anpet
brazilian association for transportation research and education
TRANSPORTES
ISSN: 2237-1346
anpet.org.br/transportes

Comparative analysis of tropical soil classification methods for highway pavement applications

Análise comparativa de métodos de classificação de solos tropicais para aplicações em pavimentos rodoviários

Manoel Leandro Araújo e Farias[1], **John Kennedy Guedes Rodrigues**[1], **Ana Letícia Feitosa de Macêdo**[1], **Jonny Dantas Patricio**[1], **Ana Maria Gonçalves Duarte Mendonça**[1], **Leonardo Rodrigues Guedes**[1], **Henrique Antônio Oliveira Araújo**[1]

[1]Universidade Federal de Campina Grande, Campina Grande, Paraíba, Brasil

Contact: mlaf.engcivil@gmail.com, (MLAF); profkennedy@hotmail.com, (JKGR); leticiamacedo.engcivil@gmail.com, (ALFM); jonny_dantas@hotmail.com, (JDP); ana.duartemendonca@gmail.com, (AMGDM); leonardo.guedes@estudante.ufcg.edu.br, (LRG); henrique.zamoura@gmail.com, (HAOA)

Submitted:
1 September, 2024
Revised:
21 February, 2025
Accepted for publication:
6 March, 2025
Published:
16 May, 2025
Associate Editor:
Jorge Barbosa Soares, Universidade Federal do Ceará, Brasil

Keywords:
Tropical soil classification.
MCT and G-MCT systems.
UCLS method.
Resilient Modulus.

Palavras-chave:
Classificação de solos tropicais.
Sistemas MCT e G-MCT.
Método CUSL.
Módulo de Resiliência.

DOI: 10.58922/transportes.v33.e3046

ABSTRACT
Road agencies in tropical regions face significant challenges when applying traditional soil classification systems, such as TRB (Transportation Reserach Board), developed for temperate and lateritic soils. The MCT (Miniatura, Compactado, Tropical) and G-MCT (Granular - Miniatura, Compactado, Tropical) offer a more suitable approach by classifying tropical soils into fine and coarse categories, facilitating predicting their properties and pavement applications. The UCLS (Universal Classification Methodology for Lateritic), which takes into account factors such as texture, granulometry, and mineralogy, shows promise for classifying lateritic soils, offering a comprehensive approach aligned with the specific characteristics of these soils. This study compared these methods using 20 soil samples from five Brazilian states. The samples were analyzed for chemical, physical, and mechanical properties. The dynamic triaxial test was used to measure the Resilient Modulus. A direct mismatch between the systems was observed due to distinct contexts, with the TRB being unsuitable for tropical soils. MCT and G-MCT showed partial incompatibility with UCLS, highlighting the need for an approach more aligned with tropical characteristics to optimize pavement performance.

RESUMO
As agências rodoviárias em regiões tropicais enfrentam desafios significativos ao aplicar sistemas tradicionais de classificação de solos, como o TRB (Transportation Research Board), desenvolvido para solos temperados e lateríticos. O MCT (Miniatura, Compactado, Tropical) e o G-MCT (Granular - Miniatura, Compactado, Tropical) oferecem uma abordagem mais adequada, classificando os solos tropicais em categorias finas e grossas, facilitando a previsão de suas propriedades e aplicações em pavimentação. A metodologia CUSL (Classificação Universal de Solos Lateríticos), que leva em consideração fatores como textura, granulometria e mineralogia, mostra-se promissora para a classificação de solos lateríticos, oferecendo uma abordagem abrangente e alinhada com as características específicas desses solos. Este estudo comparou esses métodos utilizando 20 amostras de solo de cinco estados brasileiros. As amostras foram analisadas quanto às propriedades químicas, físicas e mecânicas. O teste triaxial dinâmico foi utilizado para medir o Módulo Resiliente. Foi observada uma incompatibilidade direta entre os sistemas devido aos contextos distintos, sendo o TRB inadequado para solos tropicais. MCT e G-MCT apresentaram incompatibilidade parcial com o CUSL, destacando a necessidade de uma abordagem mais alinhada com as características tropicais para otimizar o desempenho dos pavimentos.

1. INTRODUCTION

National highway agencies in tropical regions continue to face the challenge of finding materials that meet existing specifications. Laterite soils are prevalent in intertropical regions such as South America, Africa, India, Australia, and Southeast Asia. Lateritic soils are estimated to cover about 19% of the continental surface. These soils are distributed across almost the entire country in Brazil, covering approximately 65% of the Brazilian territory (Santos, 2006; Villibor and Nogami, 2009; Villibor and Alves, 2019). The varied geological and climatic conditions under which tropical soils form give them a unique behavior.

The most widespread geotechnical classifications, such as the Unified Soil Classification System (USCS) and the TRB (Transportation Research Board) classification for road purposes, developed in temperate countries and based on the particle size distribution and Atterberg limits, have limitations when used to predict tropical soil properties (Guimarães et al., 2018).

Studies and practices have shown that the recommendations based on these systems, in particular the activity of the fine fraction in the presence of water and the durability, strength, and hardness of the coarse and sandy fractions during the pre-treatment of the materials, are not compatible with the results obtained in the field and the laboratory (Rodrigues et al., 2010).

Even with reasonable control of the tests performed (same operator, low coefficients of variation), the traditional classifications do not apply to predicting the behavior of tropical soils. In the case of mature, pedogenetically developed soils with lateritic behavior, traditional classifications underestimate the behavior of these soils, usually overestimating the properties of granular soils with non-lateritic behavior (Passos, 2000; Baia, 2019; Silva, 2019).

In response to difficulties, deficiencies, and differences identified in traditional classifications, Nogami and Villibor (1995) developed an empirical classification system called MCT (Miniature, Compacted, and Tropical). This system uses laboratory tests, such as compaction and immersion in water, to simulate the conditions soils are subjected to when compacted and used in road works. Based on the results, soils are classified as lateritic or non-lateritic according to their behavior (Fabbri, 1994; Villibor et al., 2009).

Marson (2004) highlights several advantages of the MCT classification, including the absence of the need for geological, geochemical, or pedological considerations to distinguish different genetic types of tropical soils. He also emphasizes the use of laboratory tests, such as compaction and immersion in water, which simulate the conditions soils face when used in road works, as well as the lower cost, approximately 30% less than traditional methods like liquid limit, plasticity limit, and granulometry. As for the limitations, the author points out that, from an operational point of view, the methodology is more laborious when compared to traditional methods, as it requires many measurements, calculations, and graphs to obtain the classification parameters.

Villibor and Alves (2017) proposed an unprecedented classification for coarse-grained tropical soils, with a fraction retained in the sieve of 2.0 mm. It was designated G-MCT, G for granular, and MCT for the classification used to characterize granular soil fines. With MCT and G-MCT, it is possible to classify tropical soils as fine and coarse-grained, with their various soil groups, which allows for predicting their properties and hierarchizing their use in the road area. This classification considers the following aspects: (1) Definition of the types of granulometry of the total soil; (2) MCT classification of the fraction that passes through the 2.0 mm sieve obtained from the total sample.

In 2023, the DNIT 444/2023 – CLA standard was established, formalizing the classification of coarse-grained tropical soils (G-MCT) for road purposes. This classification is based on granulometric types and the MCT methodology (Miniature, Compacted, Tropical), providing a standardized framework for characterizing these soils in engineering applications.

Based on studies of the experiences of Brazilian, Portuguese, French, Indian, Australian, and different countries with tropical and subtropical climates, Rodrigues et al. (2010) proposed the Universal Classification Methodology for Lateritic Soils (UCLS), which analyzes the influence of texture, granulometry, and mineralogy on the stability and classification of these materials used in low-cost pavement layers. Farias (2023) and Farias et al. (2023), through trials with laterite soils from different regions of Brazil, improved and highlighted the potential and importance of the classification proposal, whose adaptation is present in Table 1.

Table 1: Universal Classification of Lateritic Soils for Use in Highway Layers

LATERITIC SOILS Chemical Composition and Genesis															
Sieve pass 75 µm (No. 200) ≤ 30%											Sieve pass 75 µm (No. 200) > 30%				
Sieve pass 2 mm (n° 10) ≤ 30%					Sieve pass 2 mm (n° 10) > 30%										
GRAVELLY LATERITIC SOILS (GLS)					**SANDY LATERITIC SOILS (SLS)**						**FINE LATERITIC SOILS (FLS)**				
FR ≤ 7% & DG ≤ 7%		FR > 7% or DG > 7%		FR > 7% &DG > 7%	AV ≤ 1.50 g/100 g					AV > 1.50 g/100 g	AV ≤ 3.00 g/100 g				AV > 3.00 g/100 g
					FB ≤ 60%				FB > 60%		SL ≥ 20%		SL < 20%		
CBR ≥ 60%	CBR < 60%	CBR ≥ 30%	CBR < 30%		SL ≥ 15%		SL < 15%				CBR ≥ 10%	CBR < 10%	CBR ≥ 10%	CBR < 10%	
					CBR ≥ 30%	CBR < 30%	CBR ≥ 30%	CBR < 30%							
GLS_1	**GLS_2**	**GLS_3**	**GLS_4**	**GLS_5**	**SLS_6**	**SLS_7**	**SLS_8**	**SLS_9**	**SLS_{10}**	**SLS_{11}**	**FLS_{12}**	**FLS_{13}**	**FLS_{14}**	**FLS_{15}**	**FLS_{16}**
NATURAL	**IMPROVED/STABILIZED**				**NATURAL**	**IMPROVED/STABILIZED**					**NATURAL**	**IMPROVED/STABILIZED**			
BASE [ξ ≤ 1.00%] [RM ≥ 300 MPa → N ≥ 10^6] [RM ≥ 400 MPa → N ≥ 10^7]					**BASE** [ξ ≤ 1.00%] [RM ≥ 300 MPa → N ≥ 10^6] [RM ≥ 400 MPa → N ≥ 10^7]						**BASE** [ξ ≤ 1.00%] [RM ≥ 300 MPa → N ≥ 10^6] [RM ≥ 400 MPa → N ≥ 10^7]				
NATURAL		**IMPROVED/STABILIZED**			**NATURAL**	**IMPROVED/STABILIZED**					**NATURAL**	**IMPROVED/STABILIZED**			
SUB-BASE [ξ ≤ 1.50%] [RM ≥ 200 MPa]					**SUB-BASE** [ξ ≤ 1.50%] [RM ≥ 200 MPa]						**SUB-BASE** [ξ ≤ 1.50%] [RM ≥ 200 MPa]				
					NATURAL			**IMPROVED/STABILIZED**			**NATURAL**	**IMPROVED/STABILIZED**			
					REINFORCEMENT OF THE SUBGRADE [RM ≥ 100 MPa]						**REINFORCEMENT OF THE SUBGRADE** [RM ≥ 100 MPa]				

Observations: N = Equivalent number of operations of the standard 8.2 tf axis; DG = Degradability Coefficient; FR = Fragmentability Coefficient; FB = Friability Coefficient; SL = Shrinkage/Swelling Limit; AV = Methylene Blue Adsorption Value; CBR = California Bearing Ratio; ξ = Swelling.
Source: Rodrigues et al. (2010); Farias (2023); Farias et al. (2023).

This method considers two aspects (Rodrigues et al., 2010):

- First, the metastable structure of lateritic soils, which is sensitive to variations in thermal and mechanical energy levels. In lateritic soils, this metastable state occurs because the mineralogical structure, particularly that of minerals such as kaolinite, hematite, and goethite, can be sensitive to variations in thermal and mechanical factors. This means that, under changes in temperature (such as heating) or pressure (such as compaction), the soil can undergo transformations in its composition or structure, resulting in alterations in its strength, durability, and plasticity. For example, iron and aluminum oxides can form different structures depending on the weathering level and interaction with water, making these soils susceptible to modifications in their mechanical behavior;
- Second, the physical and mineralogical properties (influenced by sesquioxides) related to strength, durability, and plasticity. Soils are classified according to their plasticity and granulometry (gravelly, sandy, or fine soils). Subdivisions are then established based on mechanical behavior, determined by the results of degradability, fragmentability, friability, load capacity, and shrinkage limit tests.

