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Geotechnical Characterization Of A Soil Of Tropical Origin: Physical, Chemical, Microstructural, Mechanical And Compressive Properties

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ABSTRACT

Due to the urban expansion of large cities, the characterization of the soils that are being used for civil construction is very significant: roads, bridges, and buildings. For this reason, in this study, soil from the Guabirotuba formation in Brazil is physically and mechanically characterized. The results show that it is predominantly silty soil but contains clay minerals that make it expansive. In addition, its geological origin shows it is in a normally consolidated state. Finally, the resistance of the soil in its natural and compacted state shows values below 500 kPa, which makes it a soil with low mechanical resistance, but which could be improved with chemical stabilization and geopolymerization techniques.

Keywords: Guabirotuba formation, tropical soils, mechanical behavior.

1. INTRODUCTION

The Guabirotuba Formation is located in the Basin Sedimentary of Curitiba, of which it is the central stratigraphic unit. Figure 1 shows the location of the Guabirotuba Formation. The sediments of this Formation are found in the municipality of Curitiba, and the Metropolitan Region, extending from Campo Largo to Quatro Barras, covering the municipalities of Curitiba, Campo Largo, Colombo, Almirante Tamandaré, Pinhais, Piraquara, Campina Grande do Sul, Quatro Barras, Araucaria, Fazenda Rio Grande, São José dos Pinhais and Tijucas do Sul, with an area of approximately 900 km². The Curitiba Sedimentary Basin has an area of 300 km² (FELIPE, 2011; Kormann, 2002).

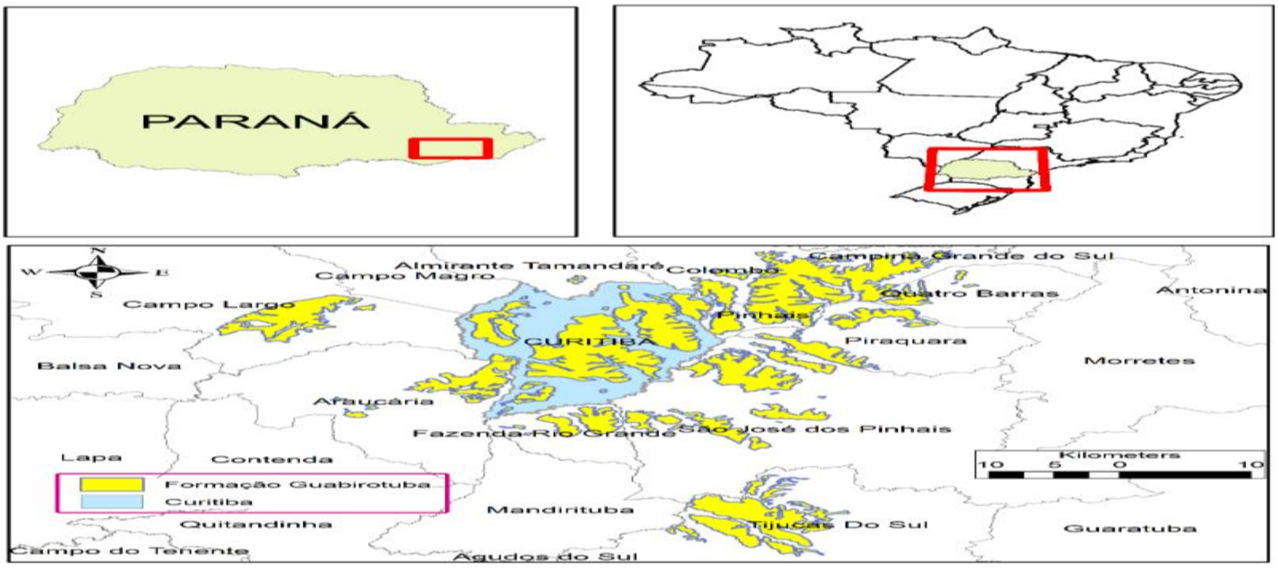


Figure 1. Location of the Guabirotuba Formation

The Formation is inserted in the First Plateau of Paraná and is limited to the east by the Serra do Mar and to the west by the Devonian escarpment (Serra de São Luiz do Purunã), corresponding to the Peripheral Depression in the State of São Paulo. The Basin has altitudes between 750 and 980 m and a gently undulating relief of basement mounds, partly destroyed by erosion and decent colluvial-alluvial sediments (SALAMUNI; EBERT; HASUI, 2004).

(SALAMUNI; SALAMUNI, 1999) divide the lithologies of the Guabirotuba Formation into four groups: clays, arkoses and archesian sands, conglomeratic deposits, and carbonate deposits, with the group of clays constituting the leading lithofaciological group of the Formation. The clays are primarily gray and of greenish-blue and brown tones, but in the more superficial layers the colors can change to red or yellow, and almost all clays have smectite as their main clay mineral. The group of arches and archesian sands appear in the middle of clay deposits where the sediment matrix is formed by sandy grains of smaller dimensions where the presence of clay and silt can still be seen. The colors of this second group range from gray to red; the layers of the arkose have thicknesses that can reach 3 meters.

