ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 12, nº 2 (2026)

https://doi.org/10.21680/2447-3359.2026v12n2ID42605

Spatial variability of the mechanical properties of sediments from the Barreiras Formation on the eastern coast of northeastern Brazil

Variabilidade espacial das propriedades mecânicas de sedimentos da Formação Barreiras do litoral leste do nordeste brasileiro

Pedro Júlio Castro dos Santos[1]; Olavo Francisco dos Santos Júnior[2]; Marial del Pilar Durante Ingunza[3]

[1] Federal University of Rio Grande do Norte, Graduate Program in Civil and Environmental Engineering (PPCIVAM), Natal, Rio Grande do Norte, Brazil. Email: pedro.julio0820@gmail.com
ORCID: https://orcid.org/0009-0009-0940-0215
[2] Federal University of Rio Grande do Norte, Graduate Program in Civil and Environmental Engineering (PPCIVAM), Natal, Rio Grande do Norte, Brazil. Email: olavo.santos@ufrn.br
ORCID: https://orcid.org/0000-0001-7552-6646
[3] Federal University of Rio Grande do Norte, Graduate Program in Civil and Environmental Engineering (PPCIVAM), Natal, Rio Grande do Norte, Brazil. Email: maria.ingunza@ufrn.br
ORCID: https://orcid.org/0000-0001-6994-7559

Abstract: The Barreiras Formation constitutes one of the most relevant geological units along the northeastern Brazilian coast, being widely used as a natural support for foundations, slopes, and escarpments. However, its lithological heterogeneity and the variable presence of different minerals result in significant geotechnical variability, requiring a detailed understanding of its mechanical behavior for engineering applications. This study aims to quantify and compare the mechanical behavior of Barreiras Formation soils from distinct geotechnical and geomorphological contexts, as well as to correlate the presence of iron oxides with physical and mechanical properties, including grain-size distribution, compressibility, permeability, and shear strength. Soil samples were collected from Bananeiras/PB, Caaporã/PB, Natal/RN, and Tibau do Sul/RN. The methodology included physical characterization tests, mineralogical and chemical analyses by X-ray diffraction (XRD) and X-ray fluorescence (XRF), as well as compaction, one-dimensional consolidation, permeability, and consolidated undrained (CU) triaxial tests. The results revealed significant differences in the mechanical behavior of the analyzed soils. The material from Bananeiras/PB showed a high iron oxide content, associated with high cohesion, low permeability, and a pronounced overconsolidated behavior. The soil from Caaporã/PB was characterized by a higher clay content, high preconsolidation stress, and predominantly frictional strength. In contrast, the soils from Natal/RN and Tibau do Sul/RN exhibited a higher sand fraction, greater permeability, and lower shear strength, indicating less cemented structures and greater susceptibility to deformation.

Keywords: Triaxial compression; Grain size distribution; Consolidation; Permeability; Chemical and mineralogical analyses; Iron oxides.

Resumo: A Formação Barreiras constitui uma das unidades geológicas mais relevantes do litoral nordeste brasileiro, sendo amplamente utilizada como suporte natural de fundações, taludes e encostas. Entretanto, sua heterogeneidade litológica e a presença variável de diferentes minerais conferem elevada variabilidade geotécnica, exigindo compreensão detalhada de seu comportamento mecânico para aplicações em engenharia. Este estudo tem como objetivo quantificar e comparar o comportamento mecânico de solos da Formação Barreiras provenientes de distintos contextos geotécnicos e geomorfológicos, bem como correlacionar a presença de óxidos de ferro com propriedades físicas e mecânicas, incluindo granulometria, compressibilidade, permeabilidade e resistência ao cisalhamento. Foram investigadas amostras de Bananeiras/PB, Caaporã/PB, Natal/RN e Tibau do Sul/RN. A metodologia envolveu ensaios de caracterização física, análises químicas e mineralógicas por FRX e DRX, além de ensaios de compactação, adensamento unidimensional, permeabilidade e compressão triaxial CU. Os resultados evidenciaram diferenças no comportamento mecânico dos solos analisados. O material de Bananeiras/PB apresentou elevado teor de óxidos de ferro, associado a alta coesão, baixa permeabilidade e comportamento sobreadensado. O solo de Caaporã/PB destacou-se pelo maior teor de argila, elevada tensão de pré-adensamento e resistência predominantemente friccional. Já os solos de Natal/RN e Tibau do Sul/RN apresentaram maior fração arenosa, maior permeabilidade e menor resistência ao cisalhamento, indicando estruturas menos cimentadas e mais suscetíveis à deformação.

Palavras-chave: Compressão triaxial; Granulometria; Adensamento; Permeabilidade; Químicas e mineralógicas; Óxidos de ferro.

Received: 08/01/2026; Accepted: 03/07/2026; Published: 09/09/2026.

1. Introduction

Knowledge of soil behavior has always played a central role in civil and geotechnical engineering, since the performance of any engineering structure depends directly on the interaction between the foundation soil and the constructed facility. From the pioneering studies systematized by Terzaghi in the early twentieth century to contemporary advances involving numerical methods and mineralogical analyses, understanding soil behavior has proven essential to ensuring the safety, stability, and durability of engineering structures (Wu et al., 2023; Baecher, 2023; Finno et al., 2017). The complexity of these materials, resulting from geological and pedogenetic processes, poses continuous challenges and requires both laboratory and field investigations capable of quantifying parameters such as strength, compressibility, and permeability. Therefore, it is important to avoid generalizing the mechanical parameters of soils belonging to the same geological formation, which may extend over large areas within a state, region, or country (Ku et al., 2016; Napoli et al., 2022; Rabab et al., 2024).

One of the most extensive sedimentary units in Brazil is the Barreiras Formation, which extends from the Amazon region, along the entire northern and northeastern coastline, to the state of Rio de Janeiro. Of Tertiary age, it is characterized by significant textural and mineralogical heterogeneity, consisting predominantly of clastic sedimentary materials that are often enriched with iron and aluminum oxides (Nunes et al., 2011). These oxides impart the typical reddish or yellowish coloration to the deposits and, in some cases, provide cementing properties that increase soil stiffness and strength. However, under certain conditions, they may also make the material more susceptible to degradation in the presence of iron hydroxides, as reported by Ingunza et al. (2025), or when subjected to wetting–drying cycles.

Due to the high variability in its physical and mineralogical composition, the term *Barreiras* has been referred to in the geological literature as a Formation, a Group, and, formerly, as a Series. Several uncertainties still remain regarding its geological characterization, particularly with respect to its depositional age and genesis, reflecting the lack of consensus concerning its lithostratigraphic classification. These uncertainties highlight existing knowledge gaps regarding the fundamental aspects of this geological unit (Moura-Fé, 2014).

The relevance of the *Barreiras Formation* to civil and geotechnical engineering lies in its extensive distribution and its frequent occurrence as the foundation material for shallow and deep foundations, slopes, coastal cliffs, and urban hillsides. However, its inherent variability, controlled by both grain-size distribution and mineralogical composition, may result in unexpected engineering behavior, including differential settlements, construction challenges, and slope instabilities. Such problems have been increasingly reported along the northeastern Brazilian coastline in recent years, mainly due to the intensification of urban development and coastal erosion (Santos Júnior et al., 2011; Silva et al., 2020).

Although commonly associated with coastal regions, the *Barreiras Formation* also extends into inland areas, such as the municipalities of Caaporã (Paraíba State) and Bananeiras (Paraíba State), where weathering processes and, consequently, the thickness of the formation deposits differ from those observed in locations closer to the coastline, such as Natal (Rio Grande do Norte State) and Tibau do Sul (Rio Grande do Norte State) (Barbosa et al., 2008).

This heterogeneity causes soils belonging to the same geological unit to exhibit distinct mechanical parameters, making it difficult to generalize results and reinforcing the need for detailed geotechnical investigations of the soils of the Barreiras Formation along the eastern coast of northeastern Brazil. Therefore, this study aims to quantify the spatial variability of the mechanical properties of sediments from the Barreiras Formation along the eastern coast of northeastern Brazil. It seeks to understand the variability of the geotechnical properties among soils from four different municipalities: Bananeiras/PB, Caaporã/PB, Natal/RN, and Tibau do Sul/RN.

2. Methodology

2.1 Characterization of the study áreas and sample collection

The study area comprises sections of the eastern coast of northeastern Brazil, distributed across the states of Paraíba and Rio Grande do Norte. This coastal zone is characterized by a typically humid tropical climate, influenced by the trade winds and its proximity to the Atlantic Ocean, with high mean annual temperatures and a rainfall regime marked by strong seasonality. The predominant vegetation belongs to the Atlantic Forest domain and associated coastal formations, including *restingas*, mangroves, and *tabuleiro* forests, forming an ecologically sensitive environment subject to intense hydrological dynamics (Sousa et al., 2024; Scudelari et al., 2021).