These tests are particularly important for lateritic soils due to their unique characteristics, such as high density, variation in mineral composition, and sensitivity to environmental factors like moisture and temperature. Lateritic soils may exhibit high surface resistance, but their stability and performance can be compromised by processes such as degradation, fragmentation, and shrinkage, especially in tropical climates.

According to Farias (2023) and Farias et al. (2023), the Methodology for Universal Classification of Lateritic Soils proposed by Rodrigues et al. (2010) proved to be competent for the use of natural or stabilized lateritic soils in pavement layers since it takes into account the appropriate conceptions of the tropical environment and the laterization process, as well as the mechanical properties inherent to the chemical compositions of lateritic systems.

From this brief contextualization, it becomes evident that the study of tropical soils, particularly lateritic soils, for road construction requires a more comprehensive approach tailored to their specific characteristics. This need arises from the fact that traditional methods and standards, often based on studies of soils from cold and temperate climates, do not fully address the unique features of tropical soils, such as their mineralogy, mechanical behavior, and granulometric variations. Consequently, these soils remain underutilized in pavement construction, despite their abundance in tropical regions and their potential for technical applications.

In this context, accurately classifying lateritic soils is crucial to optimizing their use, enabling the proper identification of their properties, predicting their performance in pavements, and promoting their sustainable application. Based on this premise, this study proposes a comparative analysis of different classification methods for tropical soils, with an emphasis on developing more precise criteria adapted to the specific demands of road pavements.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Lateritic soils

A total of 20 soil samples were collected from five states in Brazil: four samples from the Federal District (DF), six from Goiás (GO), three from Paraíba (PB), one from Pernambuco (PE), and six from Piauí (PI). The samples were primarily collected at depths ranging from 10 to 20 cm. However, in certain cases, samples were collected from deeper layers, reaching up to 60 cm, in order to avoid contamination by organic matter. The tactile-visual analysis of the collected samples identified soils with varying particle sizes, ranging from finer fractions to more gravelly fractions. Table 2 summarizes the key information regarding the collection points. The soils from the Federal District, Goiás, Paraíba, Pernambuco, and Piauí were designated with the acronyms BSB, GO, PB, PE, and PI, respectively.

2.1.2. Methods

2.1.2.1. Soil classification methodologies

All laterite soil samples were classified according to the TRB, MCT, G-MCT, and UCLS methodologies. Farias (2023) and Farias et al. (2023) provide more information on UCLS.

Table 3 offers a overview of the tests conducted, outlining the corresponding technical standards for each. Moreover, the table specifies the classifications for each test's application. Detailed descriptions of each test are provided below.

Table 2: Pedological Information of the Soils Studied

Sample	Pedology	Location	Coordinates (decimal degrees)
BSB-1	Red Latosol	Brasília Airport (BSB)	-15.862242, -47.906551
BSB-2	Red Latosol	Brasília Airport (BSB)	-15.862832, -47.916890
BSB-3	Red Latosol	Brasília Airport (BSB)	-15.879521, -47.931480
BSB-4	Red Latosol	Brasília Airport (BSB)	-15.878631, -47.918810
GO-1	Dystrophic/Acidic Red Latosol	BR-158, Caiapônia (GO)	-16.888114, -51.801049
GO-2	Dystrophic/Acidic Red Latosol	BR-158, Caiapônia (GO)	-16.686646, -51.694608
GO-3	Dystrophic/Acidic Red Latosol	BR-158, Piranhas (GO)	-16.494726, -51.780137
GO-4	Dystrophic/Acidic Red Latosol	BR-158, Piranhas (GO)	-16.348006, -51.932068
GO-5	Dystrophic/Acidic Red Latosol	BR-158, Bom Jardim de Goiás (GO)	-16.149500, -52.171867
GO-6	Dystrophic/Acidic Red Latosol	BR-158, Aragarças (GO)	-15.964322, -52.211018
PB-1	Dystrophic Marine Quartz Sands	BR-230, Cabedelo (PB) - João Pessoa (PB)	-7.034986, -34.842575
PB-2	Red-Yellow Podzolic	PB-018, Conde (PB) - Jacumã (PB)	-7.269683, -34.885365
PB-3	Red-Yellow Podzolic	PB-008, Conde (PB) - Jacumã (PB)	-7.272631, -34.810482
PE-1	Dystrophic Red-Yellow Latosol	BR-101, Cabo de Santo Agostinho (PE)	-8.288382, -35.056605
PI-1	Yellow Latosol	BR-316, Demerval Lobão (PI)	-5.346468, -42.683137
PI-2	Yellow Latosol	BR-316, Demerval Lobão (PI)	-5.318825, -42.701102
PI-3	Yellow Latosol	BR-316, Teresina (PI)	-5.281830, -42.722741
PI-4	Yellow Latosol	BR-316, Teresina (PI)	-5.237515, -42.740705
PI-5	Yellow Latosol	BR-316, Teresina (PI)	-5.191163, -42.761119
PI-6	Yellow Latosol	BR-316, Teresina (PI)	-5.159040, -42.770510

Table 3: Summary of Tests Conducted with Corresponding Technical Standards and Classifications

Test	Standard	Classification
Scanning Electron Microscopy (SEM)	-	UCLS
X-ray Diffraction (XRD)		
X-ray Fluorescence (XRF)		
Particle Size Analysis	ASTM D6913-04	TRB; MCT; G-MCT and UCLS
Liquid Limit, Plasticity Limit, and Plasticity Index	ASTM D4318-17	TRB
Methylene Blue Adsorption Value	NF P 94-068	UCLS
Shrinkage Limit	ASTM D427-98	UCLS
Fragmentability Coefficient	NF P 94-066	UCLS
Degradability Coefficient	NF P 94-067	UCLS
Sands Friability Test	NF P 18-576	UCLS
Compaction Test using Intermediate Proctor Energy	ASTM D698-12	UCLS
California Bearing Ratio (CBR) Test	ASTM D1883-21	UCLS
Mini-MCV Test	DNIT-ME 258	MCT and G-MCT
Immersion Mass Loss Test	DNIT-ME 256	MCT and G-MCT

The methodological procedure used in the work started with the study of the soil genesis through results from Scanning Electron Microscopy (SEM), X-ray diffraction (XRD), and X-ray fluorescence (XRF) tests.

- The particle size analysis was conducted by sieving through sieves with openings of 50.8 mm (2 in.), 25.4 mm (1 in.), 9.52 mm (3/8 in.), 4.76 mm (No. 4), 2 mm (No. 10), 0.42 mm (No. 40), 0.177 mm (No. 80), and 0.075 mm (No. 200). The test was conducted in accordance with the ASTM D6913-04 standard (ASTM, 2017). This test was performed without the use of the dispersant sodium hexametaphosphate, which may have affected the dispersion of fine particles, such as clay, which tend to aggregate or form flocs. Sodium hexametaphosphate is commonly used for the complete dispersion of fine particles, especially in soils with a high clay content, like lateritic soils, as it allows for a more accurate and reliable particle size analysis. However, the decision to exclude the dispersant in this case was intentional, aimed at assessing the soil's granulometry in a more conservative manner, reflecting the natural state of the soil, where fine particles may exist in an aggregated form. In certain contexts, this approach is useful to understand the behavior of the soil in its natural conditions, without any chemical intervention that could alter the structure of the particles. It is worth noting that in Oxisols, chemical dispersion may not be fully effective, leading to the formation of pseudocomponents such as pseudosilt—particles that do not correspond to the soil's actual grain size fractions. This can result in misinterpretations of soil texture and properties (Rodrigues et al., 2011);
- The liquid limit, plasticity limit, and plasticity index tests were performed in accordance with ASTM D4318-17 (ASTM, 2018);
- The methylene blue adsorption value was determined through tests conducted in accordance with the NF P 94-068 standard (NF, 1998). The procedure involved the successive addition of varying amounts of methylene blue to the soil and monitoring adsorption after each addition. A drop of the suspension was placed on filter paper, producing a stain. Maximum adsorption was identified when a persistent light blue halo appeared around the stain's periphery. The methylene blue value (VA) was determined for the soil fraction smaller than 2 mm and expressed in grams of methylene blue per 100 grams of soil. Three experiments were performed under identical molding conditions;
- The shrinkage limit was determined following the ASTM D427-98 standard (ASTM, 2021b). The soil was initially air-dried until a noticeable color change was observed, followed by oven-drying until a constant weight was achieved. The volume change during the drying process was then measured. The degree of contraction, or volumetric contraction, was calculated as the percentage ratio of the volume difference between the initial and final volumes after drying to the initial volume. Three tests were conducted under identical molding conditions;
- The procedure for determining the fragmentability coefficient was conducted in accordance with the NF P 94-066 (NF, 1992a) standard. The test involves measuring the reduction in the effective diameter of the soil (D_{10}), where 10% of the soil, by weight, consists of particles with diameters smaller than D_{10}. This is achieved using conventional compaction with 100 strokes, applied with a small Proctor socket in a CBR mold;
- The methodology for obtaining the degradability coefficient was standardized in accordance with NF P 94-067 (NF, 1992b). The test involves subjecting the soil sample to immersion and drying cycles instead of applying blows. The prepared soil is immersed in water for eight hours, followed by drying in an oven at 105 °C for 16 hours, completing one cycle. After four cycles, a particle size analysis is conducted to determine the reduction in the effective diameter (D_{10}) of the soil;
- The sands friability test aims to observe the granulometric evolution of the material due to fragmentation in a rotating cylinder containing abrasive loads and water. The procedure

follows the NF P 18-576 (NF, 1990) standard. The test involves placing the specimen, water, and abrasive charges into a rotating cylinder, which is then rotated at 100 rpm for 15 minutes. A higher friability coefficient indicates a more friable soil, reflecting a greater tendency to disintegrate into smaller particle sizes under stress or load;

- Regarding the compaction process, for sandy lateritic soils, Intermediate Proctor energy is recommended when used in base or sub-base layers (Balbo, 2007). In the case of gravelly lateritic soils, compaction may be detrimental if the clods are fragile. This fragility can lead to an increase in fine material content by disrupting the soil structure without significantly improving the dry apparent specific gravity or bearing capacity, and may also render the material more susceptible to suction effects (Degn, 1984; Rodrigues et al., 2010). Therefore, the compaction test was conducted using Intermediate Proctor energy (13 kgf·cm/cm^3), in accordance with ASTM D698-12 (ASTM, 2021c). The soil was compacted in five equal layers, with 26 blows applied per layer. Five tests were performed with increasing moisture content to construct the compaction curve of the material. From these results, the optimum water content and maximum dry density were determined;
- The California Bearing Ratio (CBR) test was performed in accordance with ASTM D1883-21 (ASTM, 2021a). Samples were molded under optimum conditions, subjected to manual compaction, and immersed in water for 96 hours. Swelling was monitored using extensometers. After immersion, the excess water was drained, and the CBR test was conducted. The molding moisture content was maintained within ± 0.5% of the optimum, with a compaction degree ranging from 98% to 102%;
- The mini-MCV test was conducted in accordance with DNIT-ME 258 (DNIT, 1994b), compacting 200 g of soil at five moisture contents and varying energies to determine the c' and d' coefficients for classification;
- The Immersion Mass Loss Test, according to DNIT-ME 256 (DNIT, 1994a), involved partially extruding Mini-MCV specimens by 10 mm and immersing them in water for 24 hours. This test determines Pi, the percentage of dry mass lost from the extruded soil portion, used in MCT classification.

2.1.2.2. Resilient Modulus

The Resilient Modulus of lateritic samples was determined using the dynamic triaxial test, in accordance with DNIT-ME 134 (DNIT, 2018), a parameter included in the Universal Classification of Lateritic Soils (Table 1).

