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ORIGINAL PAPER

Variability of chemical, mineralogical, and morphological attributes of five soils of the Guabirotuba formation

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Abstract

Problematic soils, such as expansive clay-rich soils, need geological and geotechnical assessments before commencing any construction project. The mineralogical composition of the soil plays a crucial role in determining its physical and chemical behavior, ultimately affecting its stability and susceptibility to erosion. This study analyzed the variability of chemical, mineralogical, and morphological attributes of five soils of the Guabirotuba formation. Samples in different areas of Curitiba and the metropolitan region were collected. Chemical composition by X-ray fluorescence spectrometry (XRF), mineralogical composition by X-ray diffraction (XRD), and microstructure by scanning electron microscopy (SEM) were determined. The results showed that the five soils have a similar chemical composition, with silicon dioxide and aluminum oxide being the main constituents. The mineralogical composition varied in all analyzed soils. However, they belong to the same geological formation, and certain conditions, such as weathering, pressure, cation exchange, and climate, may differ in their mineralogy. Four of the five soils analyzed showed low expansion capacity due to kaolinite, characterized by low swelling potential and water adsorption capacity. On the other hand, one of the soils presented expansive potential because it did not have the presence of kaolinite in its mineralogical composition. Finally, the variability of soil characteristics changes from one place to another. Although they have similar chemical compositions, the cation exchange and mineralogical composition contribute to the development of several behaviors that can be useful for decision-making about the destination of said soil.

Keywords Soil · Chemical compositions · X-ray diffraction · Mineralogical composition · Scanning electron microscopy · Expansive soils · Microstructure

Introduction

Soil is a product of the interaction of factors such as material, climate, weathering, relief, organisms, and time, in addition to pedogenetic processes such as removal, transformation, and transport that produce the variability of the chemical and physical properties of soils (Ma et al. 2019). The mineralogical constitution of the soil is decisive in its physical and chemical behavior, influencing the cation exchange capacity, soil porosity, structure, aggregate stability, and susceptibility to erosion (Oliveira Junior et al. 2011; Al-Mahbashi 2023).

A fundamental characteristic of soil is its variation with depth, which results in the development of horizons, each with distinct properties. These horizons can differ regarding organic matter content, color, structure, texture, pH, saturation, cation exchange capacity, density, water-holding

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capacity, and other soil physical and chemical properties (Warrick 2001).

Problem soils, often rich in clay and known for their expansive nature, require geological and geotechnical assessment before commencing construction. These expansive soils comprise highly plastic clay, often containing active minerals like smectite. Smectite has a strong affinity for water absorption, leading to soil expansión (Hakami and Seif 2019).

Due to their significant volume changes, expansive soils are classified as hazardous for lightweight structures in climate variation zones worldwide (Al-Mahbashi 2023). These problematic soils are widespread, especially in tropical and subtropical climatic regions, including Brazil. In these regions, minerals such as kaolinite, gibbsite, hematite, goethite, and smectite have been reported (Pessoa and Libardi 2022).

The adverse effects caused in buildings by expansive soils are a phenomenon that involves the interaction and integration of various factors, including clay materials, clay minerals, soil texture, organic matter content, water content, and chemical composition (Acikel et al. 2018; Hakami and Seif 2019). The Guabirotuba geological formation constitutes the primary stratigraphic unit within the Curitiba Sedimentary Basin. This formation is characterized by a diverse range of deposits, including sandy, clayey, and conglomeratic materials, which contribute to the varied composition of the soils found in this region. The primary lithology of the Guabirotuba formation consists of claystone, typically found in shades of red, greenish-gray, or whitish colors. These claystones exhibit a predominantly massive structure with fine granulation and sparse sand grains distributed throughout. Owing to these attributes, soils originating from this formation are recognized for their expansive and retractive tendencies, rendering them exceptionally susceptible to mass movements (De Lima et al. 2013).

In this regard, soil is a complex and variable material. Despite its similar physical characteristics, its behavior can differ significantly due to its composition and seasonal variability. Hence, chemical, mineralogical, and morphological analysis is pivotal in comprehending and interpreting soils' diverse geotechnical behaviors (Al-Mahbashi 2023). Moreover, it aids in identifying potential treatments for various field applications.

Regarding the Guabirotuba formation soils, few studies correlate their chemical, mineralogical, and morphological properties. This study aims to analyze the variability of these attributes in five types of soils belonging to the same geological formation in southern Brazil. This study provides valuable insights that can enhance the geotechnical understanding of soils in the Guabirotuba formation and enable the prediction of tailored treatment techniques for each soil type in civil engineering projects. The findings of this research highlight the importance of understanding the mineralogical and chemical composition of the soil before undertaking any construction. Many regions in the world share the presence of problematic soils, such as the expansive clays described in this research. This highlights the universality of the challenges and the need for global strategies to address the prevalence of soil improvement techniques in civil engineering projects.

Materials and method

Materials

Five soils of the Guabirotuba formation in Paraná-Brazil were analyzed chemically, mineralogically, and morphologically. The soil samples were collected in Curitiba, São José dos Pinhais, and Fazenda Rio Grande municipalities.

Figure 1 shows the geological map of the Guabirotuba formation and the location of the collection points of the five soils analyzed in this research.

Figure 2 shows the five soil samples in their natural state studied in this research. The yellow soil sample was collected on a slope at a depth of 2 to 4 m and, in its natural state, presented a hygroscopic moisture of 34.25%. The gray soil sample was collected at a depth of approximately 5 m and presented a hygroscopic moisture of 33.25%. The pink soil sample was collected at a depth between 2 and 4 m, with hygroscopic moisture of 29.65%. The green soil sample was extracted at a depth between 14 and 18 m and presented a hygroscopic moisture of 28.36%. Finally, the red soil samples showed hygroscopic moisture of 32.25% and were collected at a depth of approximately 2 m.

The colorations of the soils extracted from different zones of the Guabirotuba geological formation coincide with that described by Massad et al. (1981), who mentions that the lithofacial group of the Guabirotuba formation presents more usual colorations, such as gray, with greenish or bluish shades, and brown.

The soils' specific gravity (SG) was determined according to ASTM D-854 (ASTM 2007). The SG of the five soils ranged from 2.62 to 2.77 (see Table 1), possibly due to differences in chemical, mineralogical, porosity, and cementation associated with the different analyzed soils (Saqib et al. 2016).

