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Study of the Geomechanical Behavior of a Compacted and Undisturbed Tropical Residual Soil from the Barreiras Formation in Bananeiras, PB

Estudo do comportamento geomecânico compactado e indeformado de um solo residual tropical da Formação Barreiras em Bananeiras/PB

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Abstract: The tropical residual soils of the Barreiras Formation, exhibit great geotechnical variability. This study aimed to characterize a soil profile from this formation in Bananeiras, PB, evaluating the behavior of the material in its natural and compacted states, with emphasis on the influence of compaction on its mechanical properties. The profile, derived from sandstone, comprises three distinct layers analyzed through grain size distribution, X-ray diffraction (XRD), X-ray fluorescence (XRF), Crumb Test, permeability, suction, Standard Penetration Test (SPT), oedometer compression, direct shear, and triaxial tests. The first layer (AM-01), a sandy clay (CL), exhibited instantaneous collapse and low swelling potential; the second (AM-02), a sandy silt (ML), showed higher strength and expansion; and the third (AM-03), a clay (CL), revealed intermediate behavior. The results confirm the heterogeneity of the Barreiras Formation Soils and demonstrate that compaction significantly reduces hydraulic conductivity and volumetric instability, making the material more stable and suitable for geotechnical applications, despite occasional strength losses associated with the breakdown of natural cementation.

Keywords: Collapsibility; heterogeneity; Permeability.

Resumo: Os solos residuais tropicais da Formação Barreiras, apresentam grande variabilidade geotécnica. Este estudo teve como objetivo caracterizar um perfil de solo dessa formação no município de Bananeiras/PB, avaliando o comportamento do material nos estados indeformado e compactado, com foco na influência da compactação sobre suas propriedades mecânicas. O perfil, derivado de rocha arenítica, apresenta três camadas distintas analisadas por ensaios de granulometria, DRX, FRX, Crumb Test, permeabilidade, sucção, SPT, compressão edométrica, cisalhamento direto e triaxial. A primeira camada (AM-01), argila arenosa (CL), mostrou colapso instantâneo e baixo potencial expansivo; a segunda (AM-02), silte arenoso (ML), apresentou maior resistência e expansão; e a terceira (AM-03), argila (CL), revelou comportamento intermediário. Os resultados confirmam a heterogeneidade dos solos da Formação Barreiras e evidenciam que a compactação reduz significativamente a condutividade hidráulica e a instabilidade volumétrica, tornando o material mais estável e adequado a aplicações geotécnicas, apesar de eventuais perdas de resistência associadas à ruptura da cimentação natural.
Palavras-chave: Colapsibilidade; heterogeneidade; permeabilidade.

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1. Introduction

In tropical regions, numerous factors favor the development of deep residual soil profiles. Factors such as climate (temperature and precipitation), parent material, water movement (drainage and topography), age, and vegetation are responsible for the resulting soil profile. Due to the heterogeneity of residual soils in tropical climates, understanding their behavior has become increasingly important, driving researchers to delve deeper into establishing the primary characteristics of each soil type.

Residual soil is recognized for behaving considerably differently from sedimentary soil. While sedimentary soil is formed through transport and deposition processes that typically increase strength and stiffness, residual soil results from the weathering of the parent rock, a process that weakens and softens the original resistance (ZHANG, 2020). Understanding and generalizing the formation process of weathering profiles in residual soils is extremely complex, which makes correlating soil properties with the parent rock a difficult task (BLIGHT & LEONG, 2012).

The soils of the Barreiras Formation are derived from sedimentary rocks and extend along the Brazilian coastline from Amapá to Rio de Janeiro. Studies regarding this formation date back to the early 20th century, beginning with the work of Branner (1902). Since then, numerous authors have dedicated themselves to understanding and providing information about this formation (GUSMÃO FILHO et al., 1986; SANTOS JR, COUTINHO & SEVERO, 2015; MORAIS, SANTOS JR & FREITAS NETO, 2020; FREIRE et al., 2022).

This study aims to analyze the geomechanical behavior of a soil derived from sandstone within the Barreiras Formation in the municipality of Bananeiras, Paraíba (PB). The objective is to compare the physical parameters of the soil matrix in both its natural and compacted states.

1.1 Geological Aspects

The Barreiras Formation outcrops across an extensive area in the eastern portion of the state of Paraíba, primarily within the Paraíba Basin. In the state's interior, its occurrence is found near the Serra dos Martins Formation, exhibiting similarities at the base of the formation. Bananeiras, a municipality in Paraíba (Figure 1), possesses a geological unit originating in the Cenozoic Eon, related to reworked sediments from other rocks. This unit is characterized by plateau reliefs and sandy-conglomerate or silty-clay covers associated with planation surfaces. Furthermore, this unit features horizontal layers with good lateral geotechnical and hydraulic homogeneity, dominated by poorly consistent sediments with low shear strength and resistance to penetration. The residual soils derived from these silty-clay sediments are notable for their high porosity and high water storage capacity (JOÃO, TEIXEIRA & FONSECA, 2016).

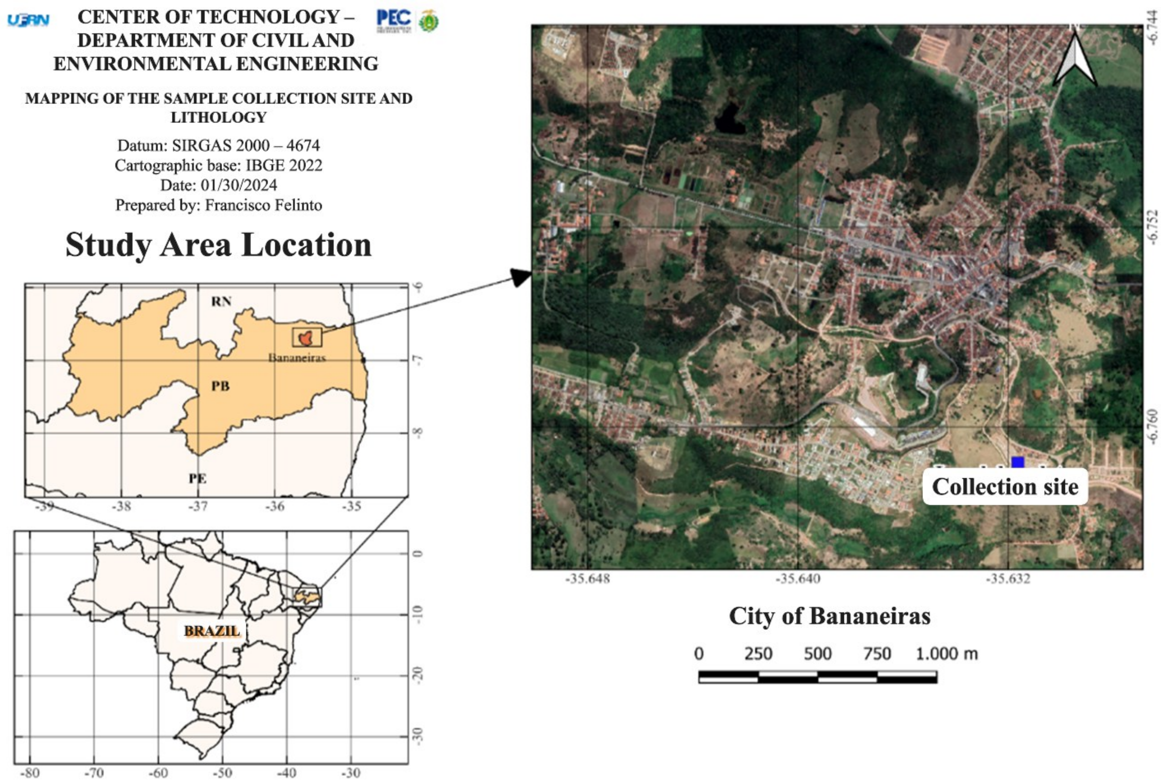


Figure 1 – Geographic location of the study area. Source: Authors (2025).

The materials composing the slope used in this research were extracted from sediments of the Barreiras Formation, as indicated on the geological map of the city of Bananeira (Figure 2). In the soil of the region corresponding to the Barreiras Group (ENb), clayey and conglomerate sandstones are present, generally kaolinized and with a friable aspect. In this region, whitish sandstones are found, poorly sorted, locally conglomeratic, rich in kaolin, homogeneous, and easily disaggregated (GUIMARÃES et al., 2008). According to Menezes (1999), the Barreiras Formation consists of sandy to sandy-clayey or conglomeratic deposits, with varied colors (yellow, red, ochre).