Cylindrical specimens (100 mm x 200 mm) were compacted in 10 layers, with ten dynamic strokes applied to each layer using Intermediate Proctor energy (13 kgf.cm/cm^3). The top of each layer was scarified, and the final layer was overfilled by 30% to facilitate leveling. The samples were then moistened to optimal moisture content and sealed for 24 hours to ensure uniformity. Three specimens were molded per test, maintaining moisture levels within ± 0.5% of the optimum and achieving a compaction degree between 98% and 102% of the target density.

While the analysis of permanent deformation would be valuable, the primary focus here is to discuss the classifications, with the Resilient Modulus serving as a key parameter in the characterization of lateritic soils.

3. RESULTS

3.1. Identification of lateritic genesis

The study on the genesis of soils is presented, utilizing results from SEM tests combined with the EDS technique for chemical composition identification, XRD, and XRF.

3.2. SEM-EDS

The analysis of the microscopic photographs suggests that all the samples have a lateritic genesis, showing patterns that demonstrate cementation between their particles. The structure observed features quartz concretions surrounded by smaller grains, connected by an amorphous mass, as verified by Nogami and Villibor (1995), Mahalinga-Iyer and Williams (1991), Rodrigues et al. (2010), Biswal et al. (2020), and Farias et al. (2023).

It is possible to observe the narrow organization between the fine particles (kaolinite) and the quartz grains. Figures 1 to 5 shows the SEM of the studied soils. The fine particles are aggregated and form a film that coats the larger-sized quartz particles. That association thus constitutes an agglomeration. The results corroborate the findings of Lemaire et al. (2013) and Mengue et al. (2017).

The EDS (Table 4) analysis revealed that the studied soils exhibit a predominance of oxygen, silicon, aluminum, and iron, indicating typical characteristics of lateritic soils. The samples from Brasília (BSB) and Goiás (GO) show higher iron concentrations (up to 30.19% in BSB-4), suggesting intense lateritization and the presence of hematite and goethite. In contrast, the samples from Paraíba (PB), Pernambuco (PE), and Piauí (PI) have lower iron concentrations but maintain high aluminum contents, indicating a mineralogical composition dominated by kaolinite and gibbsite. Silicon appears in varying amounts (7.83% to 26.31%), which may be associated with the presence of quartz and clay minerals. These variations in elemental composition reflect differences in the degree of weathering and the geological processes that led to the formation of the analyzed soils.

Table 4: EDS test results: percentages of constituent elements (8000X)

	Compounds (%)											
Sample	**O**	**Si**	**Al**	**Fe**	**Ti**	**C**	**K**	**Ca**	**In**	**Au**	**Rb**	**Ba**
BSB-1	63.36	11.51	14.59	10.51	-	-	-	-	-	-	-	-
BSB-2	41.48	8.23	16.89	25.96	-	7.44	0.90	-	-	-	-	-
BSB-3	51.97	13.54	13.81	20.69	-	-	-	-	-	-	-	-
BSB-4	44.43	8.00	15.57	30.19	1.81	-	-	-	-	-	-	-
GO-1	66.99	12.57	15.51	4.09	0.83	-	-	-	-	-	-	-
GO-2	60.56	19.01	14.02	5.01	0.82	-	0.59	-	-	-	-	-
GO-3	62.28	19.45	15.18	1.98	-	-	1.11	-	-	-	-	-
GO-4	65.07	14.92	17.42	-	0.68	-	0.73	-	0.88	0.31	-	-
GO-5	75.05	7.83	14.72	-	1.10	-	1.30	-	-	-	-	-
GO-6	71.69	17.31	10.13	-	-	-	0.87	-	-	-	-	-
PB-1	58.96	19.76	17.08	1.97	-	-	-	2.23	-	-	-	-
PB-2	66.18	17.23	13.07	2.72	0.81	-	-	-	-	-	-	-
PB-3	77.23	17.41	1.62	1.74	-	-	-	-	-	-	1.69	0.31
PE-1	53.89	19.11	20.76	6.24	-	-	-	-	-	-	-	-
PI-1	62.59	9.27	18.60	-	2.05	7.49	-	-	-	-	-	-
PI-2	67.58	14.66	17.34	-	0.42	-	-	-	-	-	-	-
PI-3	70.74	17.50	9.93	1.36	-	-	0.47	-	-	-	-	-
PI-4	69.62	14.39	12.72	2.78	0.49	-	-	-	-	-	-	-
PI-5	62.11	22.73	12.18	2.18	0.79	-	-	-	-	-	-	-
PI-6	63.94	26.31	9.75	-	-	-	-	-	-	-	-	-

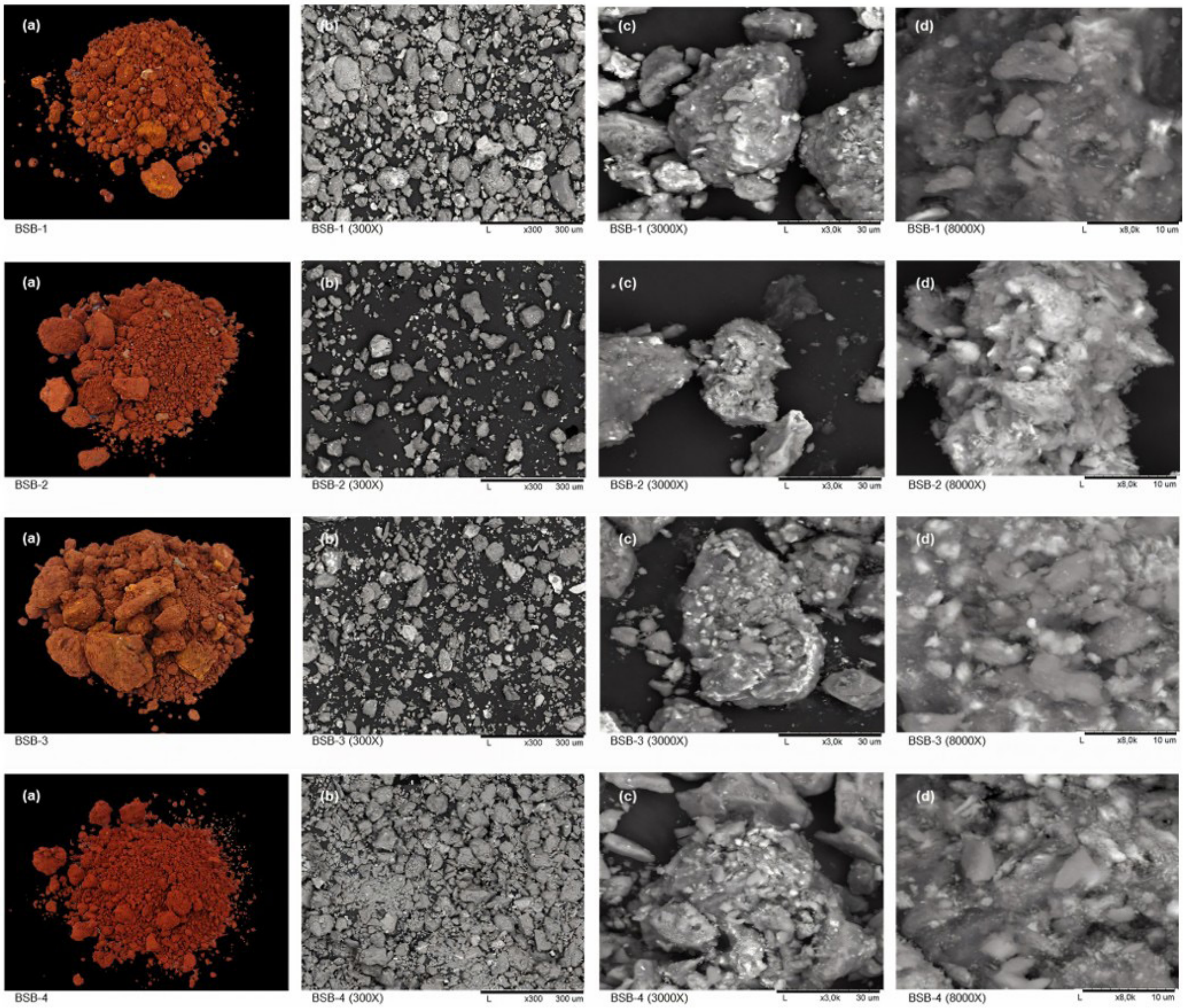

Figure 1. Brasília: BSB-1; BSB-2; BSB-3; BSB-4. SEM of the analyzed soils – (a) Photograph; (b) Micrograph 300x; (c) Micrograph 3000x; (d) Micrograph 8000x.

3.3. XRD

The peaks in the X-ray diffractograms of the soils studied indicated the presence of kaolinite as the predominant clay mineral. Figures 6 to 10 shows the data for the studied soils. Only for the PE-1 soil was montmorillonite also observed, but with kaolinite as the predominant clay mineral. Primary minerals and 2:1 clay minerals such as illites and smectites may be present in less-weathered soils.

Minerals such as gibbsite, hematite, goethite, magnetite, and poorly crystallized iron and aluminum oxides were identified in the clay fraction of these soils. These findings are in agreement with Nogami and Villibor (1995) and Farias (2023), who state that lateritic soils contain iron and aluminum oxides and hydroxides. Additionally, they highlight that the clay mineral typically present is kaolinite, with other members of the kaolinite group, such as halloysite and nacrite, also being found.

According to Biswal et al. (2016), mineralogical analysis of laterite soils indicates a substantial amount of quartz and some amount of feldspar, hematite, goethite, and muscovite as non-clay minerals. Kaolinite is the predominant clay mineral; illite is also present in some soils. Mahalinga-Iyer and Williams (1991), Rodrigues et al. (2010), and Biswal et al. (2020), through analysis in X-ray diffractograms, observed that the main minerals present in granular laterite soil samples are kaolinite and quartz, hematite, and goethite.