Lateritic soils are present throughout nearly the entire Brazilian territory. In the state of Paraná, the prevailing distribution of lateritic soils comprises clays, Cambisols, Latosols, Neosols, Nitosols, Gleissolos, and Spodossols. Based on the specific collection points, these soils are categorized

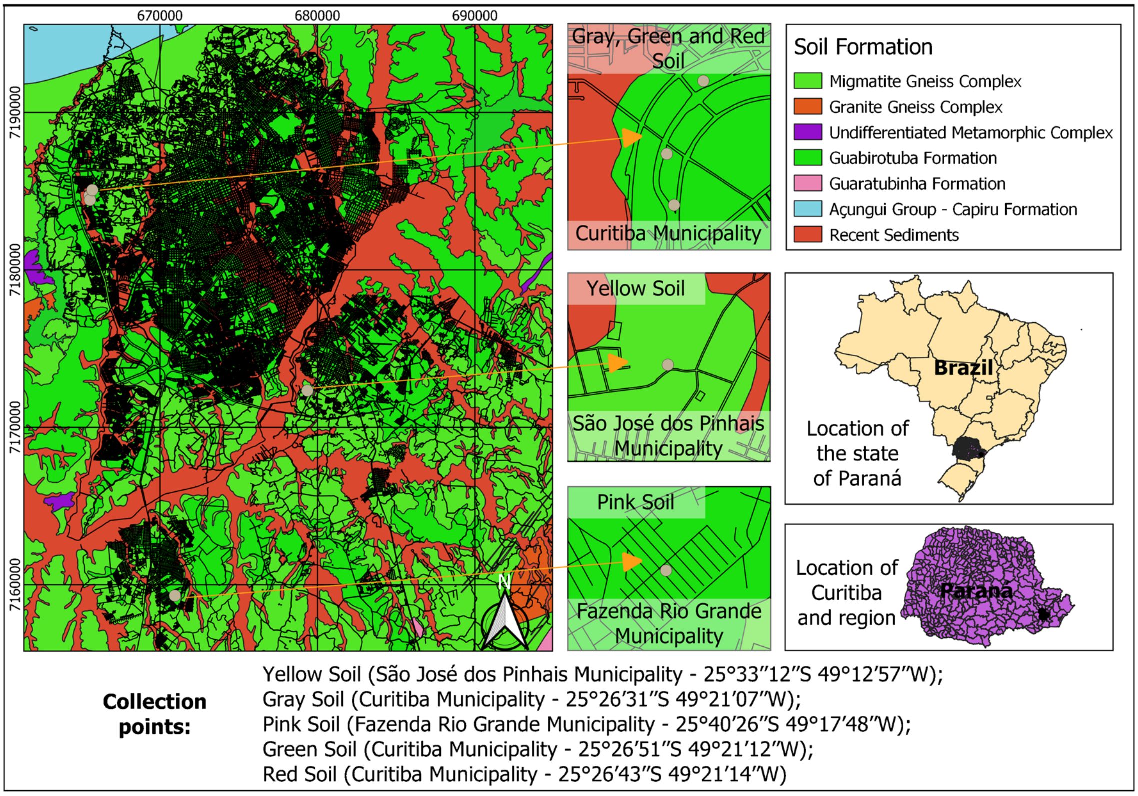

Fig. 1 Localization of the collection points of the five soils analyzed

Fig. 2 Soils of the Guabirotuba formation analyzed in this research

as a combination of Cambisols and Latosols, as Santos et al. (2018) described.

Table 1 Specific gravity of soils

Soil	SG
Yellow soil	2.62
Gray soil	2.77
Pink soil	2.68
Green soil	2.73
Red soil	2.67

Method

The collected samples were covered with plastic film. Subsequently, they were transported to the laboratory to determine their initial moisture content, following the guidelines outlined in ASTM D2216 (2019). Each soil sample was then dried in an oven at (100 ± 5) °C until it achieved a consistent weight. Each soil sample was crushed and sifted through a No. 100 sieve (0.150 mm).

The chemical compositions of the five soils were determined using X-ray fluorescence spectrometry (XRF) with the EDX-720/800HS spectrometer in the materials characterization laboratory of the Academic Department of Civil Construction at UTFPR. XRF is a technique that combines qualitative and quantitative analysis, utilizing the fundamental parameters method based on dispersive energy. The detection system consists of a Si (Li) drift detector. XRF analysis was performed under vacuum, with a measurement range from ^{11}Na to ^{92}U. Finally, the samples were excited with a rhodium tube and an electrical voltage of 50 kV and 100 Ma.

The X-ray diffractometry (XRD) assay is a semi-quantitative technique for characterizing the crystalline structures of a material. This analysis was performed with an X-ray diffractometer (Shimadzu, model XRD-7000) at the Multiuser Center for Materials Characterization (CMCM) at UTFPR.

Scanning electron microscopy (SEM) was used to visualize the morphology of the five soils studied. Samples were placed on ~12–13 mm head pin stubs with conductive adhesive. Then, the samples were covered with a gold film and analyzed using a Zeiss scanning electron microscope (SEM), model EVO MA 15, with tungsten filament and chamber for samples up to 250 mm in diameter and 500 g of mass, with entire stage movement (XYZ and tilt). In these analyses, the energy dispersion X-ray spectrometer (EDS), X-Max of 20 mm^2, was also used, which allowed the chemical microanalysis of the samples analyzed in the SEM.

Results

The results presented below provide the chemical, mineralogical, and morphological characteristics of five soils of the Guabirotuba formation.

Table 2 Chemical composition of the analyzed soils (% by mass)

Components	Yellow soil	Gray soil	Pink soil	Green soil	Red soil
SiO_2	50.170	65.736	51.716	59.968	48.773
Al_2O_3	41.487	23.333	44.003	25.954	39.256
SO_3	5.339	5.145	2.809	6.397	4.552
K_2O^-	1.038	1.967	0.632	2.485	0.799
MgO	-	2.413	-	-	-
CaO	1.289	0.827	-	4.747	-
Na_2O	-	-	-	-	5.48
TiO_2	0.312	0.348	0.473	0.27	0.817
Fe_2O_3	0.229	0.136	0.070	0.075	0.246
MnO	0.042	-	0.060	-	-

Chemical analysis

Table 2 shows the chemical composition results of the five soils analyzed by the XRF technique. The main constituents for five soils are silicon dioxide (SiO_2) and alumina or alumina oxide (Al_2O_3). These compounds are the most important in the constitution of clays (Eyankware et al. 2021).