From a geological perspective, the region is largely characterized by the presence of the Barreiras Formation, a Tertiary–Quaternary sedimentary unit composed of sandstones, siltstones, and claystones of predominantly continental origin, reworked over time by fluvial, marine, and gravitational processes. This formation covers a large portion of the coastal tablelands of eastern northeastern Brazil and exhibits variable thicknesses and degrees of cementation, influenced by lateritic processes and the concentration of iron and aluminum oxides and hydroxides. Geomorphologically, the landscape is dominated by gently undulating tabular surfaces, active sea cliffs, marine terraces, and incised valleys associated with small drainage basins. These characteristics control the distribution of soil types, the thickness of weathering profiles, and the variability of moisture conditions, all of which directly influence the geotechnical behavior of these materials, particularly with respect to erodibility, collapsibility, and susceptibility to strength loss when subjected to variations in moisture content (Barbosa et al., 2008).

The selected sites encompass different geotechnical and geomorphological settings, allowing for a comprehensive comparative analysis of the physical and mechanical behavior of soils belonging to the Barreiras Formation in the states of Paraíba and Rio Grande do Norte. The analyzed samples were collected from the municipalities of Bananeiras and Caaporã, in the state of Paraíba, and Natal and Tibau do Sul, in the state of Rio Grande do Norte (Figure 1).

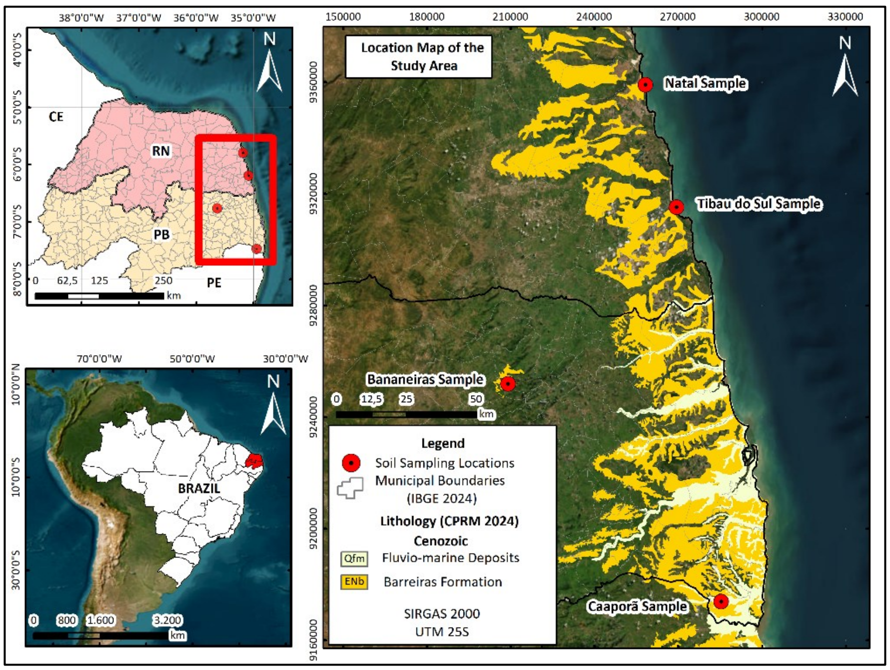


Figure 1 – Location of the sampling sites and geological setting.
Source: Authors (2026).

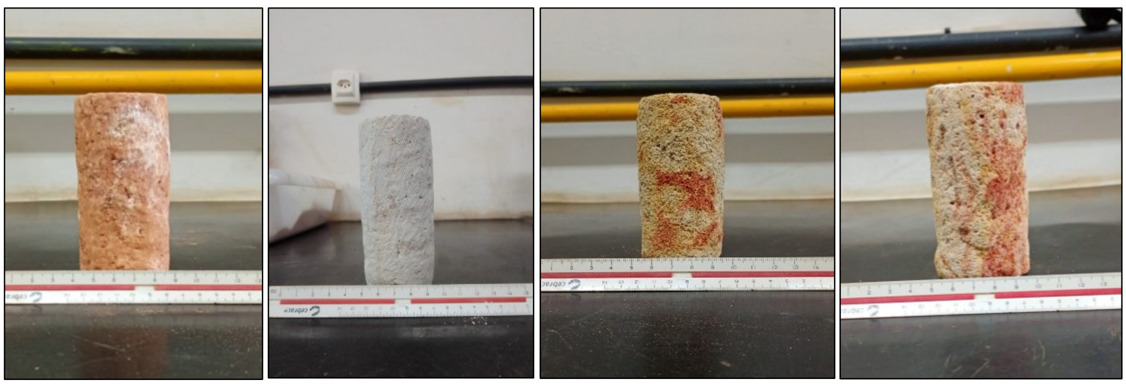
In the municipality of Bananeiras, Paraíba, sampling was conducted on a slope with a history of instability. The local soils belong to the Barreiras Formation and consist predominantly of medium-grained siltstones, ranging in color from white to reddish, and poorly sorted clayey sandstones with conglomeratic intercalations (Guimarães et al., 2008).

In Caaporã, Paraíba, the collected material corresponds to the foundation soil of the Cupissura Dam. In this region, the Barreiras Formation is the only sedimentary unit underlying both the reservoir and the dam foundation. The dam is located within the Abiaí River watershed, on the southern coast of Paraíba, where the river constitutes one of the region's main watercourses and plays a fundamental role in the sedimentary and environmental setting of the municipality of Caaporã. The river originates in the higher inland areas of the state and flows toward the Atlantic Ocean, discharging into an estuarine system directly influenced by the tidal regime. Along its course, it crosses different geological units, including areas where the Barreiras Formation is exposed in association with fluvial–marine sediments, contributing to the erosion, transport, and deposition of Quaternary sandy, silty, and clayey sediments (CAGEPA, 2018).

In the city of Natal, Rio Grande do Norte, sampling was carried out in the subsurface at Areia Preta Beach, near the shoreline. The analyzed material represents a foundation soil collected during previous feasibility studies for the construction of a building in the area, characterizing a sandy residual soil subject to marine influence and groundwater table fluctuations. These deposits belong to the Tertiary–Quaternary Barreiras Formation and are overlain by aeolian sediments. They consist of beach sandstones formed by the reworking of coastal cliffs, exhibiting irregular and incised surfaces, and are partially lithified by diagenetic processes associated with the concentration of iron oxides and clayey material (Nunes, 2011).

Finally, in the municipality of Tibau do Sul, Rio Grande do Norte, the soil was collected from the top of a coastal cliff in an area subject to intense erosive action and gravitational instability processes. Sedimentary rocks and sediments of the Barreiras Formation cover virtually the entire coastal zone of the study area and are represented, from the base to the top, by Cretaceous and Tertiary carbonate and sandstone rocks of the Potiguar Basin, followed by Tertiary–Quaternary sandy-clayey deposits, and capped by Quaternary accumulations composed of beach sandstones and sandy, clayey, and sandy-clayey sediments deposited in fluvial, lacustrine, estuarine, dune, and beach environments (Severo, 2011).

Undisturbed samples were extracted as block samples to preserve their natural structural properties, particularly pore arrangement and degree of cementation, which are essential for triaxial compression and one-dimensional consolidation tests. Disturbed samples, in turn, were collected and stored in labeled plastic bags for compaction tests and physical and mineralogical characterization. All materials were properly cataloged, packaged, and transported to the Soil Mechanics Laboratory at the Federal University of Rio Grande do Norte (UFRN), where they were prepared (Figure 2) for the experimental testing program.



(a) (b) (c) (d)

Figure 2 – Specimens trimmed from samples from: (a) Bananeiras/PB; (b) Caaporã/PB; (c) Natal/RN; (d) Tibau do Sul/RN.
Source: Authors (2025).

2.2 Physical and mechanical characterization tests

The samples were subjected to a series of laboratory tests, including particle size distribution and sedimentation tests (NBR 6458 and NBR 7181), determination of the specific gravity of solids (NBR 6508), natural moisture content (NBR 6457), Atterberg limits, namely liquid limit (LL) and plastic limit (PL) (NBR 6459 and NBR 7180), followed by soil classification according to the Unified Soil Classification System (USCS). These initial procedures aimed at the basic physical characterization of the samples and the preliminary identification of textural and plasticity differences among the analyzed soils.

Subsequently, mineralogical and chemical analyses were performed using X-ray diffraction (XRD) and X-ray fluorescence (XRF), with the aim of identifying the main constituent minerals and quantifying oxide contents, particularly iron and aluminum oxides, whose presence may directly influence the mechanical and hydraulic behavior of soils from the Barreiras Formation.

Complementary mechanical and hydraulic tests comprised the Standard Proctor compaction test (NBR 7182), one-dimensional consolidation (NBR 16853), flexible-wall permeability (ASTM D5084), and consolidated undrained triaxial compression (CU) (ASTM D4767), performed to evaluate the maximum dry density, vertical deformations, water flow behavior, and shear strength of the studied samples, respectively. The one-dimensional consolidation, permeability, and triaxial compression tests were conducted using previously prepared undisturbed samples. The selection of these tests aimed to integrate physical, chemical, and mechanical parameters, enabling the correlation between textural and mineralogical (physical) properties and deformation and strength responses (mechanical behavior).