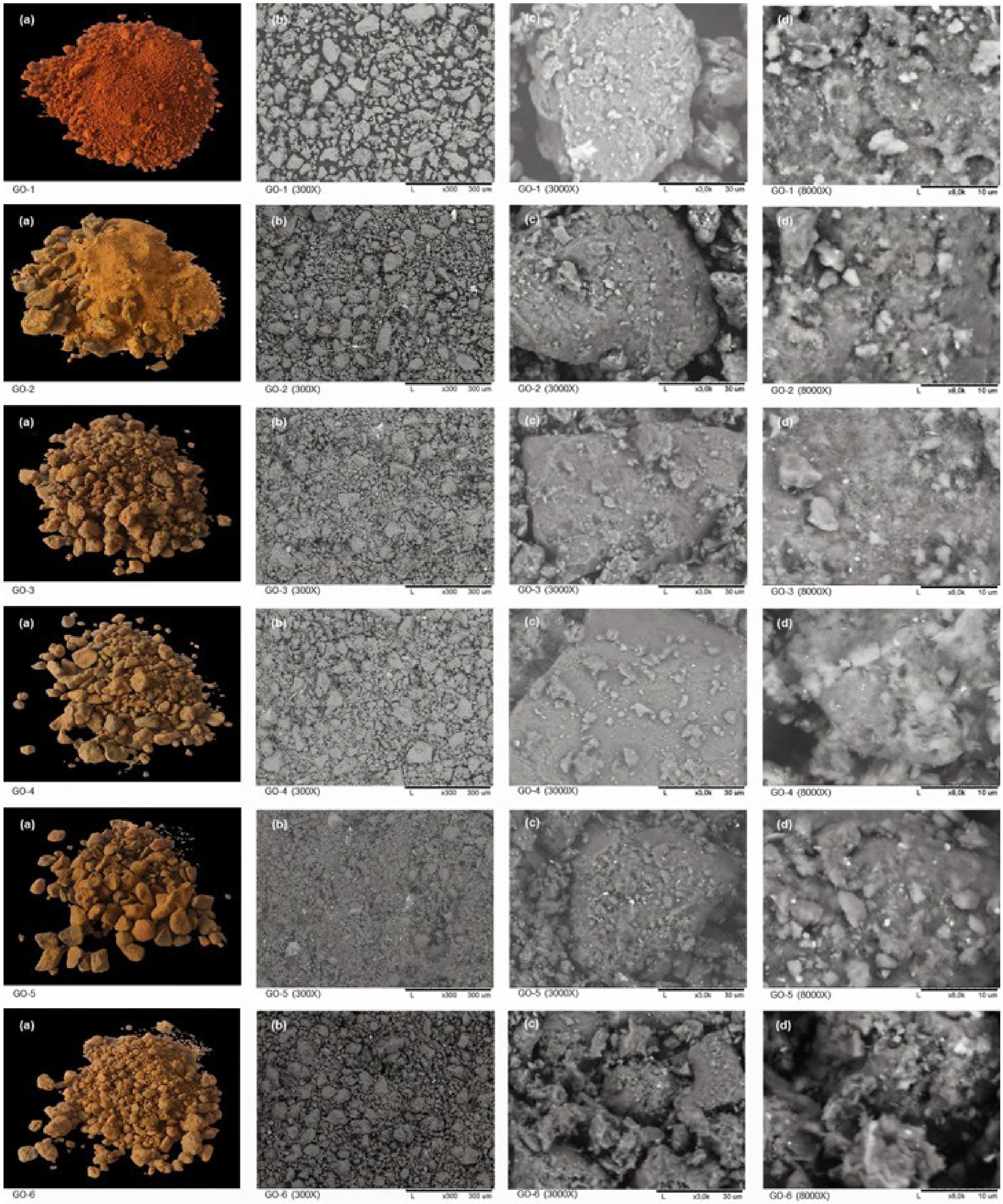

Figure 2. Goiás: GO-1; GO-2; GO-3; GO-4; GO-5; GO-6. SEM of the analyzed soils – (a) Photograph; (b) Micrograph 300x; (c) Micrograph 3000x; (d) Micrograph 8000x.

3.4. XRF

The results from XRF (Table 5) confirmed the predominant presence of aluminum and iron oxides (Al_2O_3 and Fe_2O_3) and silica (SiO_2), which together represented, on average, approximately 86% of

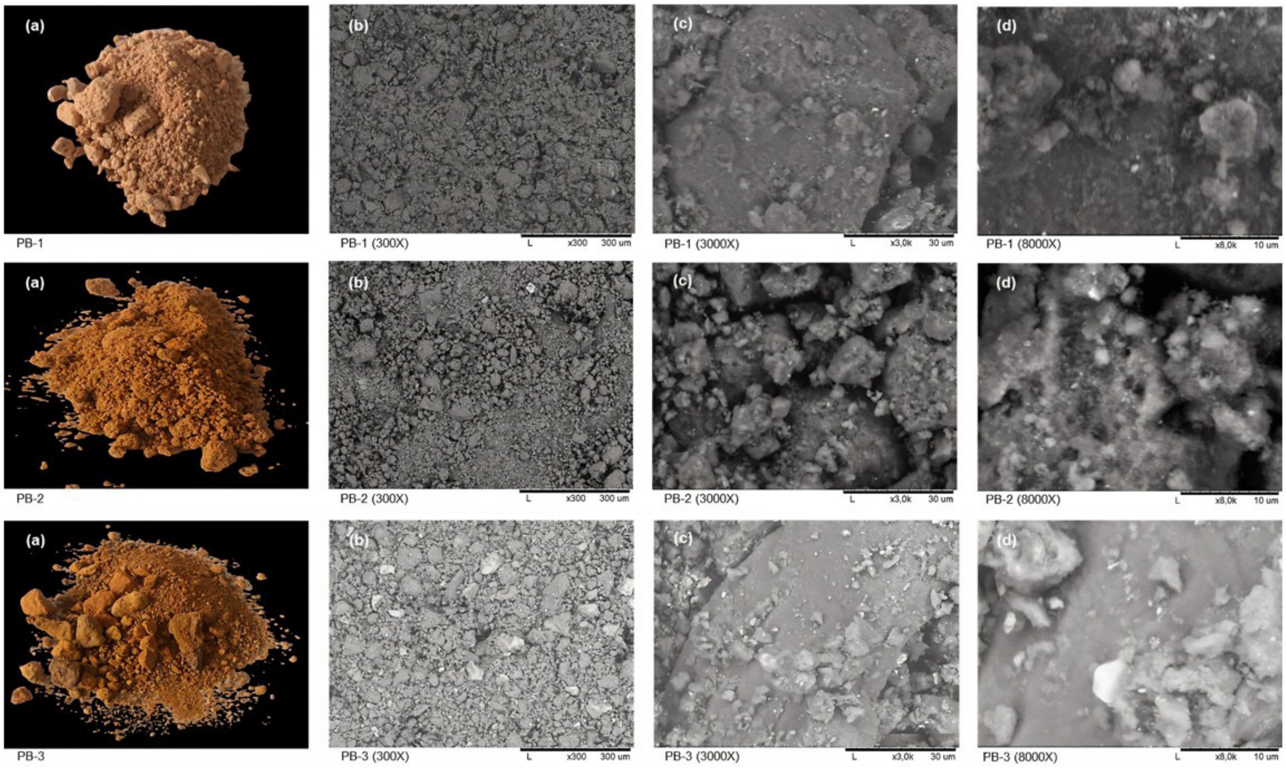

Figure 3. Paraíba: PB-1; PB-2; PB-3. SEM of the analyzed soils – (a) Photograph; (b) Micrograph 300x; (c) Micrograph 3000x; (d) Micrograph 8000x.

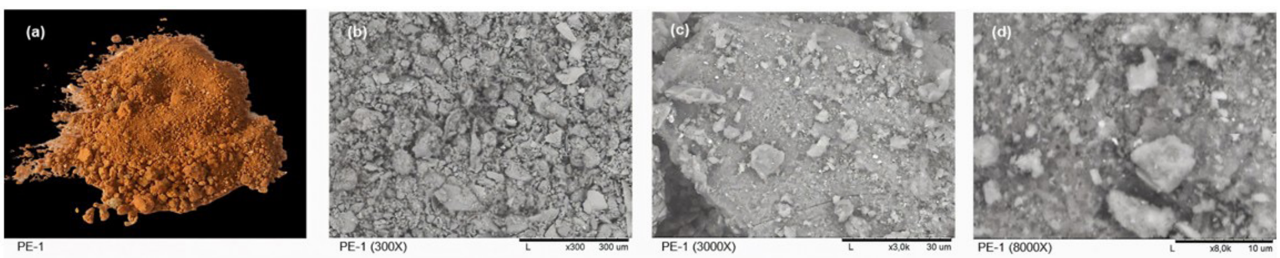

Figure 4. Pernambuco: PE-1. SEM of the analyzed soils – (a) Photograph; (b) Micrograph 300x; (c) Micrograph 3000x; (d) Micrograph 8000x.

the oxides present in the studied samples. The weathering indexes, including the Ki index (silica/alumina molecular ratio) and the Kr index (silica/sesquioxide molecular ratio), are presented in Table 6.

The lower the value of Ki and Kr, the more weathered it is, with a predominance of iron and aluminum oxides. These minerals promote the development of a microstructure with a predominance of composite packaging pores, which favors a granular-type macrostructure, determining lower soil density, a higher proportion of large pores, and more excellent permeability, i.e., lower values of field capacity (Rossi, 2019). In Oxisols, more weathered soils, it is observed that, as there is a reduction in Ki and Kr, there is also a reduction in strength values (Rocha et al., 2002).

By correlating the data presented in Table 5 with the results of the XRD assays, it is understood that silica is intrinsically linked to the occurrence of quartz, and silicates and kaolinite are influenced by alumina (Al_2O_3). The occurrence of minerals such as gibbsite, hematite, goethite, and magnetite is influenced by the concentration of iron and aluminum, which then determines the yellowish and reddish fractions in lateritic soils.

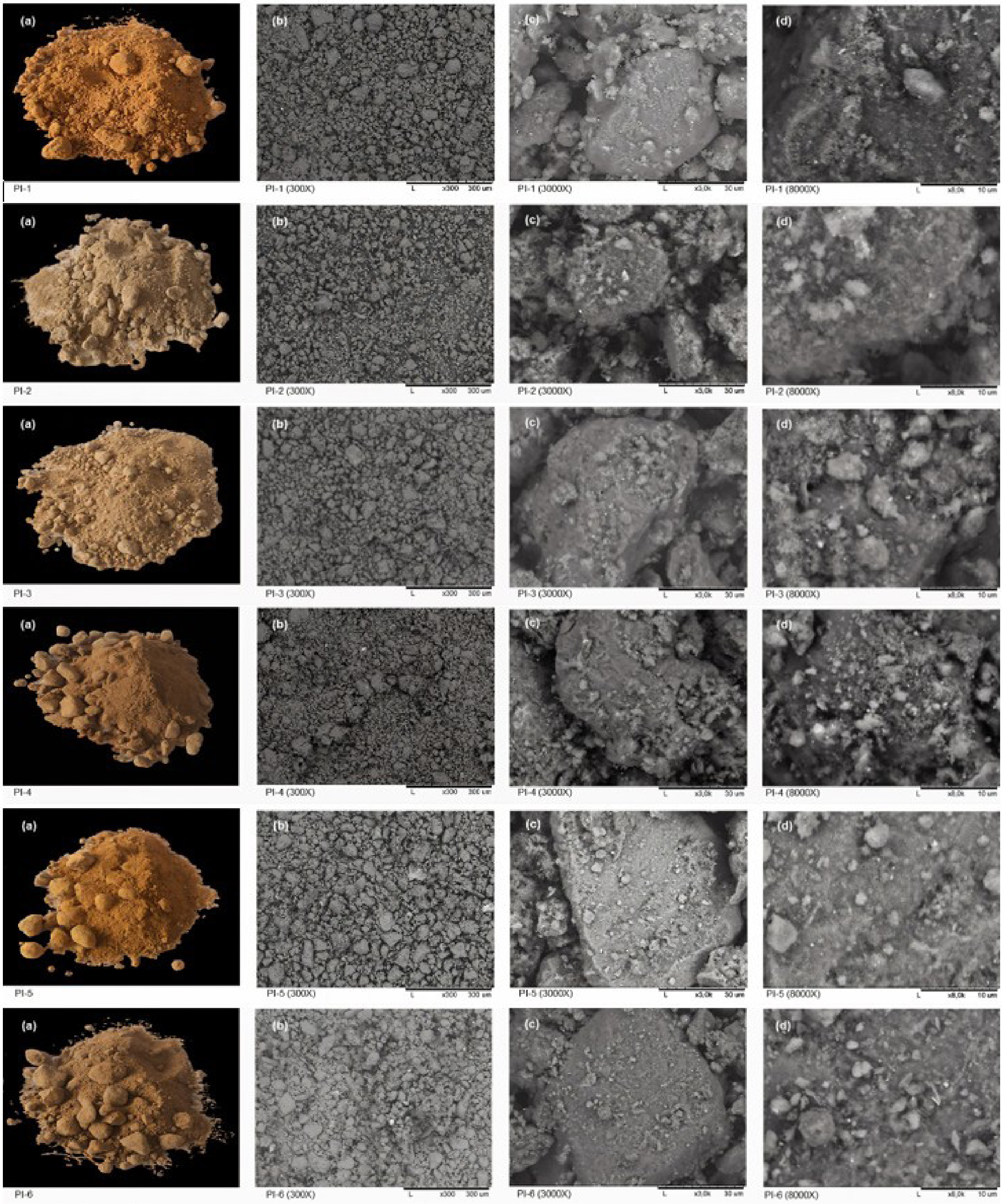

Figure 5. Piauí: PI-1; PI-2; PI-3; PI-4; PI-5; PI-6. SEM of the analyzed soils – (a) Photograph; (b) Micrograph 300x; (c) Micrograph 3000x; (d) Micrograph 8000x.

3.5. Physical properties and classification

3.5.1. TRB

Table 7 indicates the results of the TRB classification. Twelve samples belonged to group A-2, which was the predominant group. Four samples belonged to group A-7, two to group A-1, and two to group A-4.