Compounds like SiO_2 and Al_2O_3 are fundamental components that, when combined with other materials, contribute to the formation of geopolymers. Geopolymers, in turn, enhance the material's strength and are commonly utilized for various field applications, including as base and sub-base materials for pavements (Rizki Abdila et al. 2020; A. Wassie and Demir 2023). In this way, these soils could undergo evaluation for processes like soil improvement through efficient methods such as geopolymerization, making them suitable for use in civil engineering projects.

Yellow soil presented its main constituents SiO_2 (50.17%), Al_2O_3 (41.487%), and SO_3 (5.339%); the other components did not exceed the sum of 3.0%. Ordoñez Muñoz et al. (2021) studied yellow soil extracted from the São José dos Pinhais region in the state of Paraná. The authors presented the chemical composition of the soil obtained using the same technique as in this study, and they found that the main constituents were SiO_2 and SO_3, with contents of 87.09% and 10.44%, respectively. Studies conducted by Baldovino et al. (2021) on yellow soil belonging to the Guabirotuba formation found percentages of 48.78% and 44.51% for SiO_2 and Al_2O_3, respectively.

de Almeida et al. (2023) studied red soil obtained in civil construction in Curitiba. The authors found that the chemical composition was mainly based on oxygen (59.31%), aluminum (14.96%), and silica (15.31%).

Baldovino et al. (2022b) investigated the improvement of soils in the Guabirotuba formation. The authors collected pink soil from the southern region of the city of Curitiba and gray soil from the southeast region of Curitiba. These soils were collected at a depth between 2 and 3 m. The authors found similar results in the chemical composition of the pink soil, with the main components being SiO_2 (53.12%), Al_2O_3 (24.30%), and Fe_2O_3 (10.46%). While the soils evaluated in this research exhibit similar colorations to those studied by Baldovino et al. (2022b), there are differences in their chemical composition. For instance, the pink soil studied by Baldovino et al. (2022b) contained Al_2O_3, but its content was 19.7% higher than that found in the pink soil studied in this research. As for the gray soil, the authors primarily found SiO_2 (49.82%) and Al_2O_3 (43.40%) in its composition. In this case, the percentages also differed from those found for the gray soil evaluated in this research, with discrepancies of approximately 15.9% and 20% for SiO_2 and Al_2O_3, respectively.

The variability of soil properties may be attributed to complex geological and pedological processes (Castrignanò et al. 2000). In the case of the five soils analyzed in this study, the variation in chemical composition can be explained by the phenomenon of horizonation, as described by Warrick (2001), where each horizon exhibits distinct physical and chemical properties. Barbar and Melo (2008) and Salamuni et al. (1999) noted significant variability in the natural state of soils within the Guabirotuba formation concerning physical, chemical, and mineralogical attributes.

While the soils examined in this research exhibit similar coloration to those previously investigated in the Guabirotuba formation by various authors cited in this study, variations in chemical composition can be attributed to factors such as weathering, geological origin, and the specific depth from which each soil sample was collected. Therefore, studying each soil's unique properties is crucial, considering the region and the depth from which they were collected.

No studies on the chemical composition of green soil were identified in the literature. This absence can be attributed to the challenging collection process, as the samples were obtained from a depth of 14–20 m, requiring specialized equipment for extraction. Nevertheless, it is imperative to emphasize that researching these soils can substantially contribute to studying foundation construction on such soil types.

Researchers who studied various soils worldwide discovered similar chemical compositions to those in this study. For instance, Zhu et al. (2019) assessed the geotechnical properties and microstructure of silt-clay soil from Jilin province in China. The study revealed that the soil was predominantly composed of SiO_2 (67.17%) and Al_2O_3 (14.99%); Mapuna et al. (2023) investigated the mineralogical, geochemical, and physico-mechanical characteristics of lateritic clays from the Mbalmayo zone in Southern Cameroon. Geochemical findings indicate a predominance of SiO_2 (62.34 – 80.73%), followed by Al_2O_3 (9.09 – 19.13%) and Fe_2O_3 (1.82 – 6.26%); Awn and Abbas (2023) investigated the feasibility of treating saline soils collected from three different regions in Diyala province, Iraq, using cement-activated fly ash. XRF analyses revealed that the soils were primarily composed of SiO_2 and Al_2O_3, ranging from 35 to 38.1% and 14.0 to 15.4%, respectively. Finally, Meddah et al. (2023) investigated a high-plasticity clayey soil collected from the Sidi Hadjres region in M'sila, Algeria. The XRF analysis results indicated that the clay soil was primarily composed of SiO_2 (44.81%), Al_2O_3 (12.64%), and Fe_2O_3 (4.35%).

In summary, by relating the chemical composition of a regional soil to other soils globally, it is possible to identify successful soil improvement strategies in similar contexts. This integrated approach is essential for civil engineering, allowing for a more effective and targeted application of soil improvement techniques.

Mineralogical analysis

Mineralogical analysis of the five soils in this study is depicted in Figure 3 and Table 3, obtained using XRD (X-ray diffraction) technique.

Quartz is the mineral found in all five soils analyzed in this research. Other minerals like kaolinite and tridymite are also in yellow, pink, and green soils. The mineral composition analyzed in this study can be summarized as follows.

- Yellow soil is predominantly composed of minerals from the quartz, kaolinite, and corundum groups, which may explain the high levels of SiO_2 (50.17%) and Al_2O_3 (41.487%) in the soil's chemical composition. Other minerals, such as tridymite and moganite, were identified. These minerals are polymorphs of quartz, sharing the same chemical composition but featuring distinct crystalline structures. The characteristics of lateritic soils, typical in tropical zones, may vary depending on their origin and climatic conditions. In cases of intense cation leaching and moderate silica leaching, the formation of kaolinite can occur (Pessoa and Libardi 2022). One significant characteristic of this soil type is its susceptibility to weaknesses induced by defects such as fragility, shattering, and cracking (Basavarajappa and Maruthi 2018). These vulnerabilities can lead to a decrease in the geotechnical quality of the soil, as demonstrated by Baldovino et al. (2022a) and (Muñoz et al. 2023), who discovered low unconfined compressive strength, splitting tensile strength, and reduced shear strength parameters in pure yellow soil
- Gray soil is primarily composed of quartz, mica, montmorillonite, and kalsilite, aligning with the chemical composition in Table 3. Montmorillonite is a clay mineral formed through the weathering of silicate minerals, known for its stability in arid, semi-arid, and temperate climates. Montmorillonite, found in environments rich in magnesium and calcium, exhibits weak cation bind-