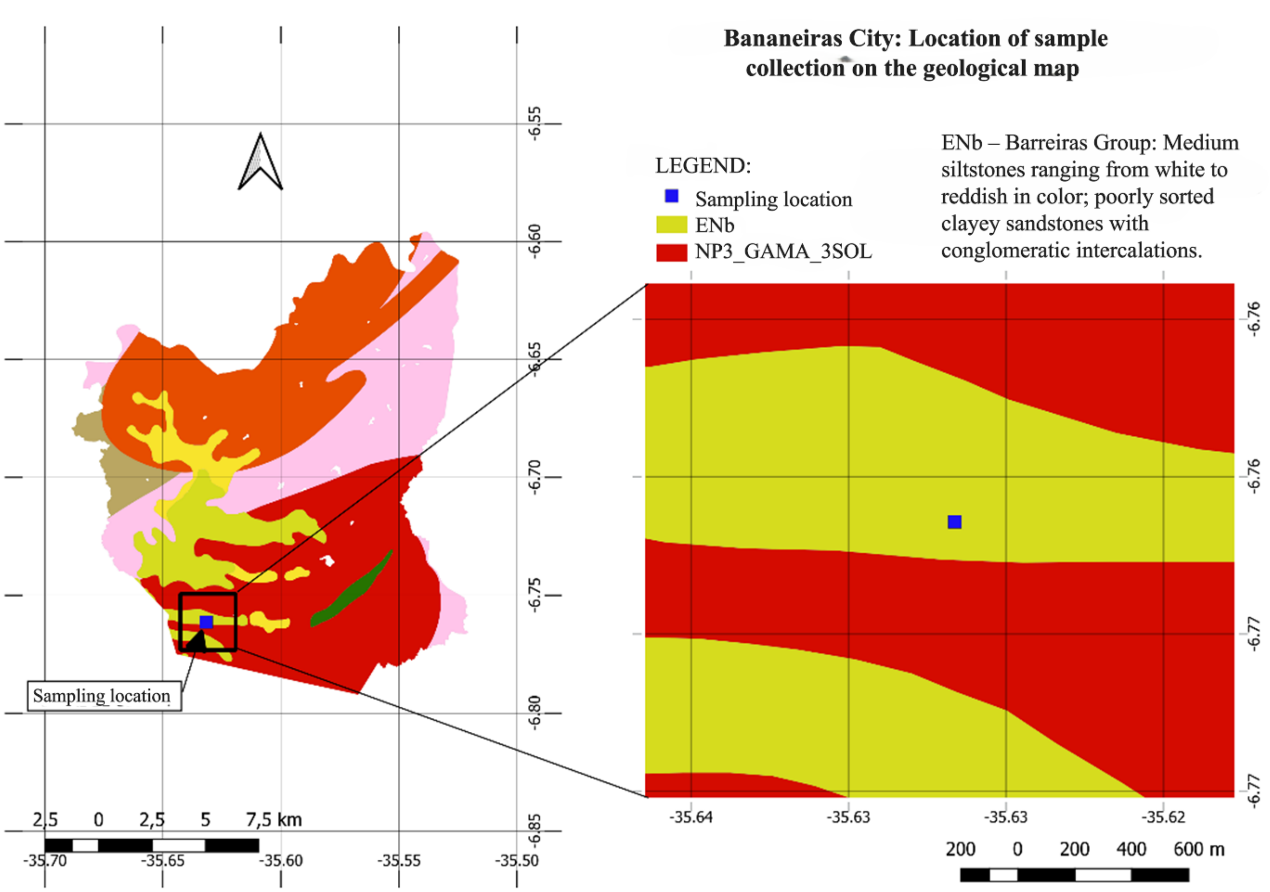


Figure 2 – Geological map of Bananeiras showing the sampling location area. Source: Authors (2025).

1.2 Geotechnical Aspects

There are many geotechnical parameters characteristic of the Barreiras Formation that have been consolidated by several researchers. Authors such as Coutinho and Severo (2009); Morais, Santos Jr., and Freitas Neto (2020); and Freire et al. (2022) demonstrated that the soils of this formation are generally classified as clayey sand (SC), low-plasticity clay (CL), or low-plasticity silt (ML). The activity of the clay fractions is usually lower than 0.75, being classified as low clay activity. Table 1 presents the studies and geotechnical parameters reported in some studies related to the Barreiras Formation.

Table 1 – Peak strength parameters, classification, and plasticity of soils from the Barreiras Formation.

Reference / Location	Test	Classification	PI (%)	Specimen Condition	c (kPa)	ϕ (º)
Gusmão Filho et al. (1986) / Olinda-PE	Triaxial (CU)	Clayey sand (SC)	31–40	Saturated	20–50	20-2
Coutinho et al. (1999); Santos (2001) – Horto Dois Irmãos Recife/PE	Direct Shear	Clayey sand (SC)	10–16	Natural	13	31
				Saturated	0	30
Lafayette (2000) – Alto do Reservatório Recife/PE	Direct Shear	Clayey sand (SC)	11–18	Natural	7–13	24–26
				Saturated		
Lima (2002) – Alto do Reservatório Recife/PE	Direct Shear	Clayey sand (SC)	16	Natural	28	31
				Saturated	10	32
Silva (2003) – Tibau do Sul/RN	Direct Shear	–	–	Natural	193–318	43–52
				Saturated	45–53	27–29
Lafayette et al. (2003; 2005) – Cabo de S. Agostinho/PE	Direct Shear	Clayey sand (SC)	9–13	Natural	33–56	33–36
				Saturated	1,5-1,8	33–35
Bandeira et al. (2004) – Camaragibe/PE	Direct Shear	Sandy silt (ML)	14–16	Natural	12	29
Silva (2005) – Camaragibe/PE	Direct Shear	Clayey sand (SC)	12–13	Natural	43–46	31–45
				Saturated	0-3.7	31–35
Severo (2005)	Direct Shear	–	–	Saturated	45.4-109.7	27.7-48.3
Severo et al. (2006) – Tibau do Sul/RN	Direct Shear	Low-plasticity clay (CL)	7–19	Natural	116–192	27–32
				Saturated	23–54	26–30
Silva (2007) – Camaragibe/PE	Direct Shear	Clayey sand (SC)	12–14	Natural	45–47	31–44
				Saturated	0-3.7	31–34
Santos Jr. et al. (2008) – Tibau do Sul/RN	Direct Shear	Low-plasticity clay (CL)	6–19	Natural	233–384	27–32
				Saturated	16.9-109,7	26–59
Meira (2008)	Direct Shear	Clayey sand (SC)	8–9	Natural	1-4,2	28–34
				Saturated	0.4-3.5	23–26
Severo (2011) – Ponta do Pirambu/RN	Triaxial (CD)	Clayey sand	5–11	Naturally compacted	6.5~8.3–110.5	28~29.4–33
Souza Jr. (2013) & Santos Jr., Coutinho, Severo (2015) – Barra de Tabatinga/RN	Direct Shear	Clayey sand (SC)	17–37	Saturated	16.9-59.9	29.5-33.6
Barbosa (2017); Taquez (2017) – Barreira do Inferno/RN	Triaxial (CW)	Silty-clayey sand (SC) – Poorly graded sand	0–18	Natural	97.6–192.1	30.88–36.4
Barbosa (2017); Taquez (2017) – Barreira do Inferno/RN	Triaxial (CU)	Silty-clayey sand (SC) – Poorly graded sand	0–18	Saturated	16.7-60.6	12.1-28.9
Souza (2018) – West zone of Natal/RN	Direct Shear	Silty sand (SM)	4–9	Natural	0.5-206.2	19.5-43
				Saturated	0	32.9–36.9
Souza (2018) – West zone of Natal/RN	Direct Shear	Clayey sand (SC)	17–20	Natural	148.6–306.8	37.6–58.1
				Saturated	17.5–106.7	27.2–33.6

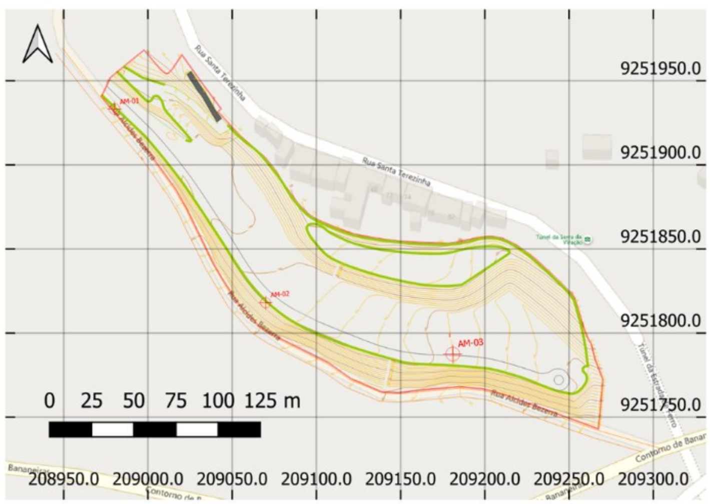
Morais, Santos Jr., Coutinho, Freitas Neto (2020) – RN	CD & CU	Soil 1: Silty-clayey sand (SM-SC)	6	Saturated	17.8	30.2
Morais, Santos Jr., Freitas Neto (2020) – Barra de Tabatinga/RN	CD & CU	Soil 2: Silty sand (SM)	3	Saturated	12	29.7
Morais, Santos Jr., Freitas Neto (2020) – Barra de Tabatinga/RN	CD & CU	Soil 1: Poorly graded sand (SP)	–	Saturated	4.65	30.7

Soucer: authors (2025)

2. Methodology

The experimental program consisted of defining the sampling locations on the slope within the Barreiras Formation soil area (Figure 3a). Three soil samples (AM-01, AM-02, and AM-03) were collected, with their respective locations shown in Table 2 and Figure 3b.

a) Soil layers on the slope.



b) Slope contour line showing the sampling locations.

Figure 3 – Sampling locations. Source: Authors (2025).

Table 2 – Geographic location of the samples.

Soil	Latitude	Longitude	Depth (m)
AM-01	-35.632336°	-6.760796°	1 - 2
AM-02	-35.631640°	-6.761489°	5 – 7
AM-03	-35.631215°	-6.761652°	7 – 9

Source: authors (2025)

To determine the soil's resistance to penetration and characterize the subsurface layers, the Standard Penetration Test (SPT) was conducted in accordance with NBR 6484 (ABNT, 2020). The report includes 17 percussion drilling tests, designated as SP-06, SP-07, SP-08, SP-10, SP-11, SP-12, SP-13, SP-14, SP-15, SP-16, SP-17, SP-18, SP-19, SP-20, SP-

21, and SP-22. The specific drilling points selected for evaluation in this research were based on the sample collection sites, centered on SP-06. Grain size analysis (including sedimentation) was performed with prior drying following Process 1 of NBR 6457 (ABNT, 2024) and NBR 7181 (ABNT, 2025). Liquid and plasticity limit tests were conducted based on NBR 6459 (ABNT, 2016) and NBR 7180 (ABNT, 2016), respectively. The specific gravity of the soil solids was determined according to NBR 6458 (ABNT, 2016) and DNER-ME 093 (ABNT, 1994).