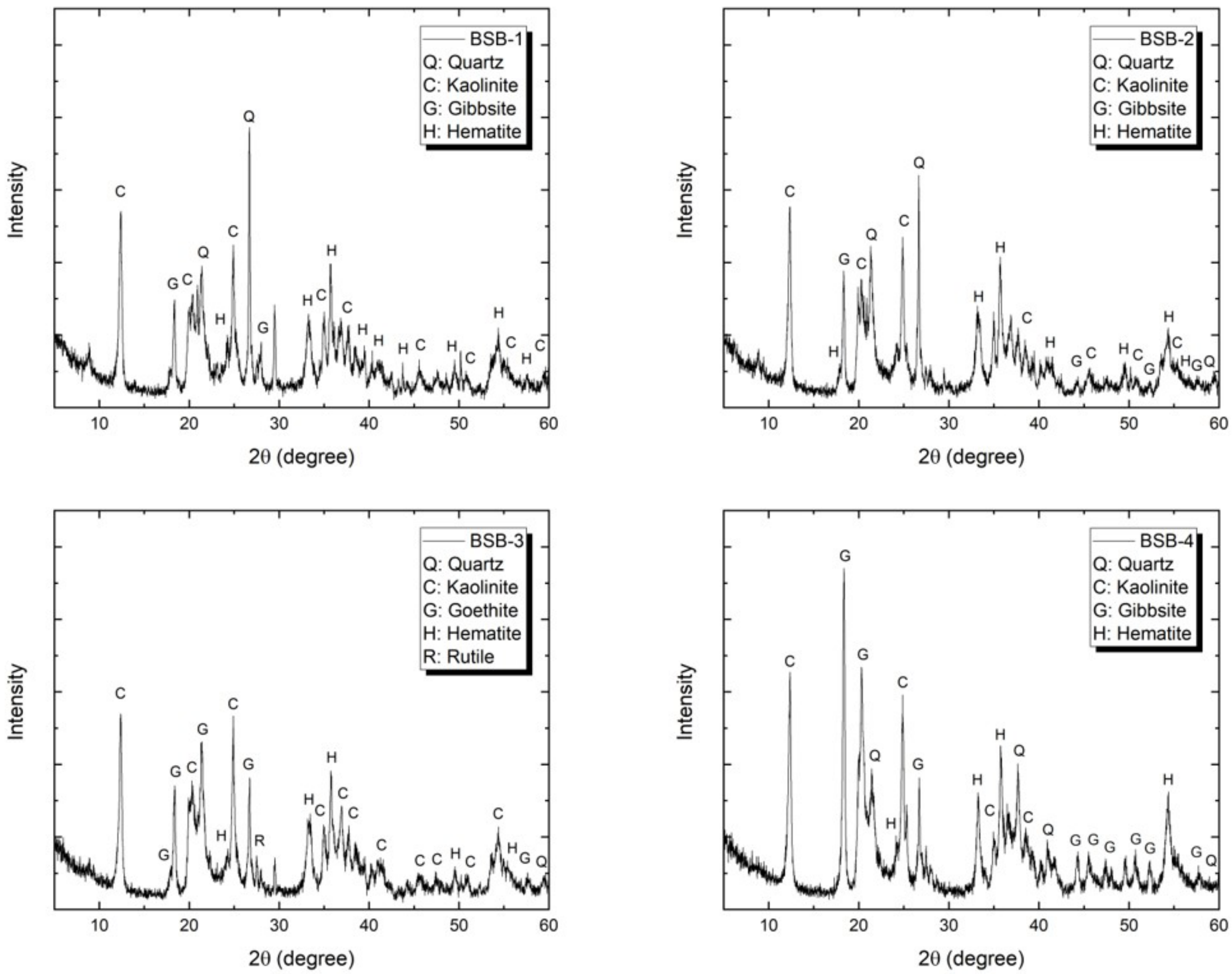

Figure 6. XRD of the analyzed soils. Brasília: BSB-1; BSB-2; BSB-3; BSB-4.

Several critical facts can be observed: Group A-2, which corresponds to more than 60% of the samples, includes soils with distinctly different particle size characteristics. For instance, the GO-5 and GO-6 samples, which are predominantly composed of pebbles, and the PB-1 and PB-2 samples, which are mainly made up of sand, illustrate this variability. The proportions between the granulometric fractions vary significantly from one soil to another, despite the identification of a predominant fraction in each case. Predicting the mechanical behavior of tropical soils through the TRB system is a practice that has raised criticism in Brazilian geotechnical and road environments, given that they are based only on physical properties (Silva et al., 2010; Silva, 2019; Farias et al., 2023).

3.5.2. MCT and G-MCT

Table 8 presents the parameters and classifications of MCT and G-MCT.

Table 8 presents the parameters and classifications of MCT and G-MCT. Soils BSB-1, BSB-3, and PB-1 were the only ones exhibiting non-lateritic behavior. In the G-MCT classification, soil BSB-1 was the only one classified as a boulder with non-lateritic clay soil (Ps-NS’). Soil BSB-3 was the only one classified as a boulder with non-lateritic sandy soil (Ps-NA’). Finally, soil PB-1 was identified as a non-lateritic sandy soil with boulder (Sp-NA’). These classifications diverge from the chemical and mineralogical analysis of the soils, indicating their lateritic nature.

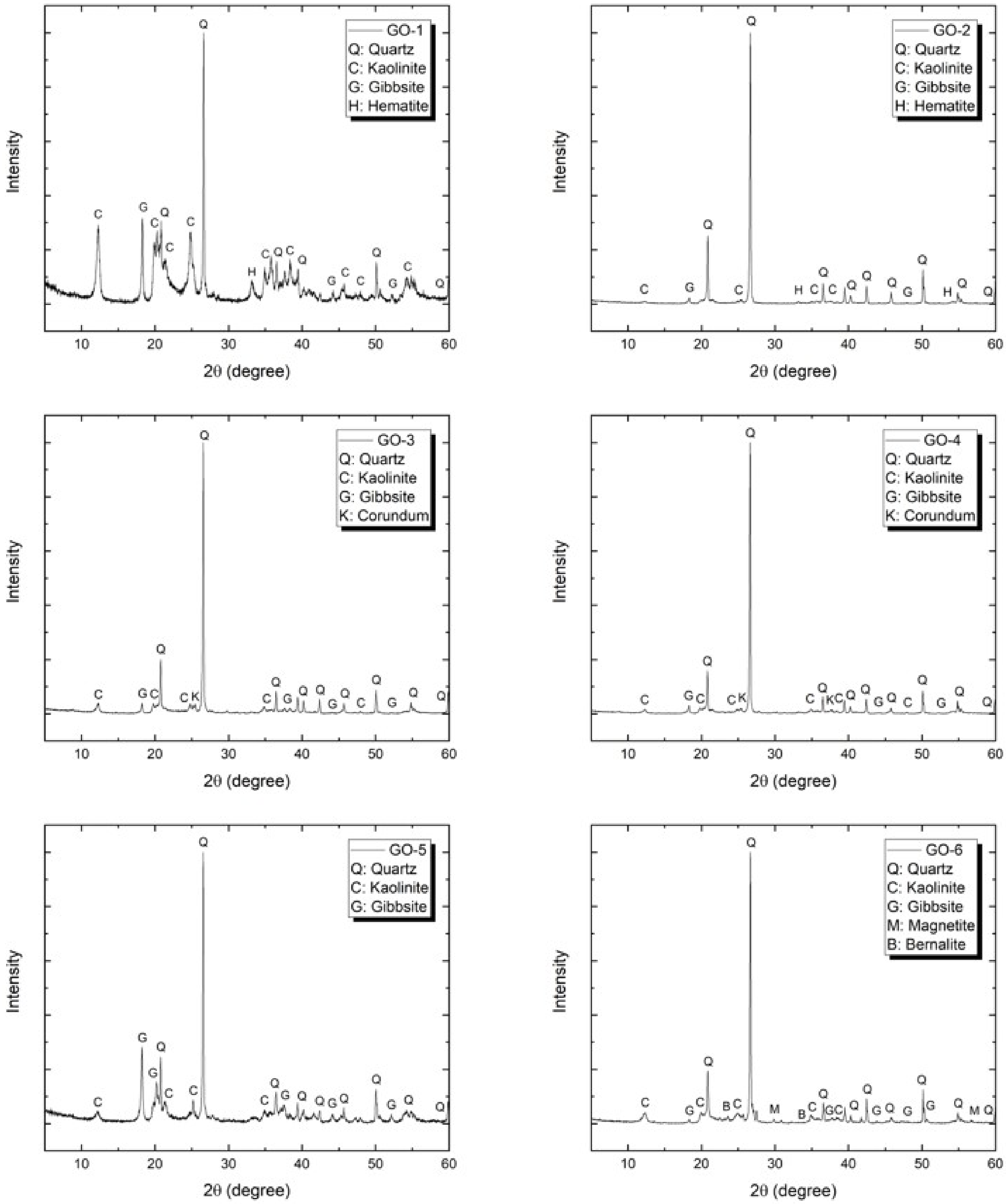

Figure 7. XRD of the analyzed soils. Goiás: GO-1; GO-2; GO-3; GO-4; GO-5; GO-6.

3.5.3. UCLS

Table 9 presents the results of the UCLS classification.

The fine lateritic soils showed low adsorption values of methylene blue (below 3.00 g/100 g of soil) and SL above 20%. The exceptions were the soils PI-2 and PI-3, which had a retraction below, denoting a worse classification. The soil with the highest swelling value was the PI-2 soil, with a value of 0.70%.

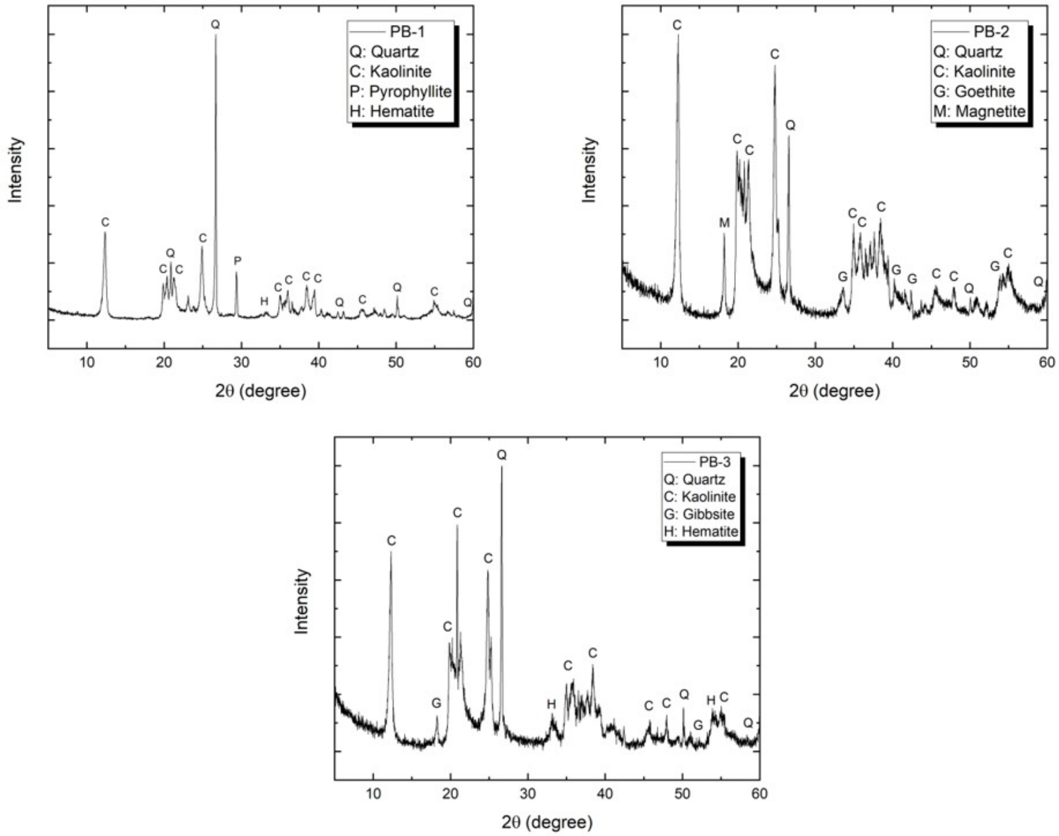

Figure 8. XRD of the analyzed soils. Paraíba: PB-1; PB-2; PB-3.