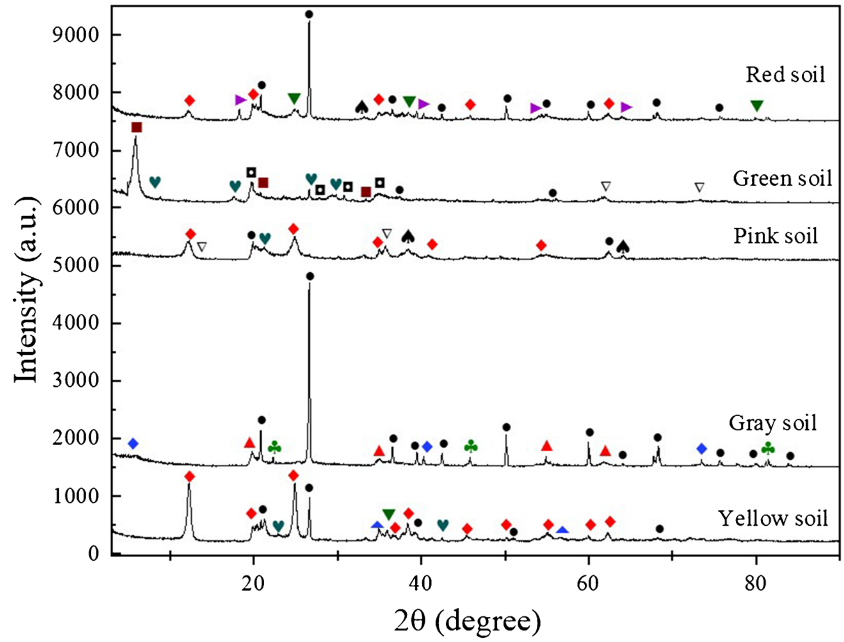

Fig. 3 X-ray diffractogram of five soils analyzed

Table 3 Identification of five soils diffractogram peaks

Ref. code	Mineral	Chemical formula	Symbol
00-001-0527	Kaolinite	$Al_2Si_2O_5(OH)_4$	♦
01-085-0794	Quartz	SiO_2	●
01-085-0419	Tridymite	SiO_2	♥
01-079-2403	Moganite	SiO_2	▲
01-077-2135	Corundum	Al_2O_3	▼
02-0009	Montmorillonite	$Si_{3,74}Al_{2,03}Fe_{0,03}Mg_{0,02}O_{11}$	♦
00-002-0227	Mica	$AlFeH_2KMgO_2Si$	▲
01-083-1220	Kalsilite	$KAlSiO_4$	♣
00-003-0165	Andalusite	Al_2SiO_5	▽
01-089-0596	Hematite	Fe_2O_3	♠
00-046-1475	Grossite	$CaAl_4O_7$	◘
00-040-0198	Perlialite	$K_{2,02}Al_2Si_{4,76}O_{13,53}$	■
00-007-0324	Gibbsite	$Al(OH)_3$	►

ing, often resulting in a high potential for soil swelling and shrinkage (Eyankware et al. 2021). Researchers such as Bossi and Lenzi (1981) and Bortoluzzi et al. (2007) mention minerals such as quartz, calcite, and montmorillonite are commonly found in fine fractions of tropical and subtropical soils in southern Brazil and characterize the soil as expansive.

- Pink soil comprises predominant minerals such as kaolinite, quartz, and hematite. According to Valášková (2015), kaolinite has the property of drying quickly but experiences minimal shrinkage. Furthermore, clay minerals like kaolinite can enhance plasticity and contribute to developing strength, porosity, and other properties, making them suitable for various applications such as brick and tile manufacturing. On the other hand, hematite is a stable structure of iron oxide; its presence in tropical and subtropical soils stands out as an indicator of pedogenic and geochemical environments (Li et al. 2016; Melo et al. 2020). The hematite concentration is directly related to the climate; it is also responsible for the coloration of soil's redness (Li et al. 2016; Singh et al. 2018).

- In green soil, tridymite, grossite, and andalusite are predominant minerals. The chemical formula of these minerals (Table 3) coincides with the chemical composition of the soil (Table 2), where silicon, aluminum, and calcium oxides predominate. Tridymite has the same chemical composition as quartz but a different crystal structure. On the other hand, the presence of andalusite may indicate reworked sediments most likely derived from clayey rocks subjected to contact metamorphism around igneous intrusions. This mineral's presence could indicate the potential of this type of soil for use in the industry related to the manufacture of ceramics (Deer et al. 2013; Tadza et al. 2019).
- Red soil comprises minerals such as quartz, kaolinite, corundum, and gibbsite. The chemical formula of these minerals (Table 3) corresponds to the soil's chemical composition, which consists mainly of silicon, aluminum, and iron oxides. Kaolinite, an important clay mineral, can be found at different depths, with its presence increasing as the level of weathering intensifies (Rahardjo et al. 2004). The weathering of rocks in tropical regions is quite intense, marked by the rapid decomposition of feldspars and ferromagnesian minerals, by the transport of silica and alkaline ions (Na_2O, K_2O, MgO), and by the absorption of iron and aluminum oxides (Gidigasu 1972). Lateritic soils are generally highly weathered reddish tropical soils with high iron and aluminum oxide concentrations and kaolinite, the predominant clay mineral (Latifi et al. 2015). Gibbsite is a mineral that favors the preservation of micro-aggregates, especially in well-drained soils (Schaefer 2001). Also, gibbsite is one of the mineral forms of aluminum hydroxide, formed through chemical weathering on rocks rich in feldspar and other aluminous minerals in hot and humid climates (Liu et al. 2014).