The standard used for the compaction test was NBR 7182 (ABNT, 2016). These tests were performed using the reuse method, with a 1000 cm³ cylinder and standard Proctor energy. A rapid dispersion test (Crumb Test) was also conducted to verify the soil's dispersibility in water, based on NBR 13601 (ABNT, 2020).

For mineralogical and chemical characterization, X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analyses were performed, respectively. Subsequently, the weathering degree for the three defined samples was estimated according to EMBRAPA (1997).

Permeability tests on compacted specimens were conducted based on NBR 14545 (ABNT, 2021), using Method "B" (rigid wall). Undisturbed samples were tested using the flexible wall method, based on HEAD (1986) and ASTM D5084 (ASTM, 2016a).

Oedometer consolidation tests followed the guidelines of ASTM D2435/D2435M (ASTM, 2011) and NBR 16853 (ABNT, 2020). The normal stresses applied to each specimen were: 5 kPa, 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, and 1600 kPa. Each loading stage was applied for a 24-hour period. Unloading was performed in stress stages of 400 kPa, 100 kPa, and 25 kPa, with each stage also lasting 24 hours.

The direct shear test was based on ASTM D3080 (ASTM, 2004) and ASTM D2435/D2435M (ASTM, 2011). The applied normal stresses were 50 kPa, 100 kPa, 150 kPa, and 200 kPa. All samples were flooded during all stages of the testing procedure. Figure 4 illustrates the compacted and undisturbed soil.

a) Specimen AM-01 carved in its natural state.

b) Specimen AM-01 molded at optimum moisture content.

Figure 4 – Specimens molded for direct shear testing. Source: Author (2025).

Shear strength was verified using a triaxial compression apparatus. The test was performed under consolidated-drained (CD/CID) conditions, with saturated specimens and drainage allowed during the failure stage, in accordance with ASTM D7181 (ASTM, 2020). The specimens (CP) were compressed under effective confining pressures of 50 kPa, 100 kPa, and 200 kPa.

Finally, to measure the soil's suction potential, a filter paper suction test was conducted based on ASTM D5298 (ASTM, 2016) and the methodology described by Marinho (1994).

3. Results and Discussion

3.1 Chemical and Mineralogical Analysis

The XRF analysis (Table 3) reveals high concentrations of alumina (Al_2O_3), silica (SiO_2), and ferric oxide (Fe_2O_3). These are considered the primary constituents of the laterization process (BASTOS, 1999; ARAÚJO et al., 2023). On average, iron, aluminum, and silica elements account for 97.18% of the total composition of the samples, highlighting the high degree of laterization in these soils.

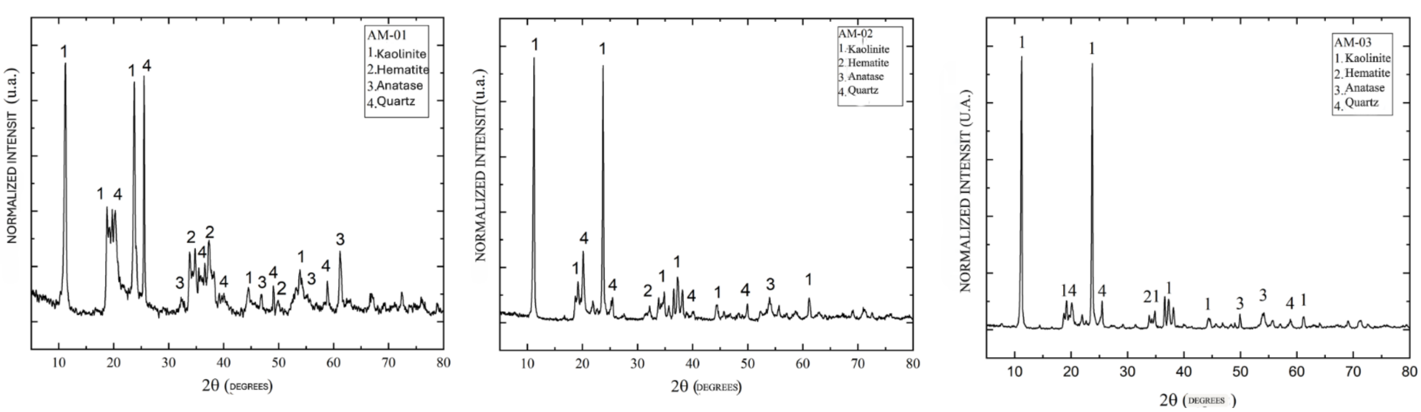
The characteristic yellowish and reddish coloring of lateritic soils is associated with the presence of iron and aluminum (ARAÚJO et al., 2023), which may explain the texture observed in samples AM-01 and AM-02. The lower iron concentration in AM-03 justifies its whitish coloration.

Table 3 – XRF analysis of the soil samples.

Constituents	AM-01 (%)	Chemical compound	AM-02 (%)	Chemical compound	AM-03 (%)
Al_2O_3	39.88	Al_2O_3	40.38	Al_2O_3	47.92
SiO_2	37.99	SiO_2	36.34	SiO_2	47.07
Fe_2O_3	18.36	Fe_2O_3	21.14	Fe_2O_3	2.47
TiO_2	3.06	TiO_2	1.52	TiO_2	1.14
ZrO_2	0.23	K_2O	0.18	K_2O	0.93
K_2O	0.21	ZrO_2	0.11	ZrO_2	0.31
CaO	0.09	Nd_2O_3	0.1	Nd_2O_3	0.08
Cr_2O_3	0.05	V_2O_5	0.1	V_2O_5	0.04
MnO	0.02	SrO	0.06	SrO	0.02
SrO	0.02	MnO	0.04	MnO	0.02
Ga_2O_3	0.02	Ir_2O_3	0.03	Ir_2O_3	0.12
CuO	0.02	CoO	0.02		
ZnO	0.02				
NbO	0.01				
Br	0.01				

Source: Authors (2025).

To identify the minerals, present in the fractions passing through the #200 sieve, X-ray Diffraction (XRD) was performed. The diffractograms from this research indicated that the primary minerals were Kaolinite, Hematite, Anatase (titanium dioxide), and Quartz (Figure 6). According to Biswal et al. (2018) and Araújo et al. (2023), the predominant minerals found in lateritic soil samples are kaolinite, quartz, hematite, and goethite.



a) AM-01. *b) AM-02.* *c) AM-03.*

Figure 5 – Diffractograms of the samples. Source: Authors (2025).

Since silica is more susceptible to leaching, it is estimated that this is the reason why the lower layer (AM-03) exhibits the highest silica concentration. As all soil layers presented similar Ki and Kr values, with a slight attenuation in AM-02, it is inferred that all soils possess a similar degree of laterization, a typical characteristic of this type of material (Table 4).

Table 4 – Degree of weathering of the soils.

SOIL	AM-01 (%)	AM-02 (%)	AM-03 (%)
Ki	1.69	1.53	1.67
Kr	1.25	1.15	1.62

Source: Authors (2025).

3.2 Geotechnical Characterization

Five physical characterization tests were conducted for AM-01 (Table 5), four tests for AM-02 (Table 6), and four for AM-03 (Table 7).

Sample AM-01 exhibits low plasticity and is classified as a low-compressibility silt (ML). It shows low clay activity, with values ranging from 0.16 to 0.24 (Table 5). Its particle size distribution curve is presented in Figure 6.

Table 5 – Physical characterization of AM-01.

Soil		AM-01	AM-01-1R	AM-01-2R	AM-01-3R	AM-01-4R
Grain size distribution	Gravel (%)	3.1	2.3	2.81	2.81	3.50
	Coarse sand (%)	8.4	9.0	9.38	8.96	12.28
	Medium sand (%)	18.7	18.4	18.42	18.12	18.70
	Fine sand (%)	12.2	10.4	11.55	10.97	10.75
	Silt (%)	5.4	4.4	7.80	7.78	10.09
	Clay (%)	52.1	55.5	50.04	51.36	44.68
Consistency limits	LL (%)	35	34	33	33	34
	PI (%)	12	8	8	8	19
USCS classification		CL	ML	ML	ML	CL
Textural classification		Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay	Sandy Clay
ρ_s (g/cm³)		2.74	2.76	2.70	2.70	2.74
HRB		A – 6	A – 4	A – 4	A – 4:	A – 6
Clay activity		0.24	0.15	0.17	0.16	0.16

Source: Authors (2025).