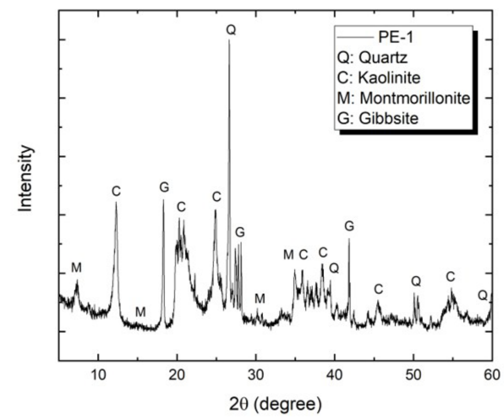

Figure 9. XRD of the analyzed soils. Pernambuco: PE-1.

The sandy lateritic soils, in turn, showed lower values of methylene blue adsorption, as expected, due to the lower amount of grains passing through the #75 µm sieve. In addition, they presented relatively low friability values (below 60%). Only the PI-5 soil presented FB slightly above 60%, which placed it in the worst classification compared to the other sandy soils. However, it is worth noting that it presented a better CBR value (138%), which indicates good support capacity.

The PI-6 soil exhibited the highest water swelling value among the analyzed soils, with an index of 1.03%. Although this is a relatively low value, this swelling can be explained by the specific characteristics of the soil. The PI-6 soil has the highest SiO_2 content, which suggests a significant fraction of fine particles with a higher surface area. These fine particles have a greater water retention capacity, contributing

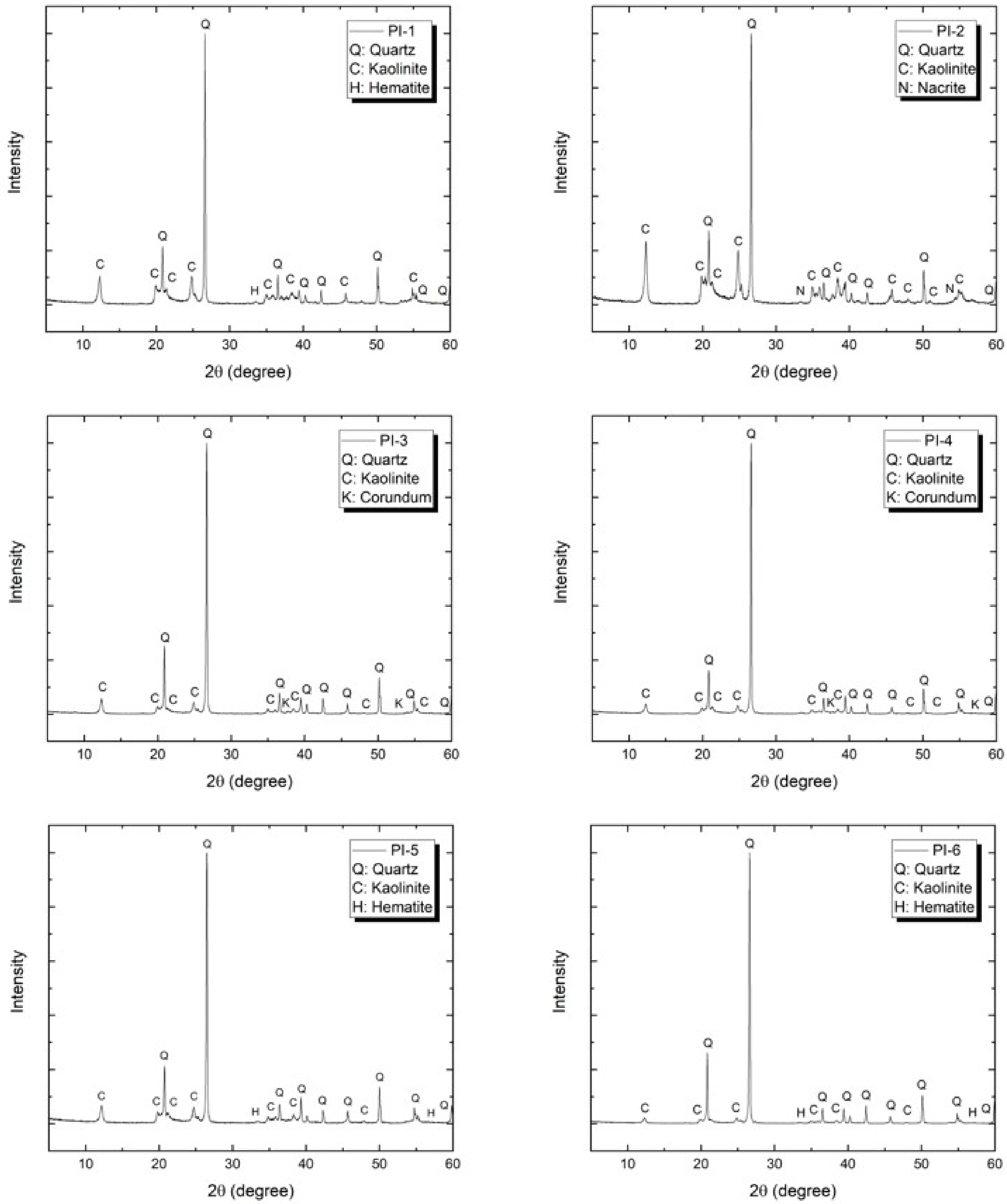

Figure 10. XRD of the analyzed soils. Piauí: PI-1; PI-2; PI-3; PI-4; PI-5; PI-6.

to soil swelling. Additionally, the PI-6 soil contains a lower amount of Al_2O_3, which implies a limited presence of less expansive minerals such as kaolinite. This prevents excessive restriction of water absorption, allowing for greater interaction between water and the soil's fine particles. Therefore, even with the presence of non-expansive SiO_2, the PI-6 soil demonstrated an swelling capacity due to the fine particles with a high surface area, which expand when in contact with water.

Table 5: Chemical analysis of soil samples

Sample	Compounds (%)												Loss on Ignition (%)
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O	MgO	ZrO_2	CaO	SO_3	BaO	MnO	Other	
BSB-1	29.69	36.35	18.04	1.15	0.73	0.00	0.04	1.55	0.21	0.00	0.05	0.11	12.08
BSB-2	26.62	39.34	18.70	1.23	0.58	0.00	0.00	0.41	0.12	0.00	0.04	0.15	12.81
BSB-3	26.03	40.30	17.93	1.18	0.43	0.00	0.03	0.70	0.00	0.00	0.03	0.11	13.25
BSB-4	20.67	47.54	10.92	1.58	0.14	0.84	0.04	0.09	0.00	0.00	0.02	0.10	18.05
GO-1	36.75	38.72	8.85	1.26	0.00	0.00	0.11	0.06	0.18	0.28	0.00	0.00	13.79
GO-2	62.66	21.11	6.57	1.41	0.59	0.68	0.17	0.11	0.23	0.00	0.00	0.01	6.45
GO-3	54.72	27.89	3.70	1.25	1.84	0.99	0.13	0.00	0.20	0.00	0.03	0.01	9.24
GO-4	53.34	28.56	5.38	1.31	1.70	0.56	0.06	0.05	0.18	0.00	0.02	0.13	8.71
GO-5	35.83	36.65	6.91	2.00	0.77	0.34	0.00	0.24	0.19	0.00	0.00	0.00	17.07
GO-6	53.67	31.27	2.87	1.14	2.02	0.59	0.28	0.00	0.24	0.22	0.03	0.03	7.64
PB-1	44.72	33.55	4.67	0.97	0.18	0.98	0.00	4.12	0.18	0.00	0.00	0.00	10.64
PB-2	40.33	39.19	6.19	1.89	0.00	0.00	0.11	0.00	0.00	0.31	0.00	0.00	11.98
PB-3	31.17	34.31	12.30	3.40	0.09	0.00	0.08	0.11	0.20	0.00	0.02	0.07	18.24
PE-1	39.89	35.39	6.77	1.00	1.32	1.18	0.09	0.00	0.18	0.00	0.03	0.01	14.14
PI-1	54.98	31.36	4.12	1.64	0.00	0.00	0.12	0.10	0.19	0.00	0.03	0.10	7.35
PI-2	52.02	32.80	2.33	1.12	0.13	0.00	0.08	0.00	0.00	0.00	0.00	0.00	11.52
PI-3	66.64	23.71	2.15	0.85	0.58	0.79	0.08	0.00	0.19	0.00	0.00	0.01	5.02
PI-4	61.22	24.43	4.76	1.08	0.00	0.62	0.10	0.00	0.15	0.00	0.00	0.01	7.64
PI-5	57.74	27.10	3.69	1.17	0.00	0.74	0.11	0.05	0.00	0.20	0.00	0.00	9.20
PI-6	69.17	19.73	3.36	0.95	0.35	0.63	0.11	0.12	0.28	0.00	0.00	0.00	5.30

Table 6: Classification of Laterization Type Using Weathering Indexes Ki and Kr

Sample	K_i	K_r	Classification
BSB-1	0.82	0.55	Highly Weathered Kaolinitic-Oxidic Soil
BSB-2	0.68	0.46	Highly Weathered Oxidic Soil (Hematitic. Goethitic. or Gibbsitic)
BSB-3	0.65	0.45	Highly Weathered Oxidic Soil (Hematitic. Goethitic. or Gibbsitic)
BSB-4	0.43	0.35	Highly Weathered Oxidic Soil (Hematitic. Goethitic. or Gibbsitic)
GO-1	0.95	0.77	Highly Weathered Kaolinitic Soil
GO-2	2.97	2.26	Slightly Weathered Kaolinitic Soil
GO-3	1.96	1.73	Highly Weathered Kaolinitic Soil
GO-4	1.87	1.57	Highly Weathered Kaolinitic Soil
GO-5	0.98	0.82	Highly Weathered Kaolinitic Soil
GO-6	1.72	1.57	Highly Weathered Kaolinitic Soil
PB-1	1.33	1.17	Highly Weathered Kaolinitic Soil
PB-2	1.03	0.89	Highly Weathered Kaolinitic Soil
PB-3	0.91	0.67	Highly Weathered Kaolinitic-Oxidic Soil
PE-1	1.13	0.95	Highly Weathered Kaolinitic Soil
PI-1	1.75	1.55	Highly Weathered Kaolinitic Soil
PI-2	1.59	1.48	Highly Weathered Kaolinitic Soil
PI-3	2.81	2.58	Slightly Weathered Kaolinitic Soil
PI-4	2.51	2.10	Slightly Weathered Kaolinitic Soil
PI-5	2.13	1.88	Highly Weathered Kaolinitic Soil
PI-6	3.51	3.00	Slightly Weathered Kaolinitic Soil