In contrast, minerals such as quartz, smectite, kaolinite, and illite exhibit expansiveness, as noted by Dafalla and Al-Shamrani (2014). Iwamoto and Sudo (1965) and Onyelowe et al. (2021) state that the three key minerals influencing pozzolanic activity, plasticity, and the expansive nature of clay soil are kaolinite, illite, and montmorillonite. Mapuna et al. (2023) analyzed the mineralogical composition of lateritic clays from southern Cameroon using XRD techniques. The study identified dominant minerals, including quartz and kaolinite, consistent with findings in this research, along with trace amounts of goethite, anatase, and gibbsite. Al-Mahbashi (2023) conducted studies on the mineralogy of soils in Saudi Arabia and found minerals similar to those identified in the present study, including quartz, kaolinite, and montmorillonite. The authors mention that applying this type of soil in the field can only be considered under treatments of chemical improvement, soil replacement, and special foundations.

On the other hand, minerals such as gibbsite in a construction area are considered hazardous in the presence of water. They can cause damage to pavements, especially when the groundwater level is shallow (Imam and Saffari 2023). However, there is evidence of failure and adverse effects on structures, such as highways, dams, and other civil construction projects, that were built on soils containing gibbsite (Solis and Zhang 2008; Yilmaz and Civelekoglu 2009; Wei et al. 2020).

Thus, considering the mineralogical composition of soils becomes crucial, primarily when they are intended for use in engineering projects. Chemical and mineralogical composition plays an important role in making decisions about stabilizing any soil; even though they are from the same geological formation, they have different mineralogical components.

Therefore, for the geotechnical treatment of this type of soil, it is recommended to apply physical, chemical, and mechanical techniques or a combination of the three to guarantee the mechanical strength and stability of the soil. Granulometric modification, achieved by adding materials like fibers, construction waste, and chemical agents such as cement or lime, coupled with mechanical stabilization, presents a viable approach for preparing soil for the base or sub-base in pavements or road embankment construction.

Previous studies on yellow soil extracted from the Guabirotuba geological formation used a combination of physical, chemical, and mechanical techniques for its geotechnical improvement (Baldovino et al. 2018; Ordoñez Muñoz et al. 2021; Muñoz et al. 2023). The authors proved that the properties of these soils, even under mechanical compaction, did not meet the necessary conditions to be used in applications such as slope stability or as a base and sub-base of pavements.

de Almeida et al. (2023) studied a red soil belonging to the Guabirotuba formation; the authors recommend including materials such as silica, lime, and fibers that allow the stabilization and reinforcement of the red soil matrix, which will increase the resistance to stiffness and reduce the potential for expansion.

Baldovino et al. (2022b) mentioned that adding roof tile waste to the pink soil of the Guabirotuba formation increases the parameters of unconfined compressive strength and splitting tensile strength. Nevertheless, the authors observed that the strength did not increase further with an elevated content of ground tile. This observation can be attributed to quartz and sericite in the ground tile, minerals found within the dispersed tissue, and the absence of pozzolanic materials.

Complications in construction activities are often associated with clay soils. Nevertheless, it is possible to enhance the behavior of these soils by incorporating small amounts of cementitious materials. Since clay soils exhibit diverse mineralogical compositions, some may be more susceptible to stabilization than others.

To explore this question, Bell (1994) evaluated three main components found in clays: kaolinite, montmorillonite, and quartz, stabilized with cement, lime, and fly ash. The inclusion of cement and fly ash resulted in a significant increase in the unconfined compressive strength and elasticity modulus of the three minerals. The most substantial enhancements were noted when cement and fly ash were introduced to quartz. For example, the unconfined compressive strength of quartz increased approximately 17-fold when cement and fly ash were incorporated in a 9:1 ratio. In contrast, there was a sevenfold increase in the strength of montmorillonite and an approximately 350% increase in the strength of kaolinite for the same proportion of cement and fly ash.

On the other hand, both quartz and kaolinite showed greater strength when pure cement was added, a phenomenon that did not occur with montmorillonite. Additionally, the elasticity modulus of montmorillonite was lower with the addition of cement compared to the inclusion of lime and fly ash. The authors attributed this phenomenon to the affinity of montmorillonite for lime; when adding cement to montmorillonite, the pH tends to decrease. Consequently, the cementitious products formed during the curing process of the mixtures of montmorillonite and cement have lower degrees of crystallinity compared to those formed in the presence of lime.

The above underscores the importance of mineralogical studies, given that minerals like kaolinite and quartz exhibit better reactions to the addition of cement. In contrast, montmorillonite can be stabilized with lime-based materials, enabling the development of pozzolanic reactions. Consequently, there is an increase in soil agglomeration, a decrease in plasticity, and an increase in mechanical strength.

In summary, although a soil's mineral characteristics are specific to a region, the fundamental principles of soil mineralogy have universal application. The general principles governing how minerals influence soil improvement and stabilization can be extended to different soil types worldwide. Therefore, comprehending local peculiarities contributes to building knowledge that can be extrapolated and applied in broader contexts.

Microstructural analysis

The micrographs of five soils, captured through scanning electron microscopy (SEM) at magnifications of 500× and 5.00 KX, are depicted in Fig. 4.

The EDS analyses of microanalysis points (1, 2, 3…15) are shown in Table 4.

Where: 1, 2, 3 …15 are the EDS points positions.

Qualitatively, the granular structure of the yellow soil consists of grains of various fractions, including particles with enlarged shapes, some angular and blocky, and others with a rhombic form (Fig. 4a). Figure 4b depicts soil grains with well-defined edges, showcasing the aggregation of smaller particles with larger ones. The EDS analyses (Table 4) revealed the presence of oxygen and silicon, indicative of silicate minerals, which align with the results obtained from the XRD analyses, where quartz predominates.

In their study, Arrieta-Baldovino et al. (2023) described the structure of yellow soil particles from the Guabirotuba formation as having angular and sub-angular shapes based on SEM assays. Ordoñez Muñoz et al. (2021) analyzed compacted soil samples under standard effort. The authors observed variations in the shapes of the soil grains, and they noted that the compaction process was not very efficient due to the presence of a large number of voids within the matrix of the compacted yellow soil. Furthermore, most of the microanalysis points revealed the presence of elements such as oxygen and silicon.

The grains of gray soil (Fig. 4c, d) exhibited an agglomerated distribution, potentially featuring adhered clay minerals. Additionally, macro and micro-pores were present, formed through the contact of clay mineral plates arranged in various directions. The EDS analysis of microanalysis points 4, 5, and 6 (Table 4) reveals that the primary elements detected are oxygen, aluminum, and silicon, which align with the mineralogical composition observed in the XRD analysis of gray soil.