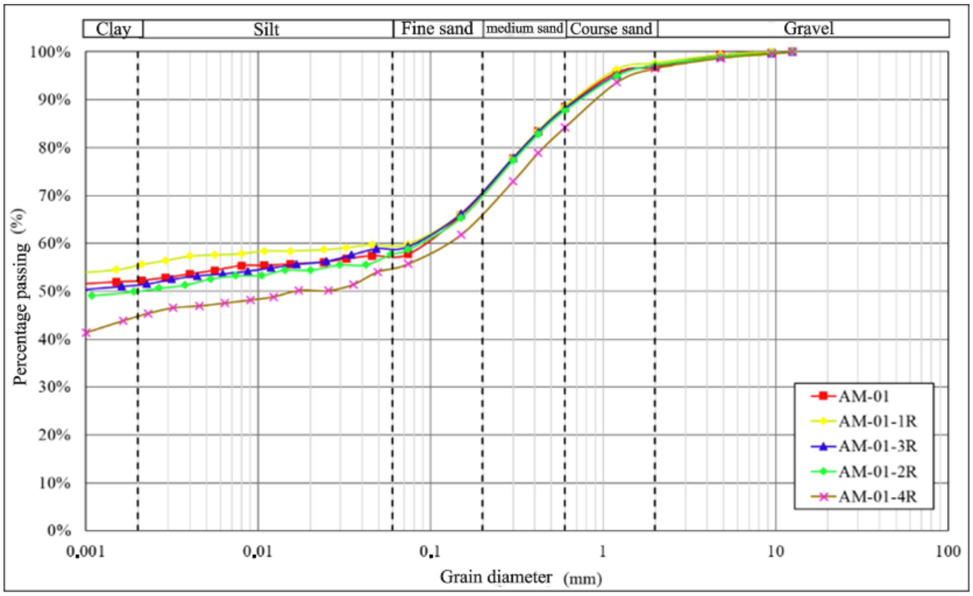


Figure 6 – Grain size curve of sample AM-01. Source: Authors (2025).

Sample AM-02 is classified as an ML. It exhibited medium plasticity and high clay activity. Its grain size curves can be seen in Figure 7.

Table 6 – Physical characterization of sample AM-02.

Soil		AM-02	AM-02-1R	AM-02-2R	AM-02-3R
Grain size distribution	Gravel (%)	1.2	0.3	0.17	0.17
	Coarse sand (%)	12.4	12.9	16.43	14.48
	Medium sand (%)	12.2	12.1	13.99	13.62
	Fine sand (%)	7.2	7.1	9.13	8.93
	Silt (%)	64.4	64.3	60.48	62.26
	Clay (%)	2.6	3.2	0.39	0.53
Consistency limits	LL (%)	41	43	43	43
	PI (%)	13	19	11	11
USCS classification		ML	CL	CL	ML
Textural classification		Sandy Silt	Sandy Silt	Sandy Silt	Sandy Silt
ρ_s (g/cm³)		2.76	2.77	2.70	2.68
HRB		A – 4	A – 7 – 5	A-7-5	A-7-5
Clay activity		5.18	6.44	28.20	20.75

Source: Authors (2025).

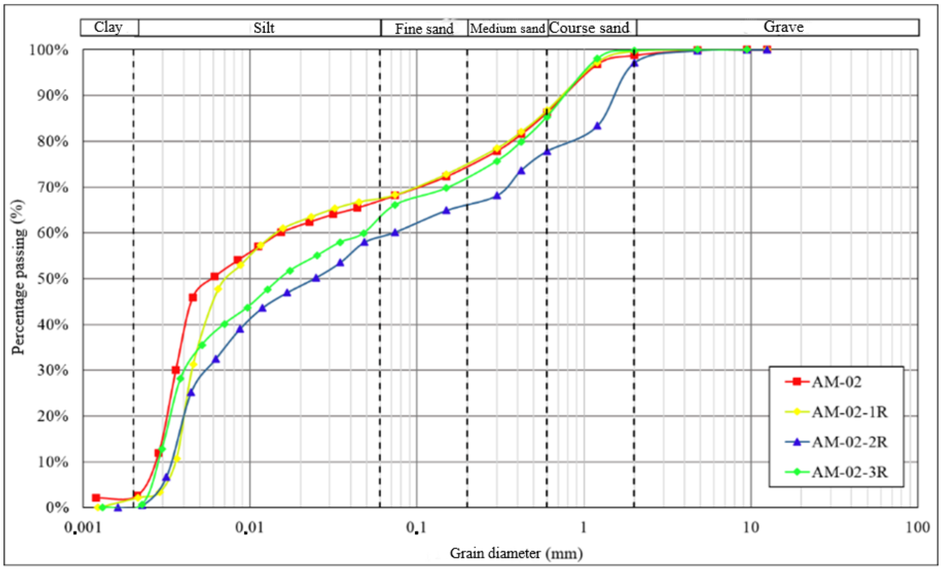


Figure 7 – Grain size curve of sample AM-02. Source: Authors (2025).

According to the USCS classification, all characterizations of sample AM-03 were considered to be low compressibility clays (CL). The activity of the clays in AM-03 is considered high. Figure 8 shows their particle size distribution curves.

Table 7 – Physical characterization of sample AM-03.

Soil		AM-03	AM-03-1R	AM-03-2R	AM-03-3R
Grain size distribution	Gravel (%)	3.4	4.2	3.91	3.91
	Coarse sand (%)	22.4	24.7	25.08	25.99
	Medium sand (%)	17.1	15.3	12.24	12.16
	Fine sand (%)	5.0	4.9	5.52	5.92
	Silt (%)	42.8	46.8	51.39	49.66
	Clay (%)	9.2	4.1	1.86	2.36
Consistensy limits	LL (%)	33	33	33	33
	PI (%)	15	14	14	14
USCS classification		CL	CL	CL	CL
Textural classification		Silty Sand	Sandy Silt	Sandy Silt	Sandy Silt
ρ_s (g/cm³)		2.77	2.77	2.65	2.65
HRB		A – 7 – 5	A – 6	A-6	A-6
Clay activity		1.67	3.43	7.53	5.93

Source: Authors (2025).

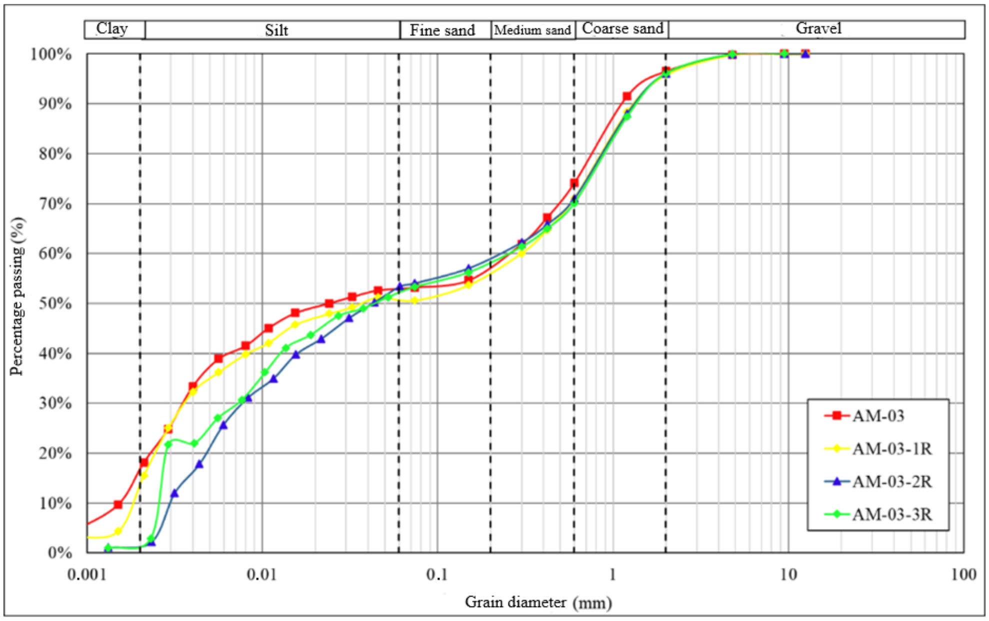
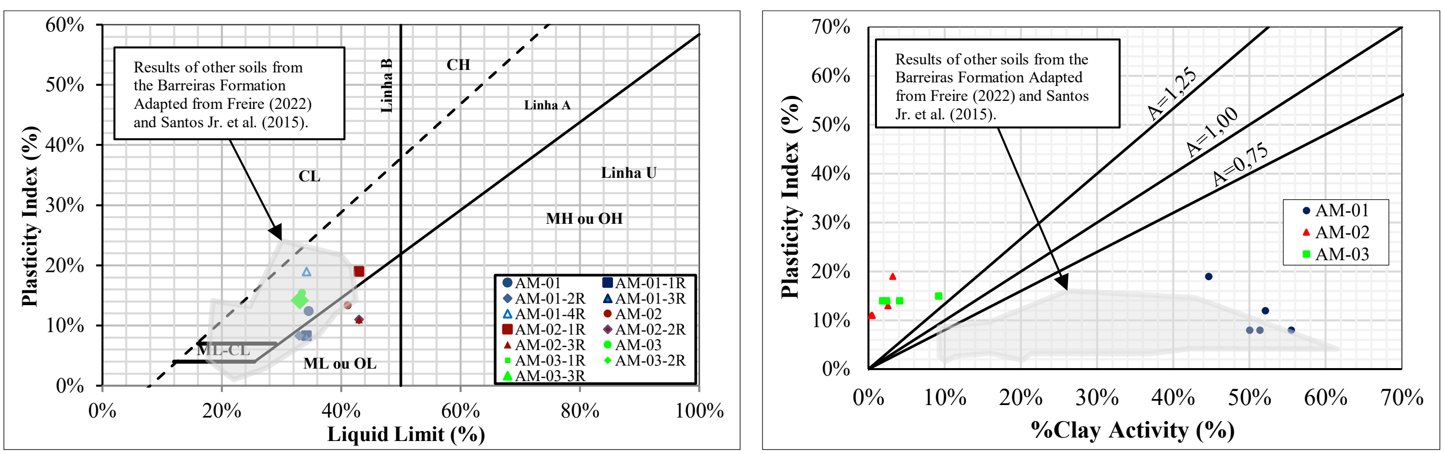


Figure 7 – Grain size curve of sample AM-03. Source: Authors (2025).