Table 7: TRB Classification

Sample	Granulometric Fraction (%)			Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Group Index	Classification
	Silt and Clay	Sand	Gravel					
BSB-1	22.00	19.00	59.00	28	16	12	0	A-2-6
BSB-2	65.00	8.00	27.00	46	27	19	10	A-7-6
BSB-3	25.00	18.00	57.00	32	19	13	0	A-2-6
BSB-4	79.00	9.00	12.00	45	27	18	12	A-7-6
GO-1	59.00	40.00	1.00	47	35	12	7	A-7-5
GO-2	35.00	19.00	46.00	27	NP	NP	0	A-2-4
GO-3	6.96	28.22	64.82	36	26	10	0	A-2-4
GO-4	10.73	11.94	77.33	27	21	6	0	A-1-a
GO-5	3.80	6.70	89.50	33	20	13	0	A-2-6
GO-6	7.48	20.82	71.70	32	23	9	0	A-2-4
PB-1	10.71	79.38	9.91	NL	NP	NP	0	A-2-4
PB-2	21.24	78.17	0.59	NL	NP	NP	0	A-2-4
PB-3	8.27	20.10	71.63	NL	NP	NP	0	A-1-a
PE-1	57.39	40.40	2.22	42	29	13	6	A-7-6
PI-1	46.23	53.09	0.69	26	23	3	0	A-4
PI-2	31.49	59.42	9.09	NL	NP	NP	0	A-2-4
PI-3	43.42	30.12	26.46	NL	NP	NP	0	A-4
PI-4	26.00	30.00	44.00	NL	NP	NP	0	A-2-4
PI-5	20.78	23.58	55.64	NL	NP	NP	0	A-2-4
PI-6	21.89	25.74	52.37	NL	NP	NP	0	A-2-4

Table 8: MCT and G-MCT Classifications

Sample	Coefficient c’	Index e’	MCT Classification	Passing (%)		G-MCT Classification
				#10 (2.00 mm)	#200 (0.075 mm)	
BSB-1	1.03	1.48	NS’	41.00	22.00	Ps-NS’
BSB-2	1.66	1.08	LG’	73.00	65.00	Gf-LG’
BSB-3	0.96	1.45	NA’	43.00	25.00	Ps-NA’
BSB-4	1.99	0.98	LG’	88.00	79.00	Gf-LG’
GO-1	2.25	1.11	LG’	99.00	59.00	Gf-LG’
GO-2	1.15	1.09	LA’	54.00	35.00	Gf-LA’
GO-3	1.35	0.95	LA’	35.18	6.96	Ps-LA’
GO-4	1.01	1.00	LA’	22.67	10.73	Ps-LA’
GO-5	0.75	1.03	LA’	10.50	3.80	Ps-LA’
GO-6	1.29	0.97	LA’	28.30	7.48	Ps-LA’
PB-1	1.03	1.19	NA’	90.09	10.71	Sp-NA’
PB-2	1.35	0.91	LA’	99.41	21.24	Sp-LA’
PB-3	1.18	1.09	LA’	28.37	8.27	Ps-LA’
PE-1	2.06	0.97	LG’	97.78	57.39	Gf-LG’
PI-1	1.35	1.02	LA’	99.31	46.23	Gf-LA’
PI-2	1.26	0.93	LA’	90.91	31.49	Gf-LA’
PI-3	1.29	0.97	LA’	73.54	43.42	Gf-LA’
PI-4	1.35	1.09	LA’	56.00	26.00	Sp-LA’
PI-5	1.29	1.06	LA’	44.36	20.78	Ps-LA’
PI-6	1.01	1.09	LA’	47.63	21.89	Ps-LA’

Table 9: UCLS Classification

Group	Sample	AV (g/100 g)	SL	FB	FR	DG	CBR	Swelling (%)	Classification
FLS	BSB-2	0.68	32.34%	-	-	-	11%	0.20	FLS_{12}
	BSB-4	1.30	30.82%	-	-	-	21%	0.00	FLS_{12}
	GO-1	1.28	30.48%	-	-	-	9%	0.50	FLS_{13}
	GO-2	0.73	20.68%	-	-	-	194%	0.05	FLS_{12}
	PE-1	1.86	23.98%	-	-	-	29%	0.40	FLS_{12}
	PI-1	1.03	20.50%	-	-	-	34%	0.03	FLS_{12}
	PI-2	0.79	8.84%	-	-	-	12%	0.70	FLS_{14}
	PI-3	0.78	9.16%	-	-	-	16%	0.40	FLS_{14}
SLS	BSB-1	0.52	23.49%	36.75%	-	-	37%	0.00	SLS_{6}
	BSB-3	0.60	26.33%	43.71%	-	-	24%	0.22	SLS_{7}
	GO-3	0.64	22.03%	35.39%	-	-	114%	0.40	SLS_{6}
	PB-1	0.36	32.84%	30.99%	-	-	55%	0.02	SLS_{6}
	PB-2	0.50	14.15%	39.38%	-	-	33%	0.08	SLS_{8}
	PI-4	0.43	19.67%	48.60%	-	-	30%	0.87	SLS_{6}
	PI-5	0.41	15.46%	61.43%	-	-	138%	0.11	SLS_{10}
	PI-6	0.51	14.24%	50.07%	-	-	60%	1.03	SLS_{8}
GLS	GO-4	-	-	-	2.20%	1.02%	50%	0.09	GLS_{2}
	GO-5	-	-	-	1.08%	1.06%	52%	0.08	GLS_{2}
	GO-6	-	-	-	1.15%	1.07%	104%	0.19	GLS_{1}
	PB-3	-	-	-	13.75%	1.41%	58%	0.47	GLS_{3}

Although the PE-1 soil contains montmorillonite, its high SiO_2 content, considerable Al_2O_3 content, and the presence of other non-expansive minerals may have limited the montmorillonite's water swelling, resulting in relatively low overall swelling. Furthermore, the loss on ignition value of 14.14% may indicate a significant amount of organic matter or other volatile compounds, which, when present in large quantities, can alter the soil structure and limit swelling rather than enhance it.

In general, the values of retraction/contraction limits were similar for fine and sandy soils, with an average of around 21%. Such numbers are consistent with materials that contain clay minerals of little activity, as is the case of kaolinite in lateritic soils.

Finally, the gravelly lateritic soils showed good CBR values, emphasizing the GO-6 soil, which presented a CBR above 60%. A higher percentage of soil in the sandy fraction can explain these values. In other words, when the amount of sand in the mixture increases, the CBR also increases; this occurs due to the increase in the variety of particle sizes present in the sample, reducing the voids, forcing a more excellent interplay between the grains, which results in the improvement of the bearing capacity of the soil when compacted. Furthermore, the results show that the gravelly lateritic soils did not exhibit degradability or fragmentability. They perform well when subjected to the combined action of climatic or hydrogeological agents and mechanical stresses. The exception is the PB-3 soil, which presented a fragmentability coefficient above 7%. The soil with the highest swelling value was the PB-3 soil, with a value of 0.47%.

It is important to note that all soils exhibited swelling values less than or equal to 1.00%, meeting the expansion criteria for potential use in base layers according to the Universal Classification of Lateritic Soils (UCLS). This reference value is based on limits established by the DNIT Manual (DNIT, 2006) and supported by experimental data from CBR tests and other mechanistic-empirical laboratory analyses. However, the PI-6 soil recorded a swelling value of 1.03%, slightly exceeding the stipulated limit. This minor deviation can be attributed to the inherent variability in CBR test results and should be carefully evaluated in the context of pavement performance requirements.

3.6. Comparison between classification systems

Table 10 shows the classification of soils according to the TRB, MCT, G-MCT, and UCLS methodologies.

Table 10: Comparative Analysis of Classification Methodologies

		Classification			
Group	Sample	TRB	MCT	G-MCT	UCLS
FLS	BSB-2	A-7-6	LG’	Gf-LG’	FLS_{12}
	BSB-4	A-7-6	LG’	Gf-LG’	FLS_{12}
	GO-1	A-7-5	LG’	Gf-LG’	FLS_{13}
	GO-2	A-2-4	LA’	Gf-LA’	FLS_{12}
	PE-1	A-7-6	LG’	Gf-LG’	FLS_{12}
	PI-1	A-4	LA’	Gf-LA’	FLS_{12}
	PI-2	A-2-4	LA’	Gf-LA’	FLS_{14}
	PI-3	A-4	LA’	Gf-LA’	FLS_{14}
SLS	BSB-1	A-2-6	NS’	Ps-NS’	SLS_{6}
	BSB-3	A-2-6	NA’	Ps-NA’	SLS_{7}
	GO-3	A-2-4	LA’	Ps-LA’	SLS_{6}
	PB-1	A-2-4	NA’	Sp-NA’	SLS_{6}
	PB-2	A-2-4	LA’	Sp-LA’	SLS_{8}
	PI-4	A-2-4	LA’	Sp-LA’	SLS_{6}
	PI-5	A-2-4	LA’	Ps-LA’	SLS_{10}
	PI-6	A-2-4	LA’	Ps-LA’	SLS_{8}
GLS	GO-4	A-1-a	LA’	Ps-LA’	GLS_{2}
	GO-5	A-2-6	LA’	Ps-LA’	GLS_{2}
	GO-6	A-2-4	LA’	Ps-LA’	GLS_{1}
	PB-3	A-1-a	LA’	Ps-LA’	GLS_{3}

According to the TRB Classification, soils classified in groups A-1, A-2, and A-3 perform excellently. In turn, soils belonging to groups A-4, A-5, A-6, and A-7 manifest regularly to poor behavior.

When comparing the TRB and UCLS classifications, the most significant differences are observed in the fine and gravelly lateritic soils. For the fine lateritic soils (FLS), the samples are classified into groups A-2 (GO-2 and PI-2), A-4 (PI-1 and PI-3), and A-7 (BSB-2, BSB-4, GO-1, and PE-1). In other words, the TRB classification limits the use of six out of these eight fine lateritic soil samples, particularly in base and subbase layers, due to their high fines content, elevated liquid limits, and significant plasticity. Specifically, samples classified as A-7-5 and A-7-6 (BSB-2, BSB-4, GO-1, and PE-1) contain a high percentage of silt and clay (up to 79%) and exhibit liquid limits exceeding 40% and plasticity indices reaching 19%. Similarly, the A-4 samples (PI-1 and PI-3), despite having lower plasticity, still present a high fine fraction, which could indicate lower strength and stability.

However, the TRB classification, which relies exclusively on granulometric analysis and Atterberg limits, exhibits limitations, particularly when applied to tropical soils. In tropical regions, where lateritic soils are predominant, these parameters do not adequately characterize the soil's mechanical-empirical behavior. Critical factors such as the soil's response to moisture variation, compaction characteristics, and strength under dynamic loading are not encompassed by these classification methods. Consequently, soils that may exhibit favorable performance in tropical environments — particularly those enriched with iron and aluminum oxides, which enhance stability and durability — may be improperly excluded or disregarded.

All lateritic soils identified as sandy in the UCLS were classified into the same TRB methodology group, group A-2. However, these soils exhibit significant differences in some of the properties studied, such as friability, which ranged from 30.99% to 61.43%, and contraction limit, which varied from 14.15% to 32.84%. In the gravelly lateritic soils, the PB-3 sample, despite its high fragmentability, received a better classification in the TRB methodology, belonging to group A-1, compared to the other samples.

When comparing the MCT and G-MCT classifications with the UCLS classification, partial incompatibility is observed, as samples classified in the same group under UCLS were assigned to different groups in MCT and G-MCT. The following observations are noteworthy:

- Some soils showed non-lateritic behavior under the MCT and G-MCT methodology;
- The only lateritic soils classified as lateritic clayey (LG') in the MCT were also fine lateritic soils (FLS) in the UCLS;
- All fine lateritic soils (FLS) of UCLS showed granulometric type Gf (fine granular) in G-MCT;
- All GLS (gravelly lateritic soils) of UCLS presented particle size type Ps (gravel with soil) in G-MCT;
- The only soils that presented particle size type Sp (soil with gravel) are in the UCLS SLS classification (sandy lateritic soils).

Therefore, corroborating Marson (2004), the coefficient c', which correlates mainly with the soil's granulometric behavior, proved to be fundamental and coherent with the other classifications. However, index e', which evaluates the lateritic character, was not adequate and not very sensitive to the soil's genetic characteristics. Furthermore, according to Nogami and Villibor (1995), its mathematical formulation is entirely empirical and depends on d', whose determination, in some cases, is complex.

The morphological, mineralogical, and chemical analysis present in the UCLS classification proved to be important since soils with proven lateritic genesis were located in groups of non-lateritic behavior in the MCT and G-MCT classifications.