The samples used in the CU triaxial tests were subjected to effective confining stresses of 50, 100, 200, and 400 kPa, with continuous recording of deviator stress (σ_1–σ_3), axial strain (ε_a), and pore water pressure (u) throughout the shearing stage. For soils with a higher fines content, such as those from Bananeiras and Caaporã, a shear rate of 0.067 mm/min was adopted, allowing for an axial strain of 20% of the specimen height (approximately 20 mm) over an experimental duration of about 5 hours. This rate was determined based on the t_{50} time obtained during the consolidation phase, ensuring that loading occurred slowly enough to prevent significant drainage of pore water, thereby maintaining undrained conditions, but not so slowly as to allow partial drainage, which would alter the test conditions.

In contrast, for the more sandy soils corresponding to the samples from Natal and Tibau do Sul, a shear rate of 0.10 mm/min was adopted, resulting in a total testing time of approximately 3 hours and 30 minutes to reach the same 20% axial strain. Based on the experimental results, Mohr–Coulomb strength envelopes were constructed, allowing for the determination of cohesion (c) and internal friction angle (φ), which are essential parameters for evaluating the shear strength of the soils.

Flexible-wall permeability tests were also performed using the triaxial compression apparatus, employing the same undisturbed samples immediately after the full saturation stage. The procedure consisted of applying hydraulic head differentials of –5 kPa, –10 kPa, and –15 kPa, allowing water flow through the specimen. Water flow was monitored using a high-precision volume measuring device, with the permeated volume recorded as a function of time. For each applied pressure difference, the permeability coefficient (k) was calculated, and the arithmetic mean of the three obtained values was adopted as the representative coefficient of the sample.

3. Results and discussion

3.1 Physical characterization

The grain size analysis (Figure 3) revealed a significant textural variability among the soils from the four studied locations, reflecting the different depositional and weathering conditions of the Barreiras Formation. The soil from Bananeiras, Paraíba, was classified as low-plasticity silt (ML), with a predominance of the silt fraction (62%) and a moderate presence of fine to medium sand (21%). Its high fines content may result in low permeability values. In Caaporã, Paraíba, an intermediate material between clayey and sandy nature was observed, classified as low-plasticity clay (CL), composed of 45% clay and 42% sand, a configuration that may confer moderate cohesive behavior and a relatively high friction angle. The soil from Natal, Rio Grande do Norte, was classified as clayey sand (SC), containing approximately 45% fine to medium sand and 29% clay, indicating a granular structure with sufficient fines to provide some cohesion and reduce permeability. In turn, the soil from Tibau do Sul, Rio Grande do Norte, collected from the upper portion of the cliff, was classified as silty sand (SM), presenting 58% fine to medium sand and 23% silt, which may result in a predominantly frictional behavior.

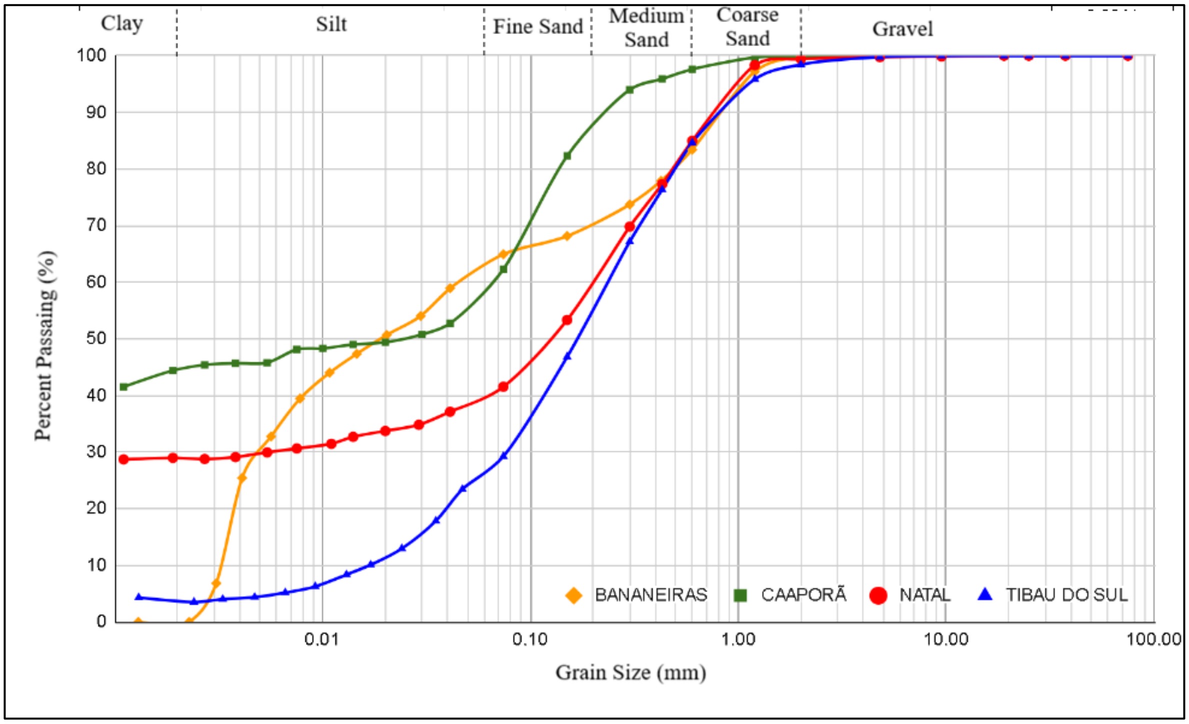


Figure 3 – Grain size distribution curves.
Source: Authors (2025).

Regarding plasticity, the soil from Caaporã, which exhibited the highest clay content, also presented the highest plasticity index (PI = 21%), whereas Bananeiras, with a higher fines content, showed a PI of 11% (Table 1). The ratio between the plasticity index and clay content (activity) for the Caaporã soil was lower than 0.75, classifying it as an inactive clay, a characteristic consistent with kaolinitic materials and residual soils from tropical regions, in which mineralogy and the degree of weathering reduce the swelling potential and sensitivity to moisture variation.

Mineralogical analysis by X-ray diffraction (XRD) (Figure 4) confirmed the predominant presence of quartz (SiO_2) and kaolinite ($Al_2Si_2O_5$) in all samples, in addition to variable contents of hematite (Fe_2O_3), anatase (TiO_2), and zircon ($ZrSiO_4$), as well as the possible presence of goethite ($FeO(OH)$) in the Caaporã sample. Based on X-ray fluorescence (XRF) results (Table 2), it was observed that the soils from Bananeiras and Tibau do Sul exhibited higher iron contents, which may initially indicate a higher degree of cementation by iron oxides and, consequently, greater structural stiffness compared to the Caaporã and Natal samples.

In contrast, the Caaporã soil stood out for presenting the highest clay content among the samples, indicating a more advanced degree of mineral alteration, evidenced by the presence of kaolinite, also identified in Bananeiras, with more intense peaks in the latter. Furthermore, the lower concentration of iron oxides observed in Caaporã suggests a more advanced stage of decomposition of primary minerals, which implies a possible reduction in interparticle cementation.

Table 1 – Data from combined grain size characterization.

	Bananeiras	**Caaporã**	**Natal**	**Tibau do Sul**
Gravel	0.2%	0.1%	0.6%	1.6%
Coarse Sand	16.4%	2.3%	14.4%	13.8%
Medium Sand	13.4%	11.4%	26.1%	31.1%
Fine Sand	7.6%	28.0%	19.2%	27.4%
Silt	62.4%	13.7%	10.7%	22.4%
Clay	0.0%	44.5%	29.0%	3.8%
LL	43%	43%	29%	30%
LP	33%	22%	21%	24%
PI	11%	21%	8%	6%
Specific gravity of soil solids (g/cm³)	2.658	2.676	2.623	2.585
USCS Classification	ML – Low Plasticity Silt	CL – Low Plasticity Clay	SC – Clayey Sand	SM – Silty Sand

Source: Authors (2025).