Consistency limit tests were conducted in previous studies on the Barreiras Formation by Cunha (1992), Silva (2003), Pereira (2004), Severo (2005, 2011), Pereira (2012), Souza Jr. (2013), and Freire et al. (2022). In all these studies, the sediments of the Barreiras Formation exhibited low to medium plasticity, as shown in Figure 9a. According to Freire et al. (2022) and Santos Jr. et al. (2015), soils from the Barreiras Formation display low clay activity (Figure 9b). Sample AM-01 is consistent with literature; however, samples AM-02 and AM-03 exhibit high clay activity, which does not align with the findings reported by other authors.



a) Plasticity chart. *b) Clay activity.*

Figure 9 – Plasticity chart and clay activity of samples from the Barreiras Formation. Source: adapted from Freire (2022) and Santos Jr. et al. (2025).

The results of the soil dispersivity tests are shown in Table 8. Sample AM-01 was classified as non-dispersive, sample AM-02 exhibited moderately dispersive behavior, and AM-03 showed a dispersivity level of 2, being considered slightly dispersive.

According to Duikier et al. (2003), the stability of soil aggregates results from the interaction between variable-charge minerals, such as iron and aluminum oxides, and organic matter, which carries predominantly negative charges. Lollo (2008) states that soil dispersivity is an indicator of collapsibility.

Table 8 – Result of the soil dispersibility degree (Crumb Test).

Time (min)	Dispersibility Degree		
	AM-01	AM-02	AM-03
1	1	3	1
2	1	3	3
15	1	3	2
30	1	3	2
60	1	3	2

Fonte: authors (2025).

3.3 Compaction

The borehole investigation revealed that in the first 5.00 m, AM-01, a sandy clay, was very stiff, with an average N_{SPT} greater than 19 and variegated coloration. Between 5.00 and 6.60 m, AM-02, a sandy silt with low clay content, had N_{SPT} values between 10 and 12, exhibited medium compaction, and showed a reddish coloration. From 6.60 m down to the impenetrable layer, AM-03, a silty sand, had N_{SPT} values between 12 and 43, indicating consistency ranging from medium compact to very stiff. The tactile-visual and grain size classifications showed good agreement.

Figure 10 presents the compaction results for samples AM-01, AM-02, and AM-03. AM-01, despite being clayey, exhibited behavior similar to a silty soil, with a w_{otm} of 16.37% and a maximum dry density (ρd_{max}) of 1.76 g/cm³. AM-02 had the highest w_{otm} of 17.69% and ρd_{max} of 1.69 g/cm³, while AM-03 exhibited sandy soil characteristics, with w_{otm} of 13.38% and ρd_{max} of 1.87 g/cm³, consistent with their grain size classifications.

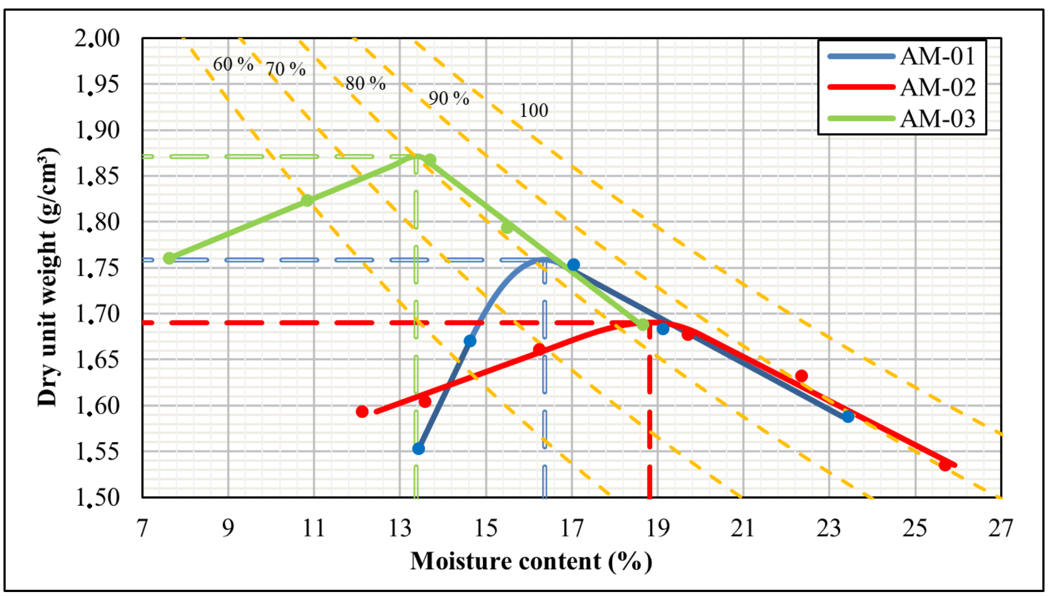


Figure 10 – Compaction curves of the three samples. Source: Authors (2025).

3.4 Permeability

The results of the permeability tests using the flexible-wall method for undisturbed specimens and the rigid-wall method for soils compacted at optimum moisture content are presented in Table 9.

The results indicate that soil AM-01 exhibits high porosity, with a void ratio of 1.11, a characteristic associated with its potential for collapsibility. This behavior is related to the leaching of soluble minerals in the surface layers, with AM-01 being precisely the top layer. The immediately underlying layer, AM-02, shows a "mineral enrichment," which explains its lower permeability in the undisturbed state.

AM-02 displayed lower permeability compared to AM-03, despite having a higher void ratio. However, evaluating only this parameter is insufficient. It is also necessary to consider the degree of connectivity between voids, as well as the degree of saturation achieved after the test.

According to Blight (1997), for tropical residual soils, generalizations of permeability values should be avoided for a given soil type. In other words, there is no technical specification establishing a regularity of values between soils with the same mineralogy or degree of weathering. Tropical residual soils differ in grain shape and size, grain interactions, porosity, mineralogy, degree of fissuring, and the orientation and depth characteristics of fissures (HUAT, SEW, and ALI, 2012).

Table 9 – Physical indices and soil permeability coefficient

	Soil	AM-01		AM-02		AM-03	
	State	Undisturbed	Compacted	Undisturbed	Compacted	Undisturbed	Compacted
Physical indices before the test	ρ (g/cm³)	1.31	1.94	1.65	1.90	1.77	2.07
	ρ_d (g/cm³)	1.29	1.65	1.64	1.61	1.76	1.85
	e	1.11	0.59	0.66	0.72	0.54	0.47
	w (%)	1.51	18.04	0.40	18.61	0.31	12.24
	Sr (%)	3.71	83.72	1.66	70.76	1.55	70.84
Physical indices after the test	ρ (g/cm³)	1.68	1.99	2.02	2.00	2.05	2.14
	ρ_d (g/cm³)	1.29	1.65	1.64	1.61	1.76	1.85
	e	1.11	0.59	0.66	0.72	0.54	0.47
	w (%)	30.74	20.43	22.81	24.09	16.43	15.84
	Sr (%)	75.59	90.63	94.40	91.60	82.86	91.67
	K (cm/s)	1.58×10^{-3}	2.41×10^{-7}	2.48×10^{-5}	6.95×10^{-7}	1.68×10^{-4}	472×10^{-7}

Source: Authors (2025).

3.5 Oedometer test

Double oedometer tests were conducted on both compacted and undisturbed soil samples (Figure 11) under natural and flooded conditions to obtain the paired compression curves according to the method proposed by Jennings & Knight (1957).

Sample AM-01, in its natural moisture condition, showed a slight reduction in compressibility, whereas when flooded, it exhibited high compressibility. This occurs because residual soils display high compressibility when saturated due to the reduction of matric suction, decreased apparent strength, and softening of cementing bonds (MITCHELL & SOGA, 2005).

From Table 10, it can be observed that the preconsolidation stress of the undisturbed AM-01 sample under flooded conditions was 81.8 kPa, while the preconsolidation stress of the same soil in its natural state was 459.8 kPa, representing an increase of 462.1% compared to the flooded sample.

Barksdale and Blight (2012) state that these soils do not exhibit a well-defined virgin compression line due to their preconsolidation behavior. Blight (1997) notes that residual soils frequently behave as if overconsolidated, showing low compressibility at low stress levels. Once the yield stress is reached, compressibility increases. In general, soils with high collapse potential experience significant deformations when flooded.

According to Fooke (1997), the behavior of compacted residual soils depends primarily on grain size distribution, clay minerals present, and the density achieved during compaction.

None of the compacted samples displayed a well-defined yield point. As Barksdale & Blight (2012) mention, deformation versus stress curves for residual soils often lack a clear yield point and may instead show a continuous increase in stiffness with increasing stress.

When natural residual soil is compacted, it loses the structure of its matrix formed over thousands of years under natural chemical and physical weathering processes. Compaction results in lower void ratios and higher densities. The control achieved through compaction yields soil specimens with uniform physical indices, significantly reducing their compressibility and volumetric instability under static and dynamic loading, as well as under saturation or seepage conditions.

For saturated soils, a reduction in strength is generally expected. However, if the material is well compacted at its optimum moisture content with maximum dry density, or close to ideal, the water present during the test does not significantly affect the specimen.