Shi et al. (2002) studied gray clay soil in southern China, where a tropical climate prevails. The authors identified similarities with the observations made in this study, noting agglomerated grains and clay plates oriented both vertically and horizontally through SEM assays. These characteristics may indicate low permeability and increased cohesion between the grains, resulting in reduced shrinkage and a higher swelling rate. In addition, the authors point out that properties such as the chemical composition of the soil and the microstructure are essential factors that influence the engineering properties of the soil.

The granular structure of pink soil (Fig. 4e, f) is characterized by numerous grains of varying shapes, with the agglomeration of clay minerals adhered to the walls of larger particles. At a magnification of 5.00 KX (Fig. 4f), one can discern the presence of pores within the soil structure and the clustering of small particles with indistinct edges.

The results of the EDS analyses (Table 4) primarily show the presence of oxygen, silicon, carbon, and aluminum. These findings are consistent with the chemical

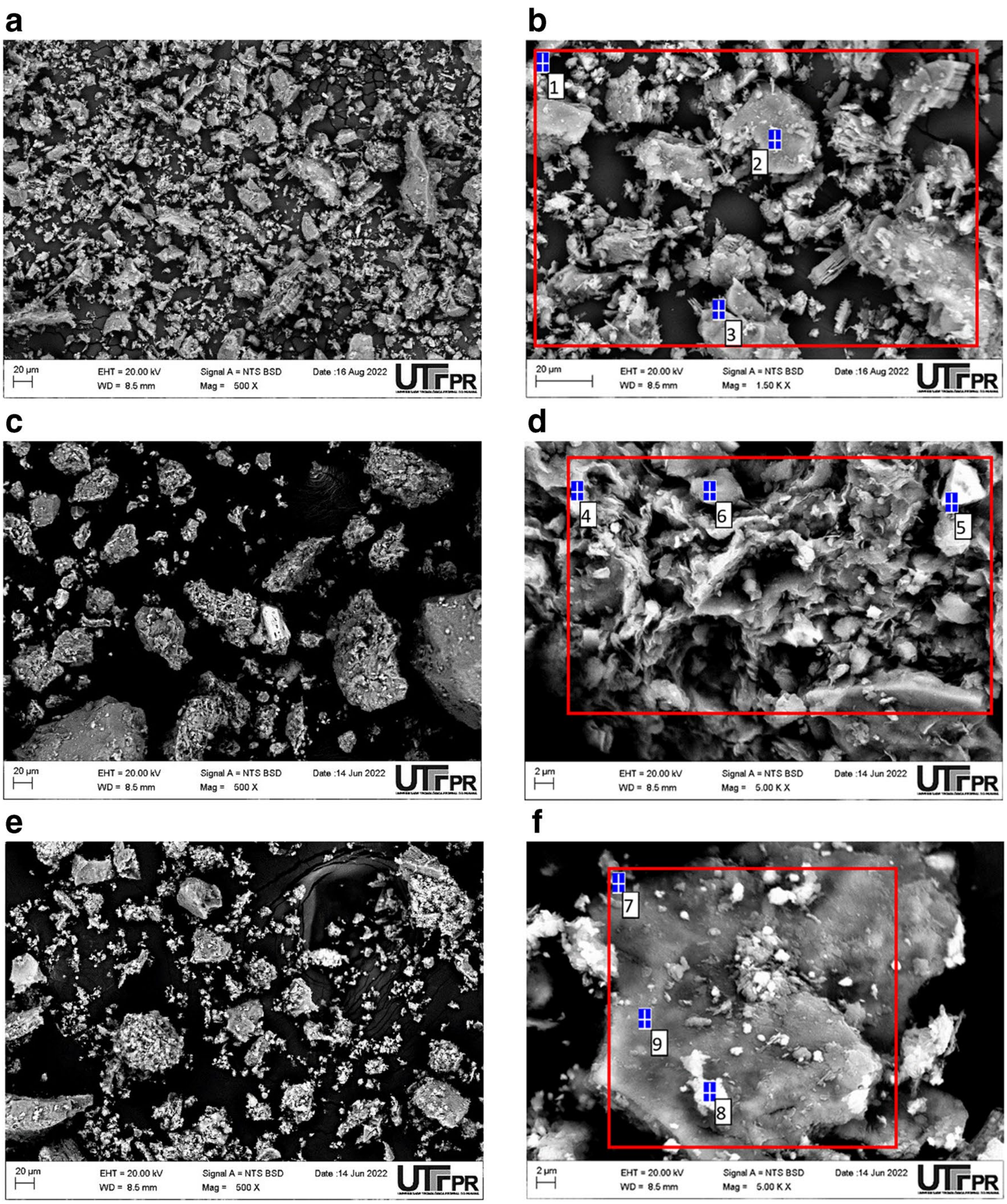

Fig. 4 Micrographs of: yellow soil a 500 × b 5.00 Kx; gray soil c 500 × d 5.00 KX; pink soil e 500 × f 5.00 KX; green soil g 500 × h 5.00 KX; and red soil h 500 × i 5.00 KX

and mineralogical analyses of the soil, where silicon and aluminum oxides are predominant.

The presence of carbon may be due to carbonates and nitrates that, according to Svisero and Atencio (1993), are found in pink deposits of the soils of the Guabirotuba formation. On the other hand, the presence of carbon may be attributed to the organic matter within the soil. This aspect can pose significant challenges, particularly in geotechnical engineering when designing structures on such soil types, known for their inherent instability and low mechanical strength.