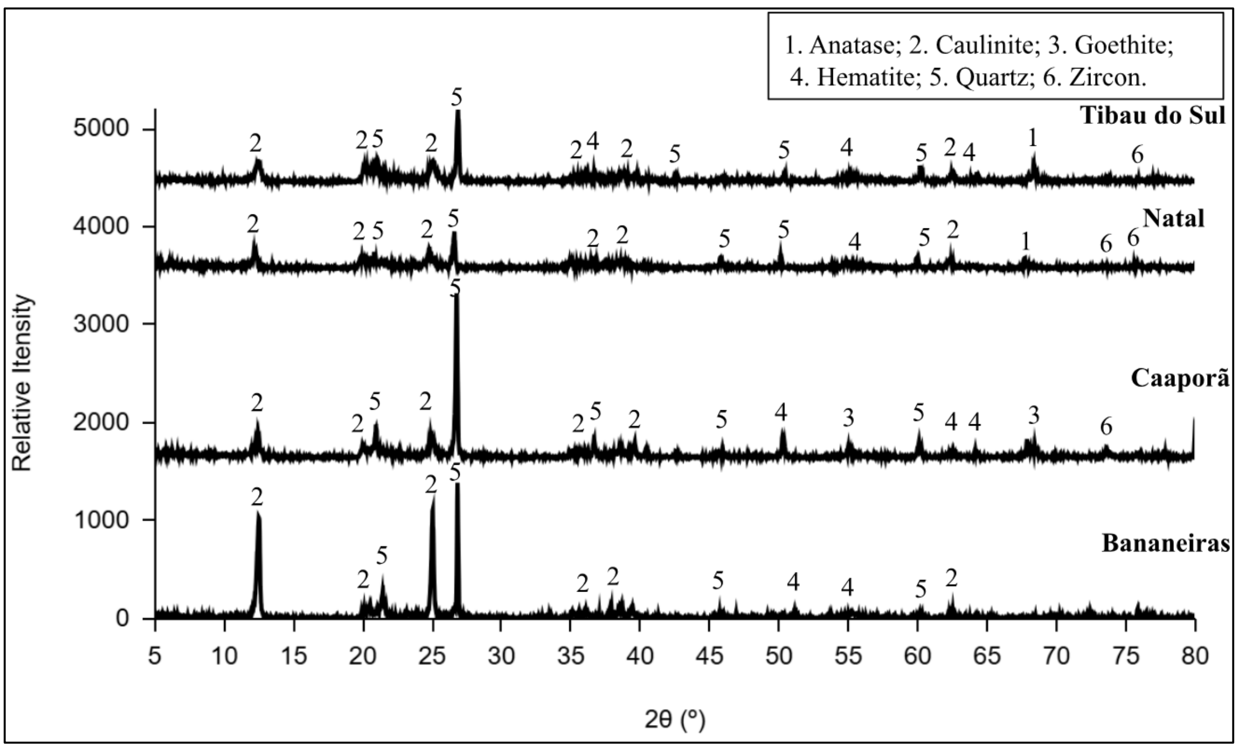


Figure 4 – X-ray diffraction patterns.
Source: Authors (2025).

Table 2 –X-ray fluorescence data.

Oxides (%)	Bananeiras	Caaporã	Natal	Tibau do Sul
Fe_2O_3	35.254	5.099	22.222	29.135
Al_2O_3	34.229	40.590	34.477	32.821
SiO_2	25.613	44.209	29.240	27.032

TiO_2	2.061	2.073	6.526	3.063
ZrO_2	2.051	4.515	6.370	6.936
SrO	0.463	0.223	-	-
K_2O	0.165	0.376	0.232	0.128
V_2O_5	0.075	-	-	-
MnO	0.057	-	-	-
PdO	0.032	-	-	-
Ag_2O	-	1.717	-	-
MgO	-	1.280	-	0.756
SO_3	-	0.070	0.032	0.027
Nb_2O_5	-	-	0.441	-
Cr_2O_3	-	-	0.218	0.102
Ga_2O_3	-	-	0.137	-
CaO	-	-	0.104	-

Source: Authors (2025).

In the soils from Caaporã, Natal, Tibau do Sul, and Bananeiras, hematite peaks were identified, confirming the presence of iron oxides evidenced by XRF analyses. In the Bananeiras soil, no goethite peaks were detected. In contrast, the Caaporã soil exhibited a goethite peak, revealing a greater diversity of iron crystalline forms. This mineralogical variation may directly influence soil mechanical behavior, since the presence of iron hydroxides can reduce interparticle cohesion, resulting in lower shear strength, as reported by Ingunza et al. (2025). Additionally, in the Caaporã, Natal, and Tibau do Sul soils, characteristic peaks of zircon were observed, consistent with the zirconium oxide (ZrO_2) contents identified in the chemical analyses. In the Natal and Tibau do Sul soils, the presence of anatase, a crystalline form of titanium dioxide (TiO_2), was also identified.

The laterization index (Ki), defined as the ratio between silica and alumina oxides, indicates that all soils exhibit relative enrichment in aluminum, a higher degree of laterization (Table 3).

Table 3 – Laterization index of the soils.

Location	$Ki = SiO_2/Al_2O_3$
Bananeiras/PB	0.75
Caaporã/PB	1.09
Natal/RN	0.85
Tibau do Sul/RN	0.82

Source: Authors (2025).

3.2 Mechanical characterization

From the results of the compaction tests (Figure 5), maximum dry unit weight values ranging from 16.5 to 17.6 kN/m³ were obtained, with optimum moisture contents ranging from 17.2% to 19.6%. By correlating the mechanical performance of the tests with the grain size distribution of the samples, it was observed that the Caaporã soil, with a mixed clay–sand texture, exhibited the highest maximum dry unit weight, whereas the Bananeiras soil, which had the highest fines content among the samples, showed the lowest value (Table 4).

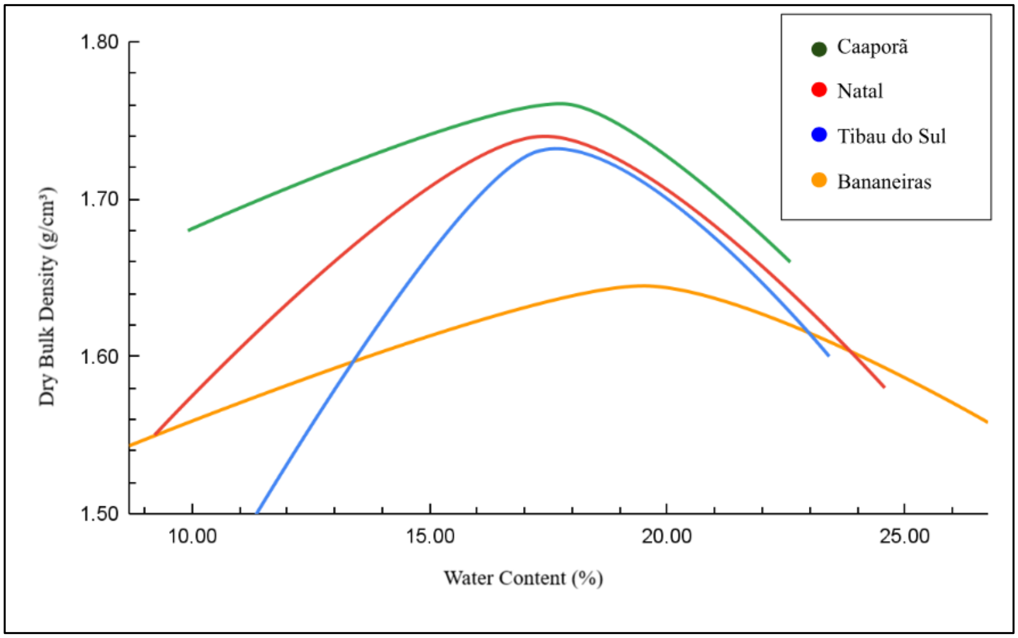


Figure 5 – Compaction test curves.
Source: Authors (2025).

Table 4 – Compaction test results.

Location	Maximum dry unit weight (kN/m³)	Optimum moisture content (%)
Bananeiras/PB	16.5	19.6
Caaporã/PB	17.6	17.7
Natal/RN	17.4	17.2
Tibau do Sul/RN	17.3	17.4

Source: Authors (2025).

In the one-dimensional consolidation tests, the preconsolidation stress (σ'_{vm}) ranged from 50 to 500 kPa, with the highest values observed in the Bananeiras and Caaporã samples (405 and 410 kPa, respectively). This behavior may indicate that these samples are in an overconsolidated state, resulting from natural cementation and hardening processes induced by weathering, as well as the burial of surface layers by more weathered soils. On the other hand, the Natal and Tibau do Sul samples exhibited lower σ'_{vm} values (approximately 310 and 205 kPa, respectively) (Table 5), which may be characteristic of soils more susceptible to volumetric deformation (Figure 6).

Table 5 – Consolidation data.

	Bananeiras	Caaporã	Natal	Tibau do Sul
σ'_{vm} (kPa)	405	410	310	205
C_C	0.23	0.35	0.18	0.36
C_R	0.05	0.08	0.05	0.06
C_S	0.05	0.06	0.02	0.02

Source: Authors (2025).