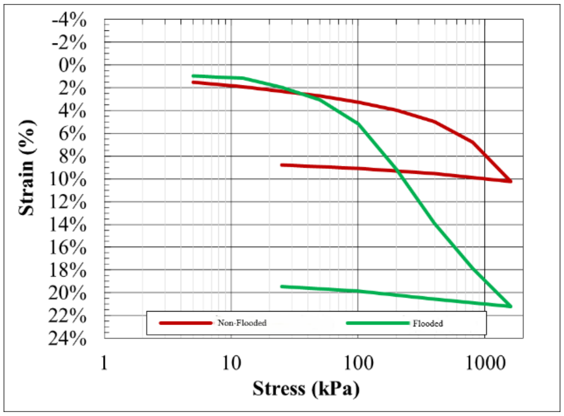
It is evident that in all compacted samples, flooding led to reduced settlements. Observing the preconsolidation stresses, the highest stresses occurred in samples that were flooded during testing. This behavior highlights the effectiveness of compaction in limiting soil compressibility, especially under saturated conditions, potentially reducing settlements under future load applications.

Collapse under the same stress (400 kPa) was also evaluated. A collapse of 9.44% was observed for AM-01, a slight expansion of approximately 1% for AM-02, and a collapse of 5.10% for AM-03. According to Vargas (1978), values above 2% indicate collapsibility. Therefore, samples AM-01 and AM-03 can be classified as collapsible, while AM-02 is not, given its minor expansion.

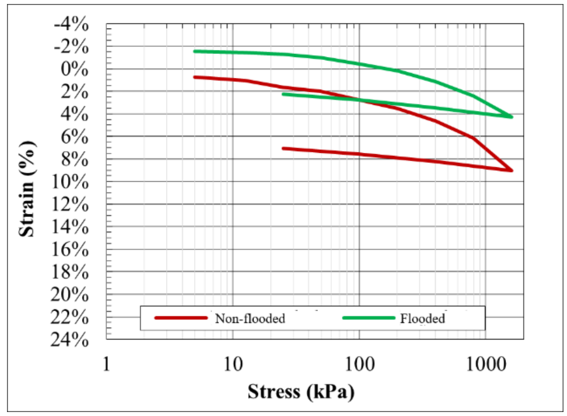
Table 10 – Parameters of compressibility tests for undisturbed and compacted soils

Soil	State	Undisturbed					Compacted			
		σ'_v (kPa)	c_c	c_r	c_d	Collapse (%)	σ'_v (kPa)	c_c	c_r	c_d
AM-01	Flooded	81.8	0.48	0.01	0.03	9.44	265.0	0.15	0.01	0.03
	Non-flooded	459.8	0.33	0.03	0.02		409.0	0.23	0.02	0.03
AM-02	Flooded	188.0	0.21	0.02	0.05	-1.00 (Expansion)	301.3	0.20	0.01	0.06
	Non-flooded	331.4	0.19	0.02	0.01		361.2	0.20	0.02	0.03
AM-03	Flooded	113.1	0.19	0.04	0.02	5.10	148.8	0.08	0.01	0.02
	Non-flooded	188.6	0.11	0.01	0.03		378.0	0.15	0.01	0.04

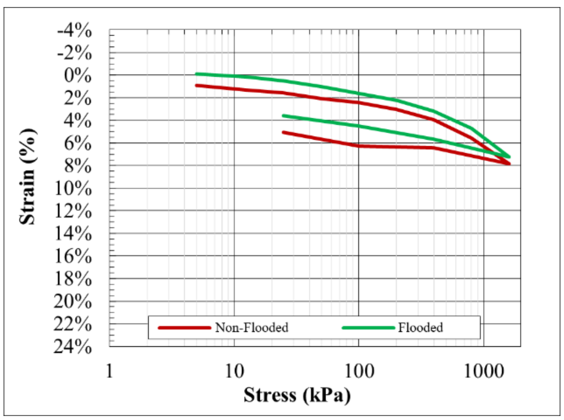
Source: Authors (2025).



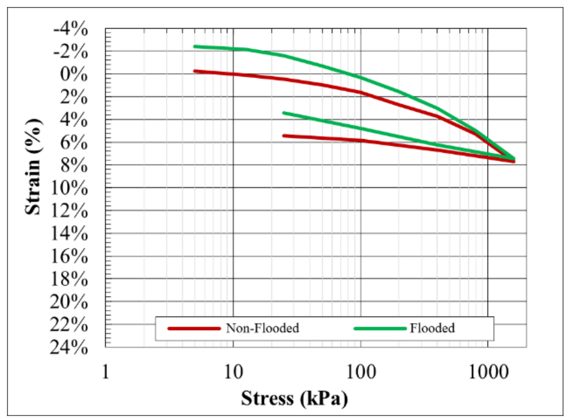
a) AM-01 – Undisturbed.



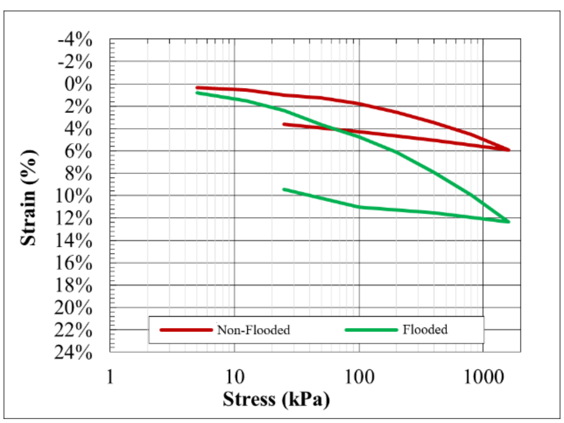
b) AM-01 – Compacted.



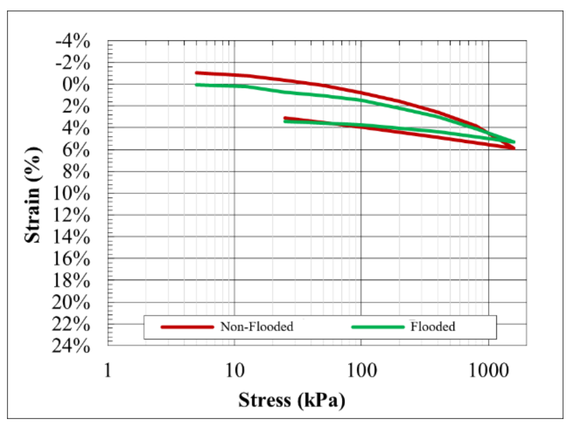
c) AM-02 – Undisturbed.



d) AM-02 – Compacted.



e) AM-03 – Undisturbed.



f) AM-03 – Compacted.

Figure 11 – Strain versus stress curves for all flooded and non-flooded samples. Source: Authors (2025).

3.6 Direct shear tests

In the direct shear test of soil AM-01, under both undisturbed and compacted conditions, a ductile behavior was observed under all applied stresses (Figure 12 - a). The undisturbed samples exhibited a volume reduction due to the soil's high void ratio, even after the consolidation stage. This behavior reflects the soil’s compressible nature in its natural state.

Variations observed in the results of the undisturbed samples, especially in vertical versus horizontal displacements, may indicate the heterogeneity of the undisturbed specimens (SALIH, 2012). In contrast, the compacted samples showed results with lower variability due to their controlled physical indexes.

For sample AM-02 in its natural condition, the soil exhibited a brittle behavior, as shown in Figure 12 - C. Conversely, the compacted sample displayed ductile behavior. The difference in strength is evident and may be attributed to ferruginous cementation present in lateritic residual soils enriched with iron. This observation is consistent with the Crumb Test, where the soil showed resistance to disaggregation in an aqueous medium.

Initially, AM-03A (undisturbed) exhibited ductile behavior (Figure 12 - E); however, upon repeated tests, the sample displayed brittle behavior. This is due to soil heterogeneity, as the sample presented different structures depending on the sampling location.

All compacted samples showed moderated volumetric variation compared to their undisturbed state under the same conditions (Figure 13). The undisturbed samples exhibited higher peak friction angles when compared to the compacted states (Table 11).

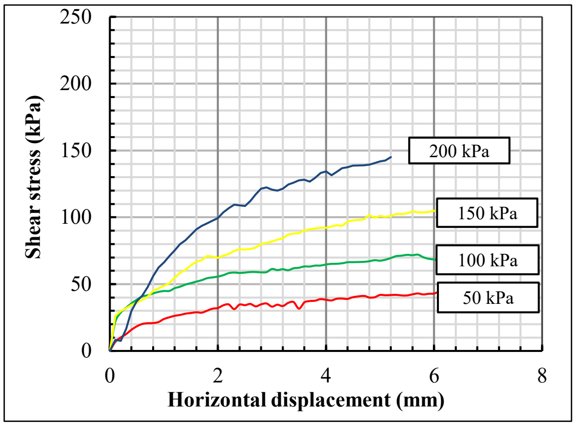
Table 11 – Friction angle and cohesion of undisturbed and compacted samples.

Soil	State	Undisturbed		Compacted	
		φº	c (kPa)	φº	c (kPa)
AM-01	Peak	33.8	4.48	33.1	22.52
	Residual	33.9	7.82	33.6	11.79
AM-02	Peak	46.2	23.83	25.7	11.95
	Residual	37.8	0	21.4	12.72
AM-03	Peak	29.7	45.22	36.4	4.38
	Residual	34.6	7.22	32.2	0

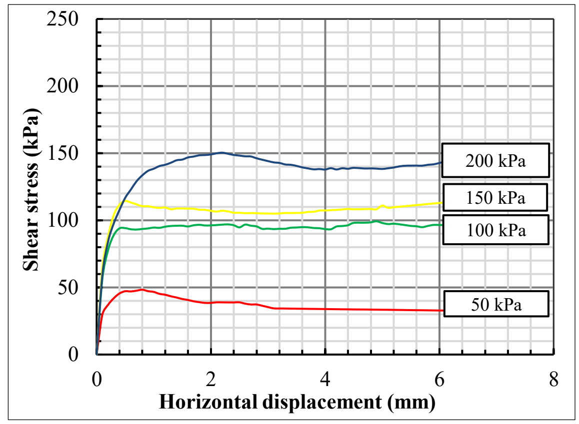
Source: Authors (2025).