Green soil consists of grains of various fractions with somewhat indistinct edges (Fig. 4g). In Fig. 4h, the green soil exhibits the presence of agglomerated clay minerals within the larger particles, resulting in a smooth and porous structure. This characteristic can be attributed to the depth

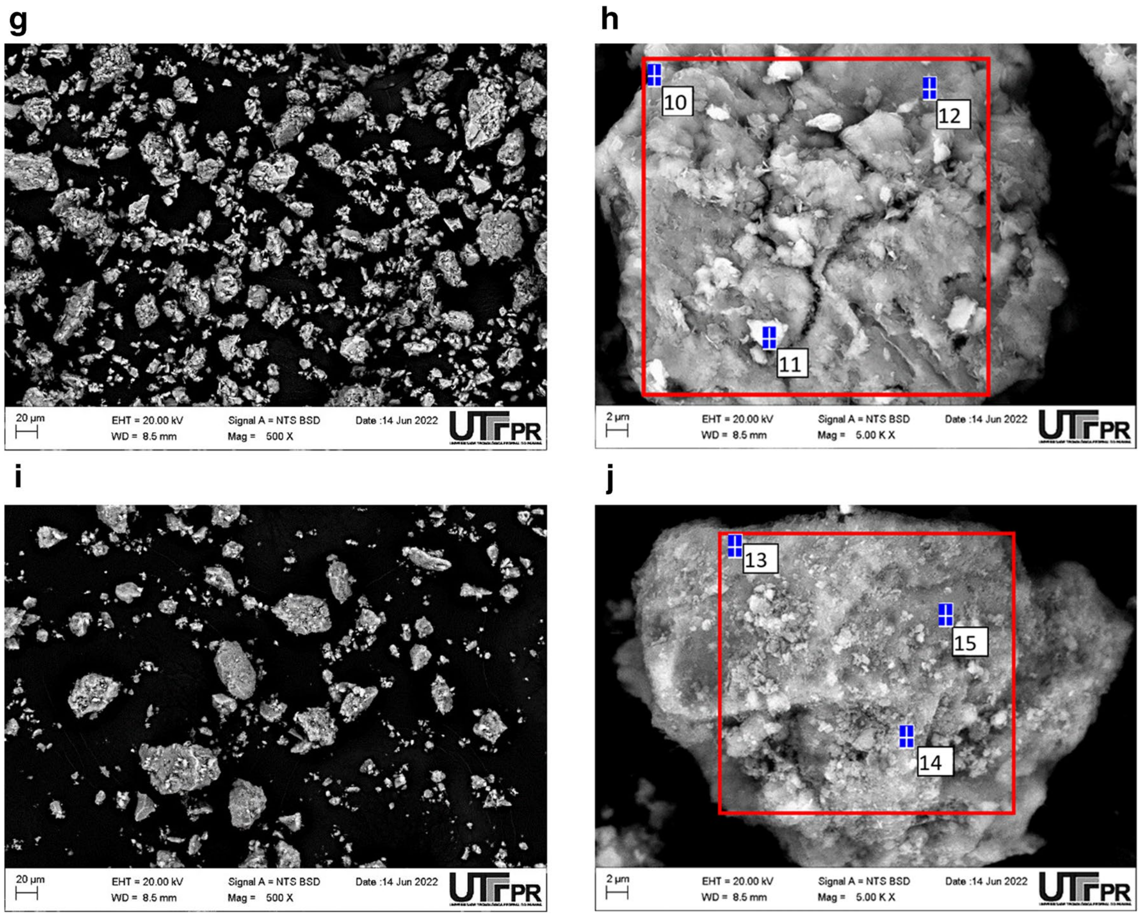

Fig. 4 (continued)

Table 4 EDS results of yellow, gray, pink, green, and red soils (all results in %)

Spectrum	C	O	Al	Si	Ti	Fe	Mg	K	Ca	Mn
1	3.25	60.71	1.25	34.02	0.48	0.29	-	-	-	-
2	7.22	64.86	13.20	13.69	-	1.04	-	-	-	-
3	7.10	59.49	0.16	33.25	-	-	-	-	-	-
4	-	61.57	8.63	23.17		3.71	0.86	0.69	0.41	-
5	3.87	48.72	0.76	0.88	24.60	20.87	-	-	-	0.3
6	-	65.13	10.01	18.71	1.11	-	1.18	0.69	0.38	
7	16.57	56.72	11.98	12.17	0.37	2.19	-	-	-	-
8	17.69	61.43	9.58	9.55	0.09	1.66	-	-	-	-
9	17.44	53.89	12.54	12.90	0.23	3.00	--	-	-	-
10	12.26	53.92	6.59	20.31	0.14	3.59	2.01	-	1.18	-
11	10.28	63.69	5.26	18.32	0.08	1.29	0.25	-	0.83	-
12	14.25	55.26	9.13	16.24	0.62	2.1	1.25	-	1.15	-
13	-	58.36	5.42	32.91	0.39	2.92	-	-	-	-
14	-	60.99	2.23	35.29	-	1.49	-	-	-	-
15	-	59.14	4.48	34.72	0.25	1.41	-	-	-	-

at which it was excavated (14–16 m), where weathering impacts are less prominent (Rahardjo et al. 2004).

The EDS analyses at points 10, 11, and 12 revealed the presence of chemical elements such as oxygen, silica, carbon, and aluminum. These findings are consistent with the soil's chemical composition and the XRD analyses' results.

According to Okewale (2020), elements such as silica and aluminum may indicate the presence of clay minerals like quartz and feldspar in tropical soils. On the other hand, Schaefer et al. (2004) mention that relatively high levels of carbon, silicon, and aluminum and low levels of iron are associated with wetter tropical climates, such as the one in Curitiba.

Micrographs of red soil (Fig. 4i, j) reveal that the soil consists of grains of various fractions and sizes, with possible clay minerals adhering to them. In Fig. 4j, one can observe the presence of pores and the clustering of small whitish-gray fractions on the surface of the analyzed particle.

Latifi et al. (2016) studied red tropical lateritic soil from Malaysia. The authors observed a dispersed and discontinuous structure in the SEM analyses, where voids and porosity were more prominent due to the absence of hydration products. The authors also point out that tropical regions with intense rainfall and high temperatures have favorable conditions for developing layers of lateritic soils with reddish coloration. This soil category is distinguished by the abundant presence of aluminum, iron, and kaolinite clays (Townsend 1985). Iron oxides give rise to the reddish coloration of lateritic soils, a color range extending from lighter shades to brown, as Syafalni et al. (2012) noted.

The EDS analyses of points 13, 14, and 15 (Table 4) revealed the presence of oxygen, silicon, aluminum, and iron, some of which constitute mineral aggregates that align with those found in the X-ray diffraction analysis, including quartz, hematite, kaolinite, and montmorillonite. These results coincide with the findings by de Almeida et al. (2023), who performed EDX analyses in the red soil of the Guabirotuba formation, finding the presence of oxygen and silica that form part of quartz and kaolinite.

Table 5 presents the results of the chemical and mineralogical composition of different soils analyzed in the literature using the XRD X-ray diffraction technique.