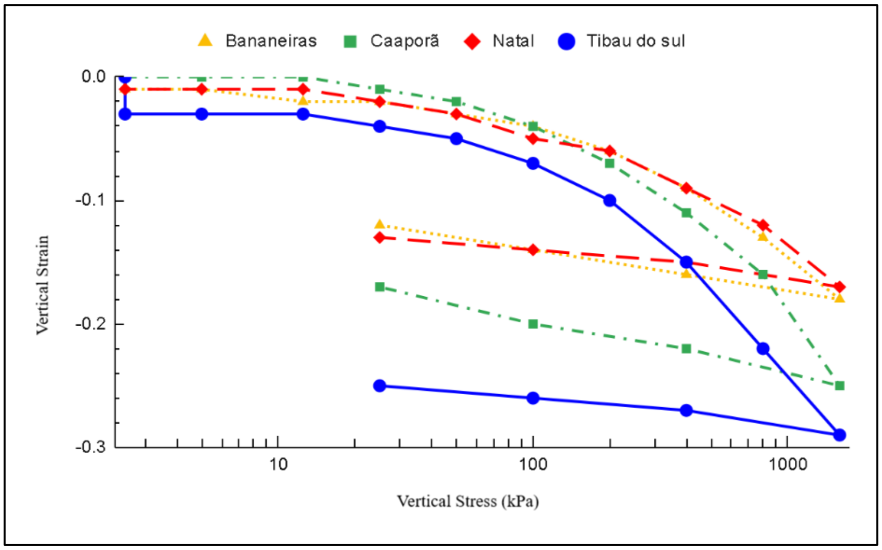
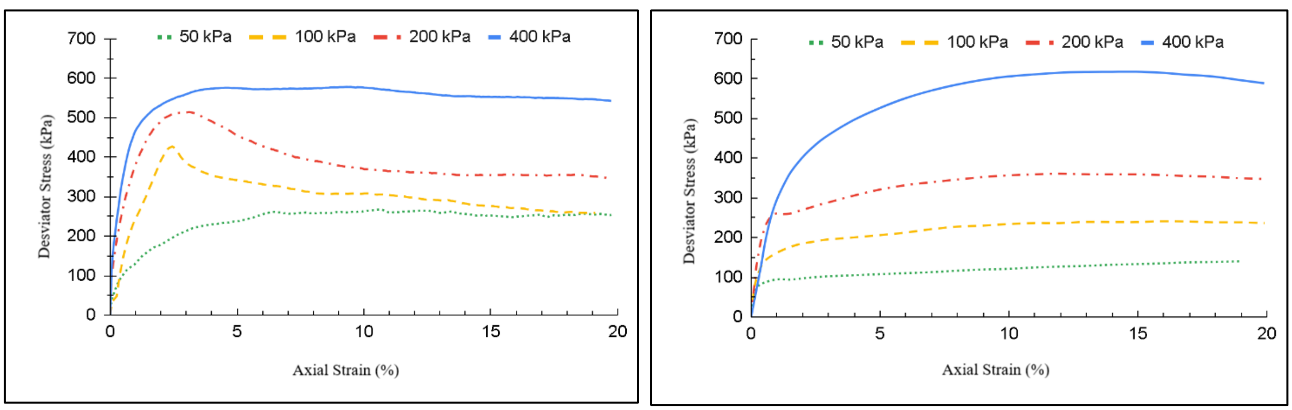
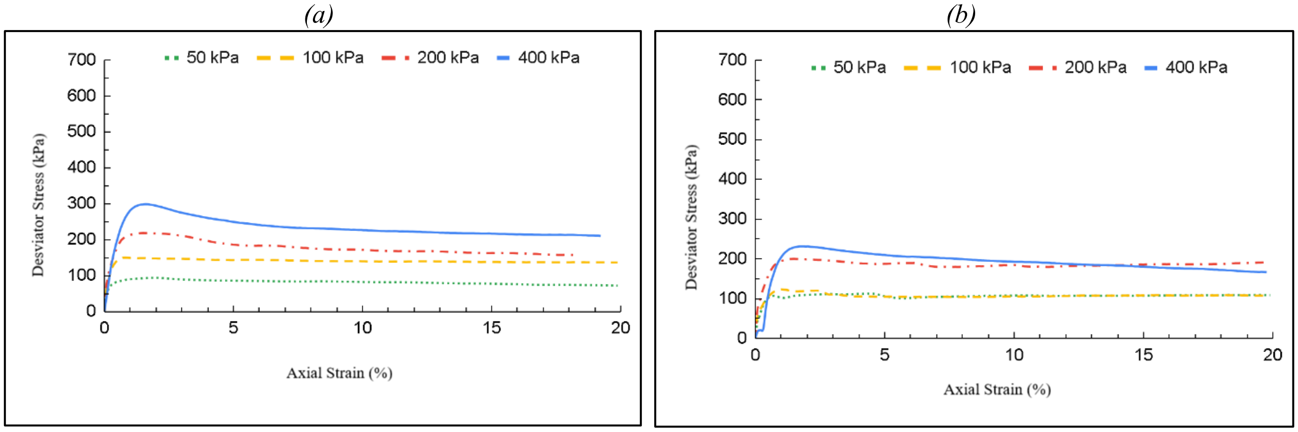


Figure 6 – Specific vetical strain vs. Logarithm of vertical stress curves.
Source: Authors (2025).

In the deviator stress versus axial strain curves from the triaxial tests (Figure 7), the Caaporã soil, whose response did not exhibit well-defined peak strength, presented the highest deviator stress values among all samples, followed by Bananeiras. In contrast, the Natal and Tibau do Sul soils exhibited a more brittle behavior at all stress levels and lower maximum deviator stress values.



(a) *(b)*

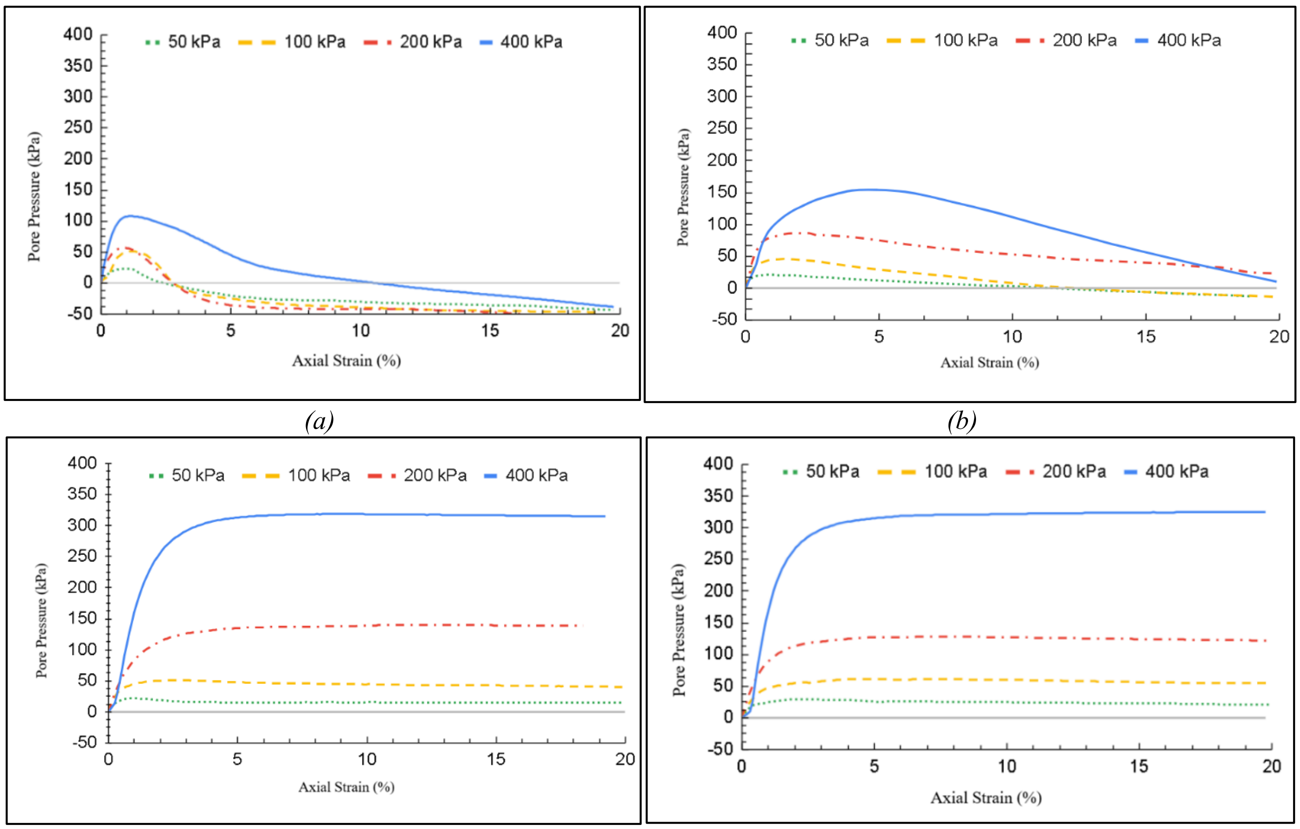


(c) *(d)*

Figure 7 – Deviator stress vs. Axial strain for soils from: (a)Bananeiras/PB;(b) Caaporã/PB; (c) Natal/RN; (d)Tibau do Sul/RN.