The main advantage of the MCT and G-MCT methodology is the material required for classification. In addition, they fundamentally require simple tests: Mini-MCV, mass loss by immersion, and granulometry in the case of G-MCT. However, the subjective and complex analysis of the results can compromise the reliable identification of soils.

UCLS, in turn, even though it requires a greater number of tests and materials for the final classification of lateritic soils, directly considers the soils' genetic, physical, and chemical properties, as well as the appropriate conceptions of the humid tropical environment.

Meanwhile, the TRB classification makes it impossible to use these materials because it is a more suitable methodology for temperate climate soils, which form under conditions different from those observed in tropical regions.

In summary, as expected, it is evident that there is no direct correspondence between the systems (Villibor and Nogami, 2009; Rodrigues et al., 2010; Guimarães et al., 2018; Silva, 2019). It can be stated that the methodologies exhibit partial incongruity with each other. The incompatibilities observed in this research can be justified by the fact that the methodologies were developed in different contexts and under entirely different physical environment conditions. In other words, due to these incompatibilities, there is a risk of discarding suitable materials or selecting materials with properties that do not meet expectations (Silva, 2019).

Understanding the chemical composition of soil is essential for explaining its behavior, as particle size distribution alone is often insufficient to fully characterize the material's properties. This is particularly true for soils with a high clay content, where chemical properties play a critical role in determining their behavior. While these soils typically exhibit characteristics such as cohesion, compressibility, and low permeability, this is not always the case. In some instances, the presence of pulverized sands or rock particles with excellent grain characteristics can significantly alter the mechanical properties of the soil. These particles may influence the soil's strength, compaction, and response to loading, masking typical clay behavior. As highlighted by Pascoal (2020), a comprehensive understanding of the mineralogical and chemical composition is essential for accurately predicting soil behavior, particularly when conventional mechanical testing does not offer a full representation of the material's properties.

Although the implementation of the UCLS methodology demands a higher investment in terms of technical expertise, laboratory resources, and labor, it significantly enhances the reliability of soil performance predictions. This is particularly important in tropical regions or areas with complex soil compositions where traditional classifications may fail to capture critical soil characteristics. Therefore, the additional cost and effort involved in applying the UCLS system are outweighed by the more accurate and robust data it provides, which can prevent costly engineering failures and improve the efficiency of soil-related decision-making in construction and infrastructure projects.

In this way, the UCLS methodology has demonstrated potential, particularly in the use of lateritic soils in the structural layers of pavements. By considering the unique characteristics of these soils, shaped by the lateralization process, UCLS enables their effective integration into pavement design, enhancing performance and durability.

3.6.1. Final considerations

The general coherence between the classification results and the chemical and mineralogical analyses is enhanced when considering the influence of chemical and mineralogical composition on the physical and mechanical behavior of soils. The UCLS, by integrating these factors more comprehensively, has proven to be a promising methodology for the classification of tropical soils, reflecting the observed chemical and mineralogical characteristics. As final considerations, the following can be highlighted:

- TRB Classification: Although the TRB classification is primarily based on physical properties, such as grain size distribution and Atterberg limits, it still reflects certain chemical and mineralogical characteristics. For example, soils with a high content of clay and silt (fine fractions) tend to be classified as A-7, which is consistent with the presence of clay minerals such as kaolinite;

- MCT and G-MCT classifications: These classifications, which consider the behavior of soils under compaction and immersion, are more sensitive to lateritic characteristics. Despite some discrepancies, the majority of soils were classified as lateritic, aligning with the chemical and mineralogical analyses. The presence of iron and aluminum oxides, which provide greater stability and strength, is reflected in both the MCT and G-MCT classifications;
- UCLS classification: The UCLS methodology, which integrates factors such as texture, grain size distribution, and mineralogy, has proven to be the most aligned with the chemical and mineralogical characteristics of the soils. The UCLS classified the soils into categories that reflect their chemical and mineralogical composition, such as fine, sandy, and gravelly lateritic soils, which is fully consistent with the XRF and XRD analyses;
- Correlation between physical and chemical properties: The correlation between physical properties (such as grain size distribution and Atterberg limits) and chemical properties (such as the presence of iron and aluminum oxides) is evident. Soils with higher contents of iron and aluminum oxides tend to be denser and more resistant, a characteristic that is reflected in the MCT, G-MCT, and UCLS classifications;
- Influence of mineralogy on mechanical behavior: The mineralogy of soils, particularly the presence of kaolinite, hematite, and goethite, directly influences mechanical behavior. Soils with higher concentrations of these minerals exhibit greater cohesion, shear strength, and resilient modulus, which is consistent with the results of the classifications;
- Natural variability of tropical soils: The natural variability of tropical soils, resulting from different degrees of weathering and geological conditions, is reflected in the chemical and mineralogical analyses. This variability is captured by the classifications, particularly the UCLS, which takes into account a broader range of factors;
- Need for further research: While the UCLS shows significant promise, further research is recommended to refine the methodology, particularly in understanding the long-term behavior of tropical soils under varying environmental conditions, such as moisture content and suction effects.

3.7. Resilient Modulus

Table 11 summarizes the values of the minimum, maximum, and average Resilient Modulus (RM) of the soils studied. It also shows the regression parameters "k" and the coefficients of determination (R^2) of the models σ_3 (confining stress), σ_d (stress deviation), and composite (confining stress na and deviation stress).

With the values exposed, it is clear that the analysis of the CBR alone can underestimate the behavior of the soils. The significant variability of CBR values is a pervasive characteristic in lateritic soils, found in the present study and several other studies (Nagaraj and Suresh, 2018; Farias, 2023; Farias et al., 2023; Nagaraju et al., 2023). Based on these results, it is not recommended to adopt the CBR as the sole criterion for evaluating the bearing capacity of these soils. A clear example is the fine soils BSB-2, PI-2, and PI-3, which exhibited low CBR values but demonstrated excellent RM data when considering both natural and compacted soils at Intermediate Proctor Energy. This emphasizes the importance of using a broader set of parameters to assess soil behavior and performance, as CBR alone may not fully reflect the material's suitability for pavement applications.

Table 11: Models and Corresponding Regression Coefficients for the Samples

Group	Sample	CBR	$RM_{Minimum}$ (MPa)	$RM_{Average}$ (MPa)	$RM_{Maximum}$ (MPa)	$RM = k_1.\sigma_3^{k_2}.\sigma_d^{k_3}$			
						k_1	k_2	k_3	R^2
FLS	BSB-2	11%	886	1237	1950	1045.02	0.32	-0.46	0.85
	BSB-4	21%	344	464	579	835.91	0.31	-0.13	0.86
	GO-1	9%	159	330	697	169.75	0.38	-0.74	0.98
	GO-2	194%	361	542	767	1083.33	0.46	-0.26	0.60
	PE-1	29%	299	462	618	412.95	0.25	-0.36	0.85
	PI-1	34%	324	476	687	889.02	0.57	-0.43	0.92
	PI-2	12%	692	932	1228	1550.85	0.39	-0.26	0.89
	PI-3	16%	682	916	1177	1477.72	0.39	-0.27	0.80
SLS	BSB-1	37%	715	1110	1745	3872.04	0.56	-0.13	0.85
	BSB-3	24%	391	690	1060	2221.50	0.51	-0.11	0.71
	GO-3	114%	224	336	472	766.11	0.50	-0.26	0.84
	PB-1	55%	239	372	626	493.31	0.43	-0.41	0.57
	PB-2	33%	319	451	649	933.23	0.51	-0.32	0.94
	PI-4	30%	283	376	532	699.01	0.46	-0.30	0.86
	PI-5	138%	589	827	1177	1579.72	0.43	-0.25	0.74
	PI-6	60%	488	574	706	812.97	0.30	-0.22	0.95
GLS	GO-4	50%	383	522	713	947.12	0.42	-0.25	0.81
	GO-5	52%	319	550	834	1923.02	0.58	-0.15	0.97
	GO-6	104%	237	344	513	1028.77	0.54	-0.19	0.92
	PB-3	58%	536	760	1329	771.13	0.41	-0.50	0.81

Considering the UCLS, all soils could be used as base layers when $N \geq 10^6$. However, considering $N \geq 10^7$, only 75% of the soils could compose a pavement structure as a base layer (the exceptions are GO-1, GO-3, PB-1, PI-4, and GO-6 soils).

However, the UCLS is not limited to RM. The PI-2 soil, for example, was classified as FLS_{14} mainly due to its low SL value (8.84%). The GO-3 and PI-4 soils, in turn, were classified as SLS_6 (the best classification of sandy soils) but presented the lowest RM values. The same happened with the GO-6 soil, classified as GLS_1, which, even though it was the best classified among the boulders, presented the lowest RM values, either through particle size or chemical stabilization.

Thus, the joint analysis of all the parameters and indexes provided for in the Universal Classification of Lateritic Soils, as well as the empirical-mechanistic evaluation, is fundamental for predicting the performance of lateritic soils in different applications in pavement layers under real traffic conditions.

4. CONCLUSIONS

The research conducts a comparative study of different methods for classifying tropical soils for paving purposes. Twenty soils from various Brazilian states were classified according to the TRB, MCT, G-MCT, and UCLS methodologies. The study provides a deeper understanding of the advantages and limitations of each method in the context of tropical soils. This analysis is crucial, as traditional methodologies are often inadequate for reflecting the specific geotechnical conditions of tropical soils, such as laterization and variations in chemical and physical properties. Therefore, the research significantly contributes to improving the selection and use of materials for road paving, promoting plausible solutions tailored to the environmental conditions of tropical and subtropical regions.

There is no direct correspondence between the classification systems evaluated, mainly due to the incompatibilities justified by the fact that the methodologies were developed in different contexts and considered completely different conditions of the physical environment.

The TRB system has been criticized in geotechnical and road circles because it is based only on soil physical properties and is a more suitable methodology for temperate soils.

The MCT and G-MCT classifications and the UCLS are partially incompatible since some samples classified in the same group in the UCLS were classified in distinct groups in the MCT and G-MCT.

UCLS has shown potential, as it adequately considers the characteristics of the tropical environment, the laterization process, and the properties inherent to the chemical compositions of lateritic soils.

The exclusive reliance on CBR analysis may lead to an underestimation of soil behavior, as some soils may exhibit low CBR values while achieving excellent RM results. Therefore, a comprehensive assessment that includes all relevant parameters and indexes, along with an empirical-mechanistic evaluation, is crucial for accurately predicting the performance of lateritic soils in various pavement layer applications.

Although permanent deformation tests were not conducted in this study, their inclusion in future research is highly recommended. These tests would offer valuable information on the long-term behavior of these soils under repeated loading, thereby improving the understanding of their suitability for use in pavement structures. It would also be valuable to investigate the influence of moisture content and suction on the mechanistic parameters of lateritic soils, as these factors significantly affect the performance of these materials under tropical and subtropical conditions.

The use of tropical soils in highway construction requires a more comprehensive view than that specified by traditional standards, which have been established based on studies of cold and temperate climate soils. Thus, specific knowledge of the possibilities and limitations of materials in tropical and subtropical climate regions can help solve problems and choose the most economical solutions for constructing road infrastructures.

AUTHORS' CONTRIBUTIONS

MLAF: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; JKGR: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Resources, Supervision, Validation, Visualization, Writing – review & editing; ALFM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; JDP: Funding acquisition, Resources, Visualization, Writing – review & editing; AMGDM: Funding acquisition, Resources, Visualization, Writing – review & editing; LRG: Investigation, Visualization, Writing – review & editing; HAOA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft.

CONFLICTS OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED

This work was prepared with the assistance of Generative Artificial Intelligence (GenAI) ChatGPT with the aim of to assist in translation and improve the quality of the text. The entire process of using this tool was supervised, reviewed and when necessary edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

ACKNOWLEDGEMENTS

The authors thank the Pavement and Geotechnical Engineering Laboratory (LEP) of the Federal University of Campina Grande (UFCG) and the Coordination for the Improvement of Higher Education Personnel (CAPES) for funding the scholarship.

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