Since AM-03 exhibited the greatest uncertainty regarding its shear strength in the direct shear test, as shown in Figure 13, it was considered highly relevant to confirm the result with a triaxial test on this sample (Figure 14). In the triaxial test, the samples exhibited brittle behavior under all applied stresses, with failure occurring between 1% and 2% axial strain. Under all stress levels, the sample displayed dilatant behavior during the triaxial compression test.

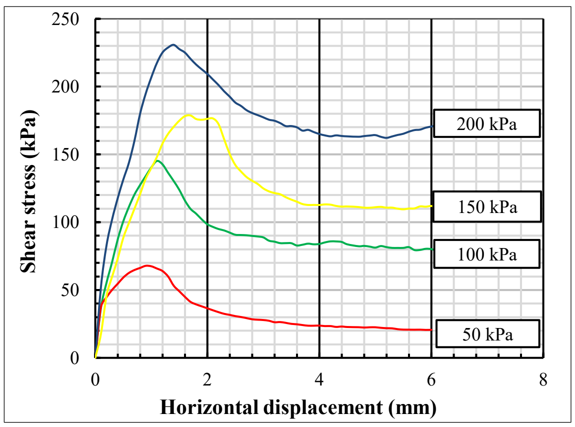
In this test, sample AM-03 reached a result of φ′ = 39.24° and c′ = 68.2 kPa, which coincided with the values obtained in the repeated direct shear tests of this sample.



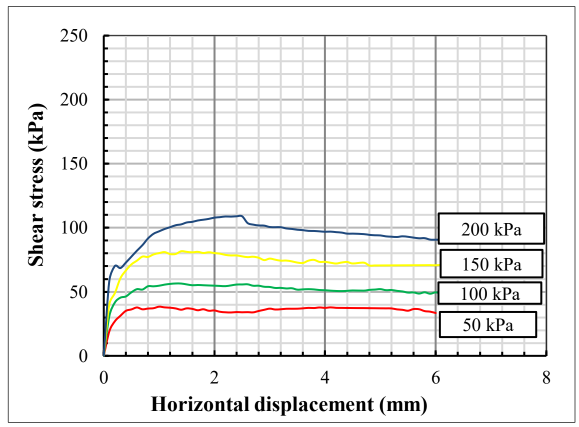
a) AM-01 – Undisturbed.



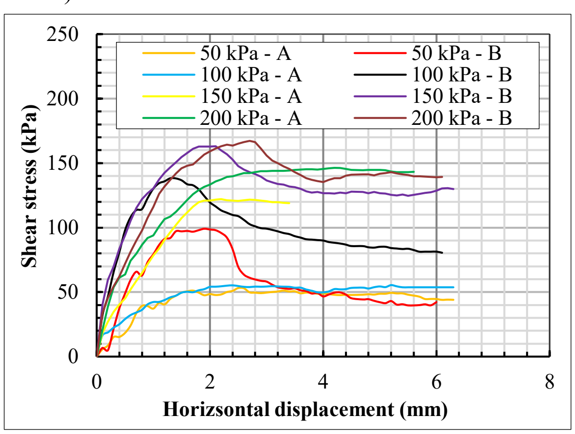
b) AM-01 – Compacted.



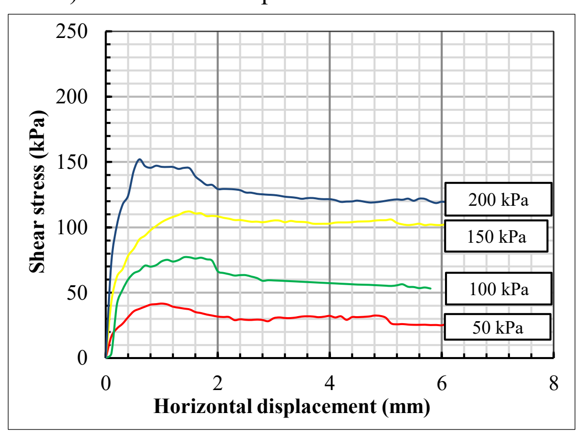
c) AM-02 – Undisturbed.



d) AM-02 – Compacted.

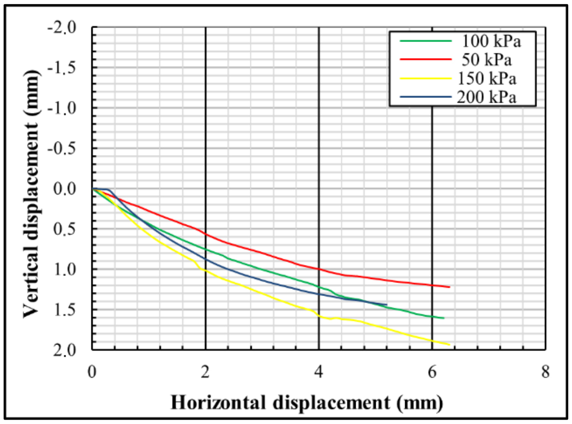


e) AM-03 – Undisturbed.

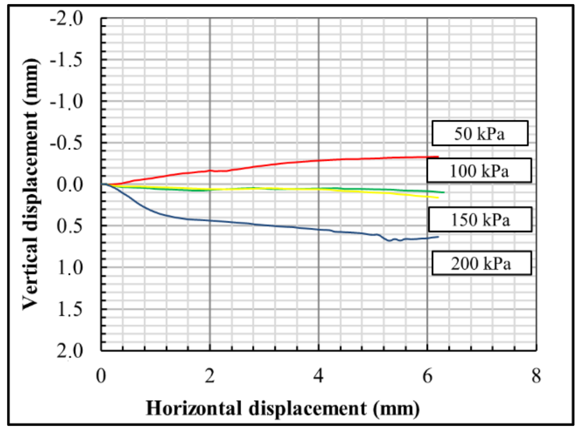


f) AM-03 – Compacted.

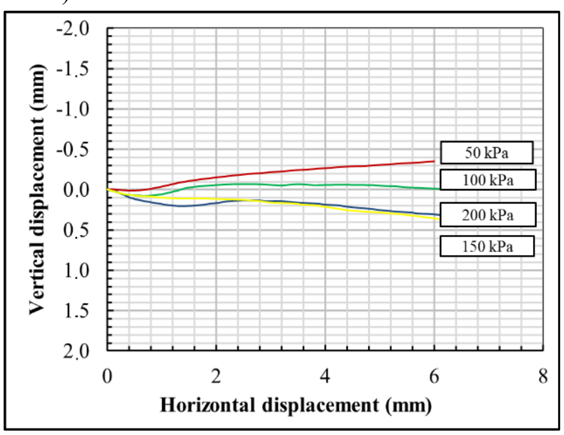
Figure 12 – Direct shear of the samples, shear stress versus horizontal displacement. Source: Authors (2025).



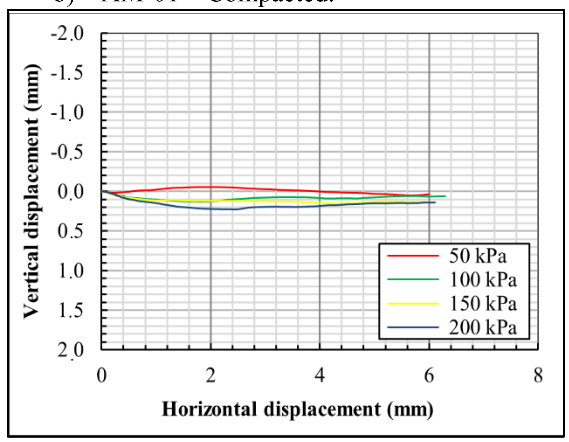
a) AM-01 – Undisturbed.



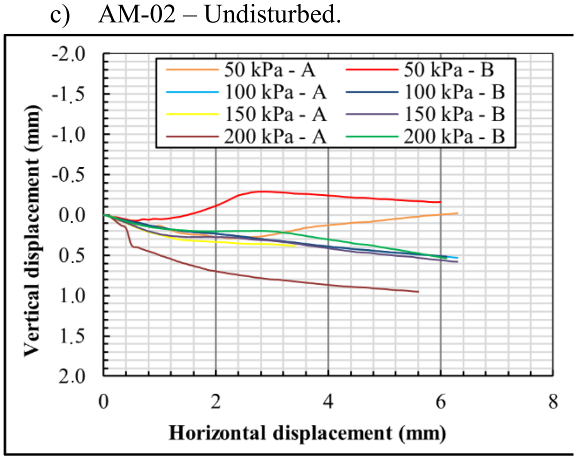
b) AM-01 – Compacted.



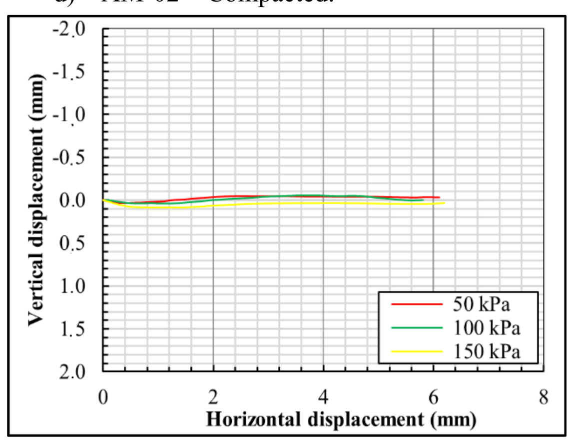
c) AM-02 – Undisturbed.



d) AM-02 – Compacted.