Source: Authors (2025).

The Bananeiras soil exhibited negative pore water pressures for all stress levels. In the Caaporã soil, the 50 and 100 kPa confining stresses also generated negative pore pressures, and no stabilization of pore pressure was observed at the end of the test for both stress levels. The Natal and Tibau do Sul samples presented similar behaviors, with the generation of positive pore pressures and eventual stabilization of pore pressure at the end of the test (Figure 8).



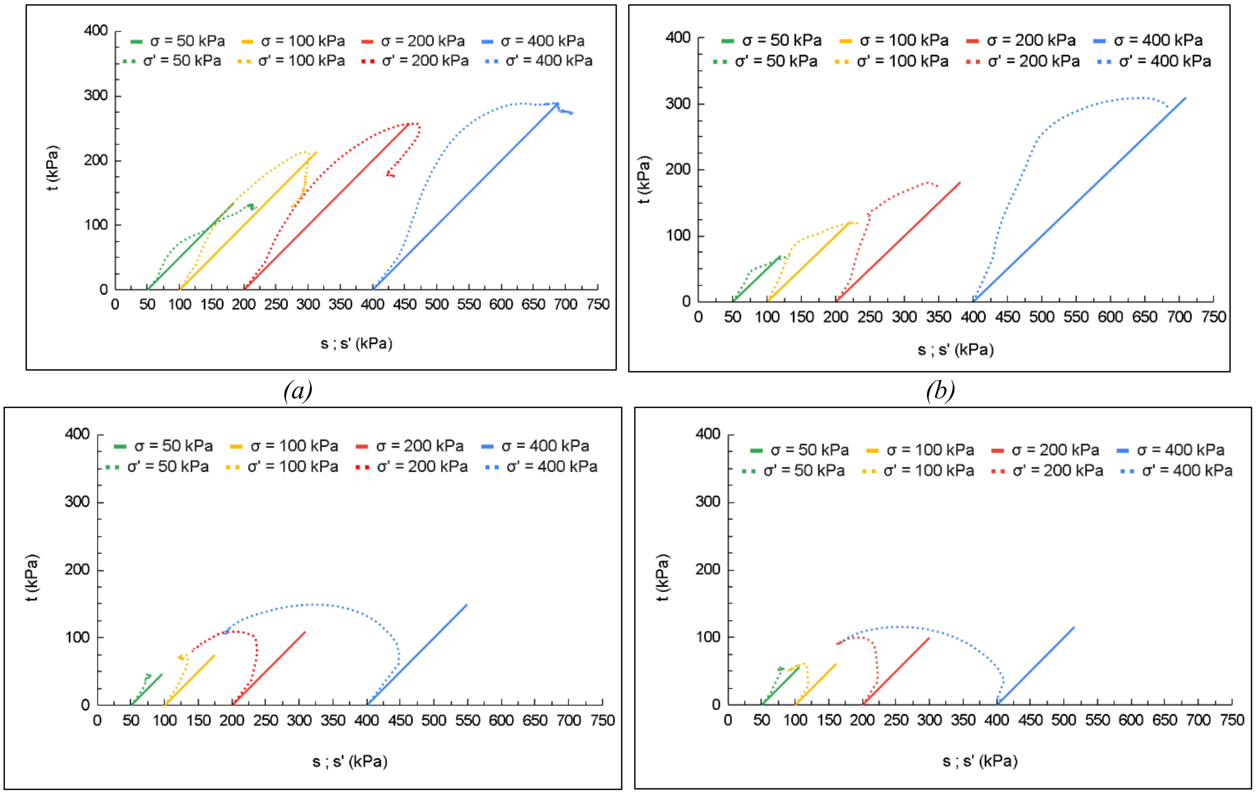
(a) *(b)*

(c) *(d)*

Figure 8 – Pore pressure vs. Axial strain for soils from: (a) Bananeiras/PB;(b) Caaporã/PB; (c) Natal/RN; (d) Tibau do Sul/RN.

Source: Authors (2025).

The stress paths (Figure 9) revealed that the Bananeiras and Caaporã soils maintained an overconsolidated behavior (OCR > 1), even under the highest stress level (400 kPa). The Natal and Tibau do Sul soils exhibited a transition in behavior, shifting from overconsolidated to normally consolidated conditions as the net effective stress increased from 50 kPa to 100 kPa.



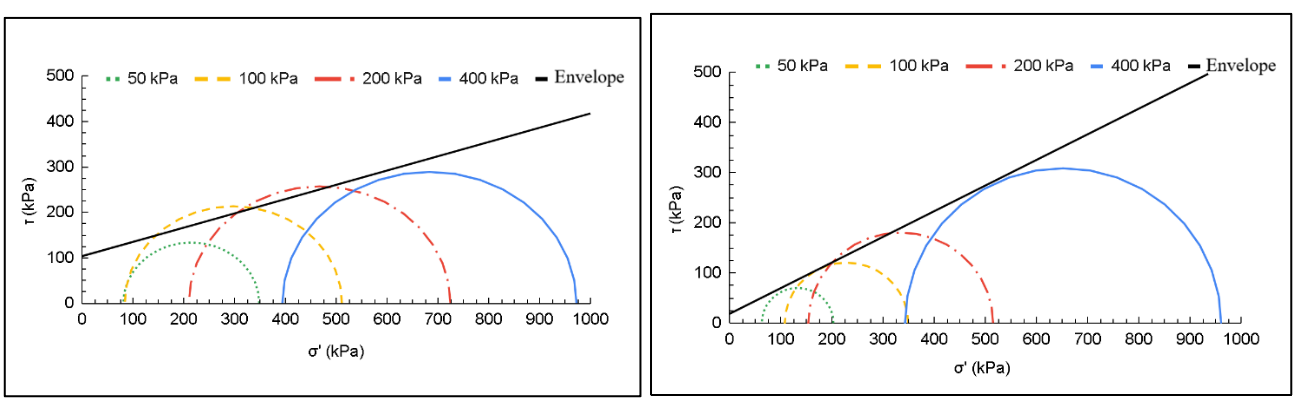
(a) *(b)*

(c) *(d)*

Figure 9 – Total and effective stress paths for samples from: (a)Bananeiras/PB;(b) Caaporã/PB; (c)Natal/RN; (d)Tibau do Sul/RN.

Source: Authors (2025).

The s–t diagrams and Mohr–Coulomb strength envelopes (Figure 10) indicated internal friction angles (φ) ranging from 18° to 27° and cohesion values (c) between 19 and 104 kPa (Table 6). The highest cohesion values were observed in the samples with higher iron oxide contents, particularly the Bananeiras sample, which exhibited a cohesion of 104 kPa, approximately 189% higher than that of Tibau do Sul (36 kPa). These results confirm the correlation between ferruginous mineralogy and increased shear strength.