Quartz is one of the most abundant minerals in all the soils analyzed, as indicated in Table 5. Generally, quartz is formed due to rock weathering, and its exceptional chemical resistance makes it a valuable raw material in various industrial applications. Quartz and calcite constitute many quartz and sandstone rocks worldwide (Jovanovski et al. 2022).

de Freitas et al. (2022) studied soil in the metropolitan region of Curitiba, finding kaolinitic material in the

Table 5 Comparison of the chemical and mineralogical composition of soils reported in the literature with those analyzed in this research

Author	Country	Chemical composition *	Minerals
Nweke et al. (2015)	Nigeria—Ebonyi State. Abakaliki formation	Al_2O_3, SiO_2, Fe_2O_3, MgO, K_2O, MnO, Na_2O, CaO, TiO_2	Montmorillonite, kaolinite, biotite, illite, and calcite.
Hakami and Seif (2019)	Saudi Arabia	-	Montmorillonite, illite, kaolinite, chlorite, and palygorskite.
Adeola and Olaleye (2017)	Sedimentary Basin of Southwest Nigeria	SiO_2, Al_2O_3, Fe_2O_3	Hematite, quartz, and anatase.
de Freitas et al. (2022)	Brazil—Metropolitan Region of Curitiba	-	Quartz, gibbsite, and mica.
Tadza et al. (2019)	Malaysia	-	Andalusite, quartz, kyanite, and mullite.
Oba et al. (2022)	Congo—Brazzaville	SiO_2, Al_2O_3, K_2O	Kaolinite, illite, quartz, anatase, hematite, and magnesite.
Mendonça et al. (2021)	Brazil—State of Paraíba	-	Quartz, feldspar, gibbsite, kaolinite, illite, smectite
Present research			
Yellow soil	Paraná—Brazil—Guabirotuba formation	SiO_2, Al_2O_3, SO_3	Kaolinite, quartz, tridymite, moganite, and corundum
Gray soil		SiO_2, Al_2O_3, SO_3	Montmorillonite, quartz, mica, and kalsilite.
Pink soil		SiO_2, Al_2O_3	Kaolinite, quartz, andalusite, tridymite, and hematite
Gray soil		SiO_2, Al_2O_3, SO_3	Grossite, perlialite, quartz, andalusite, and tridymite.
Red soil		SiO_2, Al_2O_3, Na_2O	Kaolinite, quartz, corundum, gibbsite, and hematite

Where: * Corresponds to the main chemical compounds of the analyzed soils, those present in percentages from 5 to 100%

upper Iguaçu sub-basin. The authors found that kaolinite results from chemical weathering processes of the crystalline basement rocks, including granites, gneisses, and migmatites. However, it is plausible that some of these formations might have originated in the Serra do Mar of the Paraná region and subsequently been transported due to geomorphological landscape processes.

The mechanical properties of most soils depend on the mineral type and content, interactions between mineral particles, water in the pores, and sedimentary and consolidation history.

On the other hand, the chemical composition of pore water and the type of cations also exert significant control over the swelling of expansive minerals. For instance, sodium and lithium can induce swelling within mineral layers as long as water is present, low confinement pressure, and minimal electrolyte concentration (Wagner 2013). On the other hand, iron oxides in soils primarily exist as goethite and hematite, playing a significant role in determining soil color, aggregation, and adsorption properties.

According to Karpiński and Szkodo (2015), among the primary groups of clay minerals, kaolinite consists of sheets composed of two layers of silica and two of gibbsite. This clay mineral is known for its high stability, low expansion potential, relatively small surface area, and low adsorption capacity.

On the other hand, smectites, consisting of sheets composed of two layers of silica and a central layer of gibbsite, tend to swell upon contact with water and shrink when drying. Additionally, they exhibit a large surface area, contributing to their high adsorptive capacity; this mineral group includes montmorillonite and bentonite. Consequently, one can infer that green soil is more likely to exhibit expansion, given that it is the sole soil type devoid of kaolinite in its composition. Although silica in the form of quartz and gibbsite is present, the conformation of clay mineral sheets is a significant factor in soil behavior.

It can also be concluded that soil characteristics vary from one place to another, and while they may share similar chemical compositions, cation exchange, and mineralogical composition contribute to the development of various behaviors. These behaviors can either be advantageous or not, depending on the intended use of the soil.

Another crucial factor that warrants emphasis is the specificity of each stabilizer in its suitability for particular soil types and climates. Therefore, conducting in-depth studies to map soils' physicochemical, mineralogical, and geomechanical characteristics is essential. These studies can contribute to decision-making when using these soils in civil engineering.

Conclusions

- The chemical constitution of the analyzed soils resulted mainly in silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3). These constituents are essential components of clays. Therefore, establishing a connection between the chemical composition of soils in specific regions and other soils worldwide can be a strategy for stabilizing and improving soils with similar chemical characteristics in different regions.
- According to the XRD results obtained in this research, yellow, gray, and pink soils contain kaolinite in their mineral composition, suggesting a low potential for expansion, characterized by a limited surface area and low adsorption capacity. Meanwhile, green soil exhibits a higher likelihood of expansion due to the absence of kaolinite in its composition. Although silica in the form of quartz and gibbsite is present, the arrangement of clay minerals plays a significant role in the soil's pronounced expansion.
- The mineralogical analysis revealed variations in the composition of the soils, even though they originated from the same geological formation. Identifying specific minerals, such as kaolinite and quartz, that react more favorably to cement addition, in contrast to montmorillonite, which can be stabilized with lime-based materials, demonstrates the need for customized approaches to mechanical soil improvement.
- The application of SEM in the study of soils has proven to be a valuable tool that allows the detailed observation of particles that make up the soil grains. In addition, methodologies used in this research, such as XRF, XRD, and SEM, are applicable not only in the region studied but also anywhere in the world. The adaptability of these techniques highlights their overall usefulness in assessing soil attributes.
- Finally, soil characteristics vary from one location to another despite sharing similar chemical compositions. The analysis and correlation of the mineralogical and morphological chemical composition are important factors that may differ in the possible solutions for expansive soils in civil construction. The results of this study can serve as a foundation for analyzing potential soil stabilization or improvement materials. Hence, it is advisable to employ a combination of physical, chemical, and mechanical techniques to improve the geotechnical properties of the five examined soils, aiming to maximize their effectiveness as base and subbase materials for pavements or road embankment construction.

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Declarations

Competing interests The authors declare no competing interests.

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