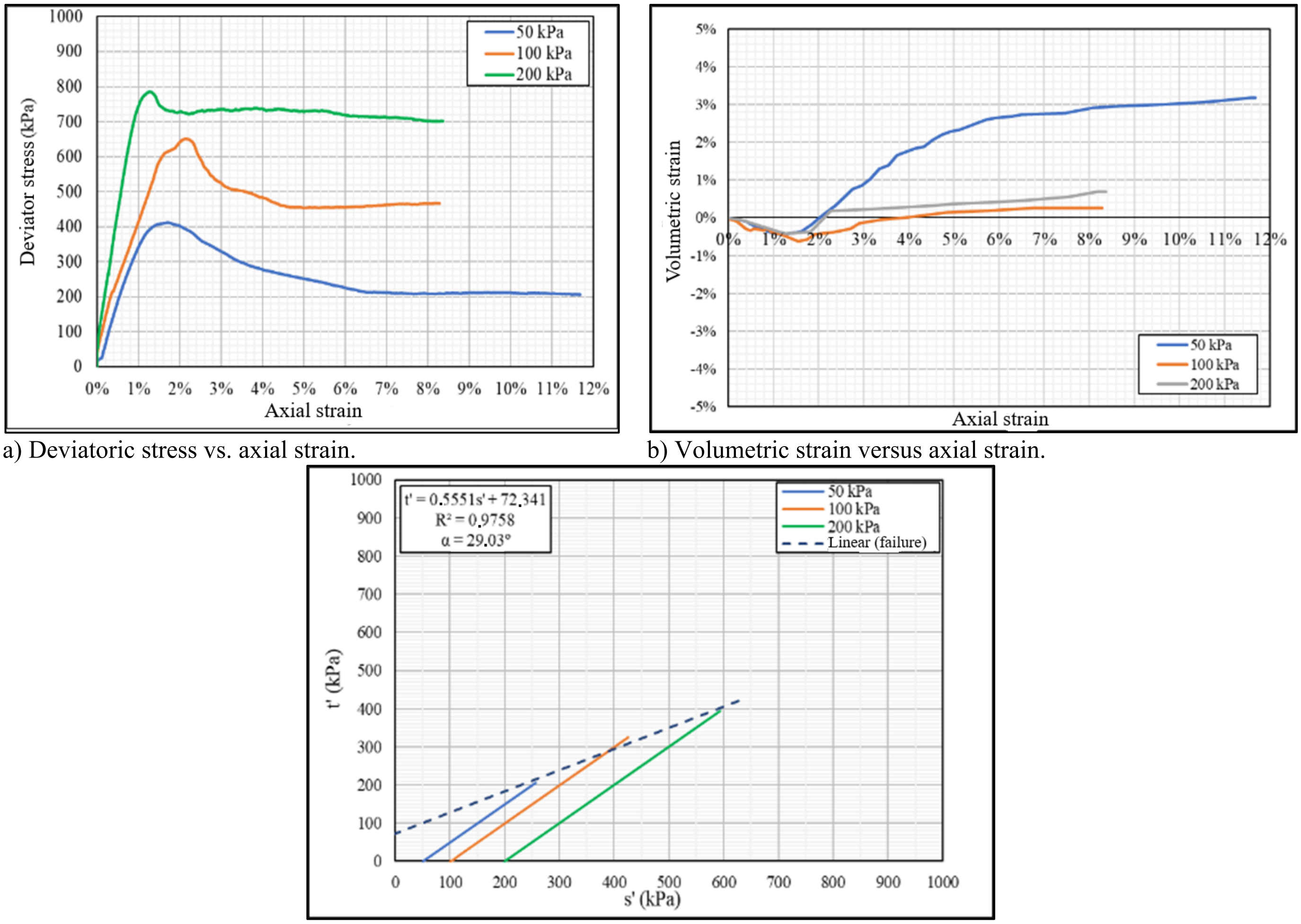


e) AM-03 – Undisturbed.



f) AM-03 – Compacted.

Figure 13 – Direct shear of the samples, vertical displacement versus horizontal displacement. Source: Authors (2025).



a) Deviatoric stress vs. axial strain. b) Volumetric strain versus axial strain.

c) t' x s'.

Figure 14 – Triaxial compression of sample AM-03. Source: Author (2025).

3.7 Suction test

The fitting of the retention curves for samples AM-01, AM-02, and AM-03 was performed using the method proposed by Fredlund & Xing (1994), as illustrated in Figure 15. All the curves presented were obtained with only a single air-entry value.

According to Fredlund & Xing (1994), the curve of sample AM-01 resembles that of a silt, while AM-02 is similar to the retention curve of a clay. The curve of AM-03, on the other hand, approaches the characteristic behavior of a sand, resembling the soil behavior observed in the compaction curve.

Soils with different particle-size distributions tend to retain water differently: the more a soil behaves like a clay, the higher its water retention capacity due to plasticity; conversely, sandy soils exhibit low water retention (Blight, 2012). Analyzing the curves obtained in this study, it is observed that the most plastic sample (AM-02) exhibited behavior consistent with the clay model described by Fredlund & Xing

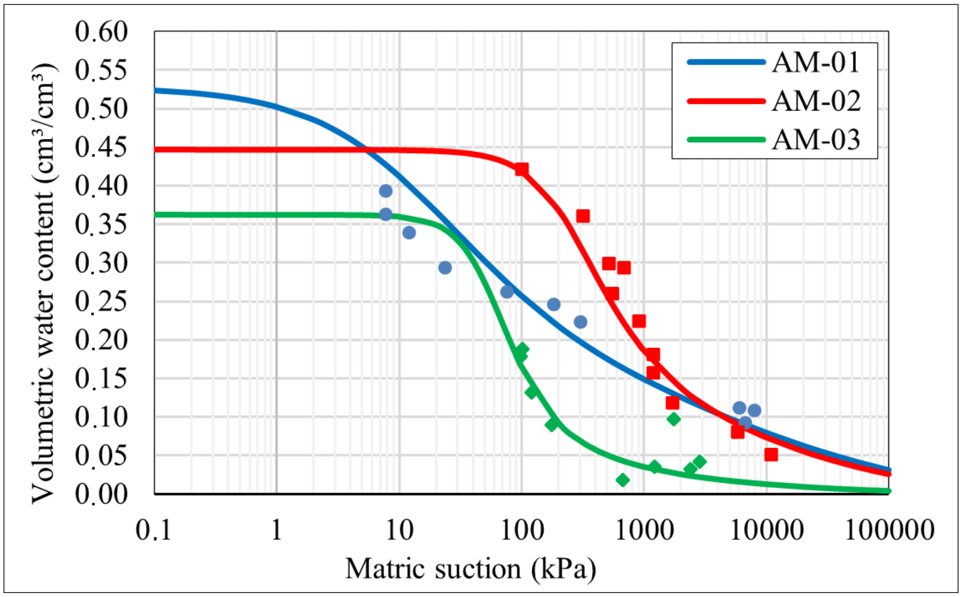


Figure 15 – Water retention curves for the undisturbed samples. Source: Author (2025).

4. Conclusions

This study conducted a geotechnical characterization based on residual soil samples collected in Bananeiras/PB. The samples, identified as AM-01, AM-02, and AM-03, were obtained from soil layers present on a slope in the region. The soils were classified as low-compressibility clay (CL) and low-compressibility silt (ML).

In the XRF tests, the soils exhibited high concentrations of alumina (Al_2O_3), silica (SiO_2), and ferric oxide (Fe_2O_3), considered the main constituents associated with the laterization process. XRD analyses indicated the presence of crystalline phases corresponding to kaolinite, hematite, anatase, and quartz. No expansive clay minerals were identified.

The combined particle-size analysis revealed significant heterogeneity among the samples from the Barreiras Formation, a common feature of tropical residual soils. Although the samples differed in particle size, color, and texture, all exhibited the same degree of laterization, with minor variations in the Kr and Ki indices.

It was observed that the permeability of the residual soils does not follow a generic pattern according to material type, as the factors influencing this parameter are related to multiple independent variables, preventing precise correlations. Compaction proved to be a determining factor in altering hydraulic conductivity. While the soil exhibited a relatively high permeability coefficient in its natural state, compaction resulted in significantly lower values. This suggests that the sandy soil of the Barreiras Formation can be fully utilized in landfill liners and earth dam systems.

The upper soil layer (AM-01), the most lateritized, exhibited nearly instantaneous collapse when undisturbed and flooded. The application of compaction energy effectively mitigated this volumetric instability, transforming the material behavior into a slightly expansive state and eliminating the risk of collapse.

The influence of compaction on effective strength parameters was observed to be variable and dependent on lithology. AM-02 in its natural state presented a high friction angle and a peak shear strength; however, after compaction, these values were drastically reduced, and the peak disappeared, indicating the breakage of the natural cementation present in the undisturbed soil. In contrast, sample AM-03 exhibited an increased friction angle after compaction, despite the loss of peak strength. This divergence highlights the importance of microstructure and the differentiated impact of compaction.

Compaction proved to be an effective geotechnical treatment for converting a high-risk soil (AM-01) into a material suitable for engineering applications, stable and with low permeability.

These results demonstrate the relevance of compaction as a geotechnical improvement technique, capable of transforming residual soils of the Barreiras Formation into stable and suitable materials for civil engineering works, such as landfill liners and earth dams, contributing to the sustainable and safe utilization of local materials in infrastructure projects.

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