(a) *(b)*

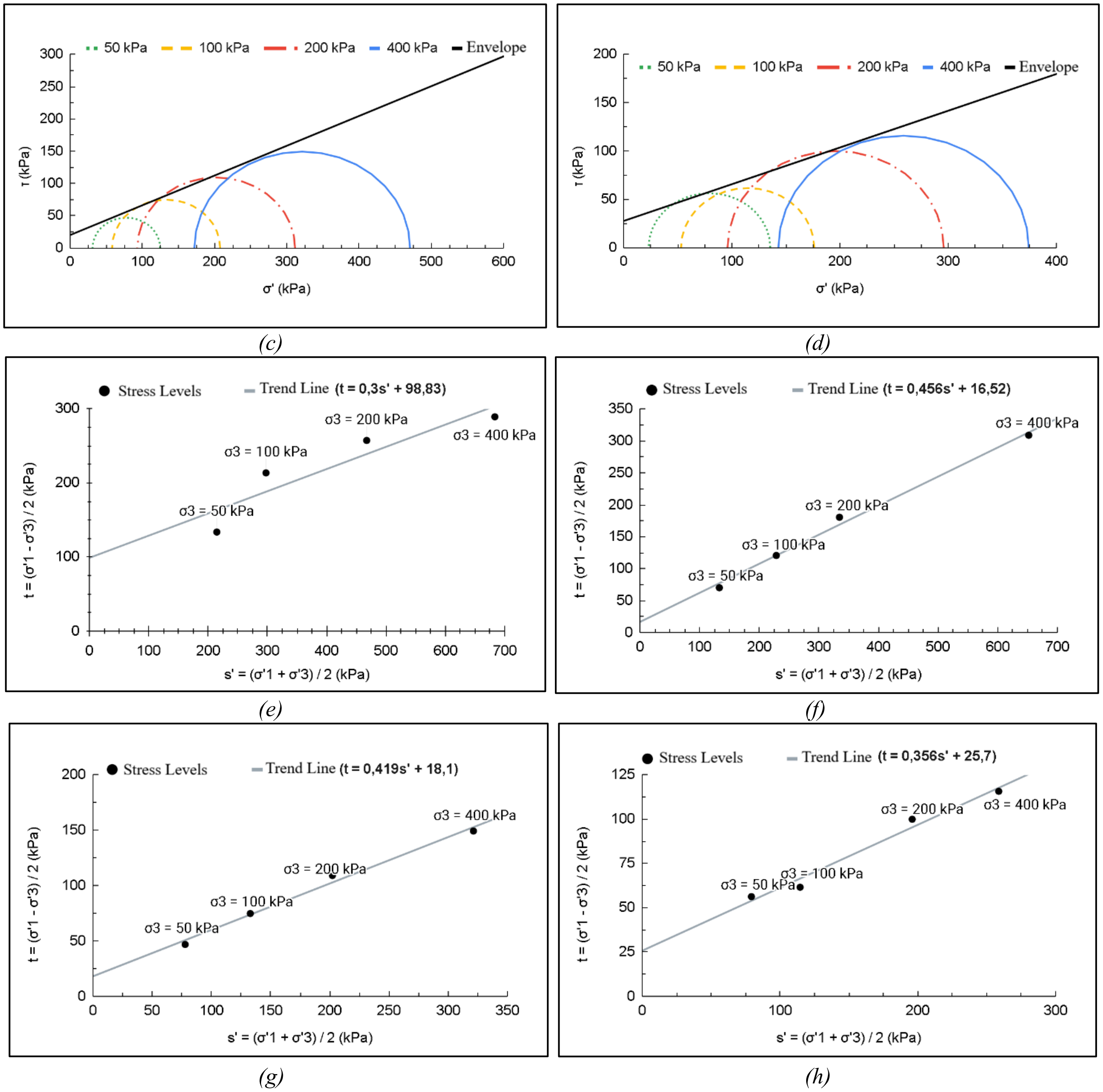


Figure 10 – Mohr-Coulomb circles and shear strength envelopes for: (a) Bananeiras/PB;(b) Caaporã/PB; (c) Natal/RN; (d) Tibau do Sul/RN; and s'-t diagrams for peak deviator stress of the samples from: (e) Bananeiras/PB;(f) Caaporã/PB; (g) Natal/RN; (h) Tibau do Sul/RN.

Source: Authors (2025).

Table 6 – Shear strength parameters.

Location	Friction angle	Cohesion
Bananeiras/PB	18º	104 kPa
Tibau do Sul/RN	19º	36 kPa
Natal/RN	25º	20 kPa
Caaporã/PB	27º	19 kPa

Source: Authors (2025).

The comparative analysis of the results reveals an exponential trend between soil cohesion and oxide contents. It is observed that the increase in iron oxide content is associated with an exponential increase in cohesion, a behavior consistent with the cementing role played by these compounds in interparticle bonding (Figure 11). In contrast, enrichment in silicon oxide (SiO_2), representative of the quartz fraction of the soil, shows an inverse trend, indicating a reduction in cohesive strength and an increase in frictional resistance between particles, as observed in the Caaporã soil.

The flexible-wall permeability tests confirmed the expected variation among the analyzed soils: the material from Bananeiras exhibited the lowest coefficient of permeability, followed by Caaporã, Natal, and Tibau do Sul (Table 7). This sequence reflects the direct influence of soil texture on hydraulic conductivity. Soils with higher fines content, such as Bananeiras, tend to present a more closed structure and smaller effective pore sizes, reducing water flow. On the other hand, more sandy materials, such as the samples from Tibau do Sul and Areia Preta, exhibit higher permeability coefficients due to the predominance of interconnected macropores. Thus, the obtained results reinforce the inverse correlation between the fine fraction and hydraulic conductivity, forming an exponential trend between the permeability coefficient (m/s) and fines content (%) of these samples (Figure 12).

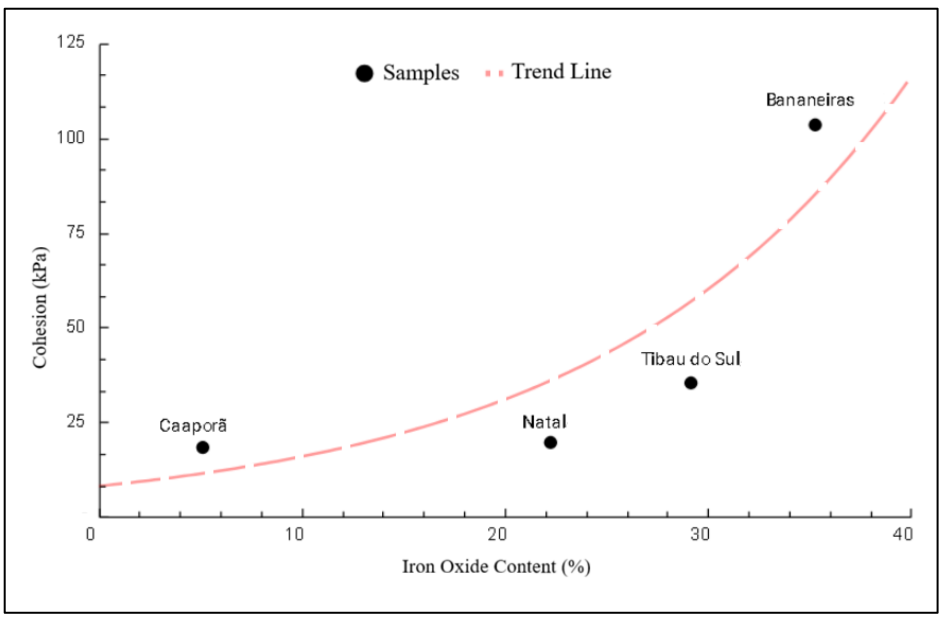


Figure 11 – Cohesion (kPa) vs. Iron oxide content (%).
Source: Authors (2025).

Table 7 – Permeability coefficients obtained from flexible-wall tests.

Location	Permeability coefficient (m/s)
Bananeiras/PB	$1.84 \cdot 10^{-6}$
Caaporã/PB	$2.34 \cdot 10^{-5}$
Natal/RN	$2.14 \cdot 10^{-4}$
Tibau do Sul/RN	$5.18 \cdot 10^{-4}$

Source: Authors (2025).

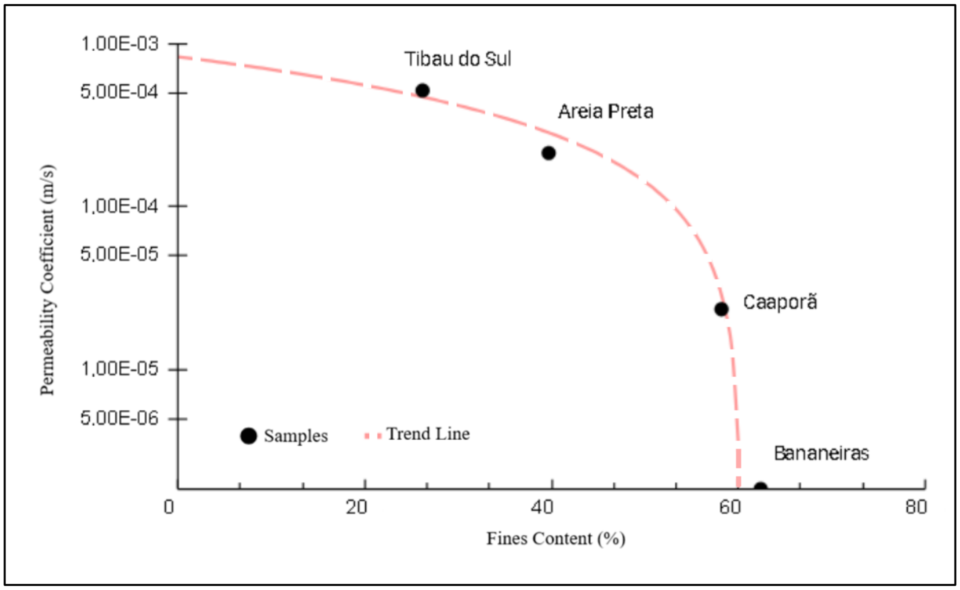


Figure 12 – Permeability coefficient (m/s) vs. Fines content (%).
Source: Authors (2025).

3.3 General remarks

The soil from Bananeiras, Paraíba, was characterized by a high silt fraction, low compressibility, and reduced permeability, in addition to high cohesion and shear strength values. These attributes may be associated with iron cementation; however, the predominantly silty grain size distribution exerted a strong influence on its behavior. The Caaporã soil, although composed of similar proportions of sand and clay, exhibited an overconsolidated response, possibly resulting from hardening associated with weathering processes.

On the other hand, the samples from Natal and Tibau do Sul exhibited more brittle behavior and lower strength. Both soils showed a tendency toward overconsolidation at low stress levels and a typically normally consolidated response under higher stresses, with emphasis on the Tibau do Sul soil, which exhibited high compressibility in the consolidation tests. These results indicate a greater susceptibility to volumetric deformations and to the development of failure mechanisms under loadings above 100 kPa, reinforcing the need for caution when using these materials in geotechnical applications.

