soils (GIDIGASU, 1976).

Accordingly, the iron minerals identified in the studied soil—goethite, hematite, and magnetite—fall within the group known as FIO (Free Iron Oxides), whose cementing role in residual soils has been proven (MAHALINGA-IYER AND WILLIAMS, 1990; ZHANG et al., 2020; ZHANG et al., 2022).

The mechanical behavior of Sample 1 can be explained by the exclusive presence of goethite as iron oxide and by the lower clay content compared to Samples 2 and 3. This behavior is due to a difference in environmental conditions, since the presence of goethite justifies higher relative soil moisture. In this sense, according to Gidigasu (1972), dehydration in the weathering process influences the geotechnical behavior of the soil, resulting in the formation of larger aggregates that can improve the mechanical strength of the soil.

4. Final considerations

The studies conducted corroborated the influence of mineralogy on the behavior of residual soils. The granitic surface alteration profile appears to consist of a quartzose material with a silt-clay matrix of a caulinitic nature and variable iron content, indicating good leaching conditions that favor chemical weathering processes. In this sense, the compositional, chemical, and mineralogical variations of the three points studied can be explained by the irregular distribution of primary minerals in the original rock body, mainly magnetite and hornblende, showing a spatial compositional variation of the rock mass. In the specific case of iron minerals, local variations in soil drainage capacity and weathering explain the presence of secondary iron oxides and hydroxides, such as goethite and hematite, originating from primary minerals—magnetite and hornblende. It should be noted that the mineralogical composition, soil structure, and cementing role of FIOs (goethite, hematite, and magnetite) are the main factors causing the mechanical behavior of the soils studied. Therefore, the presence of iron oxides improves the mechanical strength of the soil in relation to the presence of iron hydroxides. Finally, it is important to note that, in the case of mature residual soils, cementation, rather than stress history, plays a fundamental role in their mechanical behavior.

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