In the relationship between iron oxide content and shear strength, it was observed that samples with higher concentrations of these compounds exhibited higher cohesion values, corroborating the role of these oxides as cementing agents. Mineralogical analyses (XRD), together with chemical results (XRF), confirmed the presence of quartz, kaolinite, and hematite in the samples, as well as the atypical occurrence of goethite ($FeO(OH)$) in the Caaporã soil. The predominance of this iron hydroxide, associated with humid environments, may explain the lower cohesion value of this material, since the goethite structure contains hydroxyl groups capable of easily interacting with water molecules, promoting wetting processes, loss of structure, and reduction of stiffness, an effect not observed with the same intensity in hematite (Fe_2O_3), a denser and structurally more stable mineral. The influence of fluvial dynamics in the area further supports the preferential formation of these hydroxides, contributing to greater structural instability of the soil.

4. Final considerations

The results obtained confirm that the heterogeneity of the Barreiras Formation imposes significant challenges for geotechnical design and performance prediction in civil engineering works. Variations in the depositional environment result in soils with distinct textures, structures, and mineralogical compositions. This diversity makes direct correlation between physical, chemical, and mechanical parameters complex, hindering the establishment of generalizable trends. Thus, even materials belonging to the same geological unit may exhibit different geotechnical behaviors, which reinforces the importance of detailed local investigations for the proper design of foundations, slopes, retaining structures, and drainage systems in areas composed of these residual soils.

It is therefore concluded that integrated characterization, involving physical, chemical, mineralogical, mechanical, and spatial aspects, is essential for understanding the variability of the mechanical properties of soils from the Barreiras Formation. The study demonstrated that small mineralogical and textural variations, as a reflection of spatial variability, can result in significant differences in mechanical performance, directly affecting the safety and durability of engineering structures.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES) – Finance Code 001.

References

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 16853:2020 – Ensaio de adensamento unidimensional. Rio de Janeiro, 2020.

ABNT. NBR 6457:2024 – Amostragem e preparação de amostras de solo para ensaios de compactação e caracterização. Rio de Janeiro, 2024.

ABNT. NBR 6458:2025 – Determinação da granulometria de solos por peneiramento. Rio de Janeiro, 2025.

ABNT. NBR 6459:2017 – Determinação do limite de liquidez de solos. Rio de Janeiro, 2017.

ABNT. NBR 6508: Grãos de solos que passam na peneira de 4,8 mm - Determinação da massa específica. Rio de Janeiro, 1984.

ABNT. NBR 7180:2016 – Determinação do limite de plasticidade de solos. Rio de Janeiro, 2016.

ABNT. NBR 7181:2018 – Análise granulométrica de solos. Rio de Janeiro, 2018.

ABNT. NBR 7182:2016 – Ensaio de compactação de solos. Rio de Janeiro, 2016.

ASTM - AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM D4767:2020 - *Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils*. West Conshohocken, PA, 2020.

ASTM. ASTM D5084-21 - *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*. West Conshohocken, PA: ASTM International, 2021.

BAECHER, G. B. . 2021 Terzaghi Lecture: Geotechnical Systems, Uncertainty, and Risk. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 149, n. 3, 2023. DOI: 10.1061/JGGEFK.GTENG-10201.

BARBOSA, J. A.; LIMA FILHO, M.; NEUMANN, V.; MORAES, M.; SOUZA, E. M. Estratigrafia da faixa costeira Recife–Natal (Bacia da Paraíba e Plataforma de Natal), NE Brasil. 2008.

CAGEPA. Estudo de Impacto Ambiental – EIA: Implantação da Barragem Cupissura, Caaporã – Paraíba. Volume I – Caracterização do meio físico. 2018. Disponível em: https://www.cagepa.pb.gov.br/obra-barragem-cupissura/. Acesso em: 28 de outubro de 2025.

FINNO, R. J.; ZHANG, Y.; BUSCARNERA, G. Experimental validation of Terzaghi's effective stress principle for gassy sand. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 143, n. 12, 2017. DOI: 10.1061/(ASCE)GT.1943-5606.0001797.

GUIMARÃES, I. P.; BITTAR, S. M. B.; SILVA, J. M. R.; SILVA, F. M. J. V.; ARAÚJO, D. B.; ARRUDA, S. D. A.; ALCÂNTARA, V. C. Geologia da folha Solânea SB.25-Y-A-IV: escala 1:100.000. Brasília: CPRM, 2008.

INGUNZA, M. P. D.; PEROBA, P.; ROLEMBERG, G. L. M.; SANTOS JÚNIOR, O. F. A influência da mineralogia secundária no comportamento mecânico de um solo residual granítico no semiárido brasileiro = The influence of secondary mineralogy on the mechanical behavior of a granitic residual soil in the semiarid region of Brazil. *Revista de Geociências do Nordeste / Northeast Geosciences Journal*, v. 11, n. 2, p. 151-164, 2025. DOI: 10.21680/2447-3359.2025v11n2ID39986.

KU, T.; MOON, S.; GUTIERREZ, B. J. Advanced application of seismic cone penetration test at complex ground conditions. *Engineering Geology*, v. 210, p. 140–147, 2016. DOI: 10.1016/j.enggeo.2016.06.009.

MOURA-FÉ, M. M. Barreiras: série, grupo ou formação?. Revista Brasileira de Geografia Física, v. 07, n. 06, p. 1055-1061, 2014.

NAPOLI, M. L.; FESTA, A.; BARBERO, M. Practical classification of geotechnically complex formations with block-in-matrix fabrics. *Engineering Geology*, v. 301, n. 106595, 2022. DOI: 10.1016/j.enggeo.2022.106595.

NUNES, F. C.; SILVA, E. F.; VILAS BOAS, G. S. Grupo Barreiras: características, gênese e evidências de neotectonismo. Rio de Janeiro: Embrapa Solos, 2011. 31 p. (Boletim de Pesquisa e Desenvolvimento, n. 194. ISSN 1678-0892).

NUNES, L. S. Dinâmica costeira entre as praias de Areia Preta e do Forte, Natal/RN. Dissertação (Mestrado em Geografia) — Programa de Pós-Graduação em Geografia, Universidade Federal do Rio Grande do Norte, Natal, 2011.

RABAB, C.; LAOUAR, M. S.; FERNANE, A.; MESSAST, S. Experimental investigation of collapsible soils under oedometric loading: effect of internal erosion. *South Florida Journaul of Development*, v. 5, 2024. DOI: 10.46932/sfjdv5n9-012.

SANTOS JÚNIOR, O. F.; SEVERO, R. N. F.; SCUDELARI, A. C.; AMARAL, R. F. PROCESSOS DE INSTABILIZAÇÃO EM FALÉSIAS: ESTUDO DE UM CASO NO NORDESTE DO BRASIL. Geotecnia. n. 114, [s. l], p. 71-90, 2011. DOI: 10.14195/2184-8394_114_4.

SCUDELARI, A. C.; MATOS, M. F. A.; AMARO, V. E.; CAMARA, M. R.; CAVALCANTE, A. C. C. AVALIAÇÃO DE CURTO PRAZO DA RETRAÇÃO DAS FALÉSIAS DE TIBAU DO SUL-RN. Revista de Geociências do Nordeste, [S.L.], p. 202-2014, 22 set. 2021. Universidade Federal do Rio Grande do Norte - UFRN. DOI: 10.21680/2447-3359.2021v7n2ID21272.

SEVERO, R. N. F. Caracterização geotécnica da falésia da Ponta do Pirambu em Tibau do Sul — RN considerando a influência do comportamento dos solos nos estados indeformado e cimentado artificialmente. Tese (Doutorado em Engenharia Civil) — Programa de Pós-Graduação em Engenharia Civil, Universidade Federal de Pernambuco, Recife, 04 ago. 2011.

SILVA, B. M. F.; SANTOS JÚNIOR, O. F.; FREITAS NETO, O.; SCUDELARI, A. C. Erosão em falésias costeiras e movimentos de massa no Rio Grande do Norte, Nordeste do Brasil. Revista de Geociências do Nordeste, v. 39, n. 2, p. 447–461, 17 jul. 2020. DOI: 10.5016/geociencias.v39i2.14233.

SOUSA, A. F. N.; FRANÇA, L. R. C.; LACERDA, M. C.; BATISTA, G. S. Caracterização dos sistemas ambientais de municípios em colapso hídrico no estado da Paraíba. *Revista de Geociências do Nordeste*, v. 10, n. 2, 2024. DOI: 10.21680/2447-3359.2024v10n2ID36500.

WU, W.; WANG, Z.; ZHANG, Y.; EL NAGGAR, M. H.; WU, T.; WEN, M. Semi-analytical solution for negative skin friction development on deep foundations in coastal reclamation areas. *International Journal of Mechanical Sciences*, v. 241, 2023. DOI: 10.1016/j.ijmecsci.2022.107981.