Lithotype conglomeratic deposits are formed by granular materials embedded in a clayey matrix and can be found at the basin's edges (Kormann, 2002). Finally, the group of carbonate deposits is made up of caliches (hardened calcium carbonate deposits) and appears in more superficial and thinner layers. Caliches are deposits found in more significant quantities in desert areas.

In hydrogeological terms, the Guabirotuba Formation behaves like an aquiclude; only locally in sandy and archesian lenses is an aquifer behavior. In general, tubular wells in this Formation have very low productivity or, at most, temporarily medium productivity. However, the basement of the Formation above presents medium to high productivity where structural discontinuities occur, regardless of depth, behaving, as a whole, as a fractured aquifer (SALAMUNI; STELLFELD, 2001).

The position of the water table is variable in the Guabirotuba Formation and can be found close to the surface or at depths of up to 15 m. Frequently, the presence of suspended aquifers is observed, formed due to the low permeability of the complex clay matrix. The stiff clays of the Guabirotuba Formation have a gray, greenish gray, or brown color and often have a high, hard, or hard consistency, therefore called hard clays (Kormann, 2002). These stiff clays are known as "caboclo soap" because they become smooth and slippery when wet. When in direct contact with the atmosphere, a drying process with the consequent volumetric reduction of the soil is manifested, giving the material a "caked" appearance, a fundamental element in studying its erodibility (Chamecki, 2002).

The natural moisture content of the stiff clays of the Guabirotuba Formation usually is high with an average value of approximately 32%, and, consequently, the degree of saturation is high, with an average value of close to 94%. This characteristic can be associated with the phenomenon of capillary rise and regional climatic conditions, with annual rainfall in the order of 1200 to 2100 mm. The hard clay can present high levels of matrix suction, which directly interferes with the effective tensions and the soil's behavior about erosion.

Regarding the unsaturated soils of the Formation soils(KORMANN, 2002) presented a program to determine characteristic curves and suction values of samples in natural humidity for the stiff clays of the Guabirotuba Formation. For natural humidity ranging from 21.4% to 25.7%, with a degree of saturation from 84% to 98%, suctions varying between 1600 and 2500 kPa were obtained. In the case of studies carried out by (BALDOVINO et al., 2020b; MOREIRA et al., 2019b), the natural moisture content of two fine soils of the Guabirotuba Formation collected in the municipalities of São José dos

Pinhais and Fazenda Rio Grande was calculated at close to 40%. Figure 2 shows the two soils studied by the authors during field collection. Note the predominance of yellow and pink-red coloraturas, typical of the soils found in the more superficial layers of the Formation.

The predominance of clay minerals from the smectite group, with a high probability of the presence of montmorillonite, gives these soils their characteristic of expansiveness. This characteristic, associated with constant variations in surface humidity, constitutes the factor that controls and triggers intense erosive processes in these soils when exposed to the action of surface water. With drying, the soil surface is caked, and when it comes into contact with water again, it breaks down and starts an erosive process (SALAMUNI et al., 2004)

CHAMECKI, 2002 recommends avoiding the exposure of the stiff clays of the Guabirotuba Formation in slopes, excavations, and landfills due to their high erodibility. Its surface must be protected by vegetation or other materials to preserve its moisture.

(a) (b)

Figure 2. Characteristic soils of the Guabirotuba Formation. (a) Pink silt at Fazenda Rio Grande. (b) Yellow silt from São José dos Pinhais

2. EXPERIMENTAL PROGRAM

2.1 Materials and Methods

The soil was collected in a deformed and undisturbed state. The material was excavated, transported, and placed in 250-liter plastic barrels with the help of a backhoe in sufficient quantity to carry out all the tests of the experimental program. The plastic barrels were sealed, transported, and stored in the Geotechnics Laboratory of the Federal Technological University of Paraná, Ecoville campus. In addition, all care was taken during the collection, transport, and storage of the soil to avoid soil contamination and the loss of natural moisture. The soil was collected in March 2018. The soil in an undisturbed state was sampled in 25 cm edge cylinders, as shown in Figure 3.2, following the recommendations of the Brazilian Standard NBR 9604 (ABNT, 2016b).

The soil used for the present study was collected on a road slope at a depth of 2-3 m, from the saprolitic layer (layer thickness varies from 1 to 5 m) of the Guabirotuba Formation, in the municipality of São José dos Pinhais (Paraná), metropolitan area of the city of Curitiba/PR. At the time of collection, the soil presented physical characteristics of fine-grained, yellowish soil, with the presence of quartz, typical of sedimentary soil in that zone. This soil was chosen because it had not been studied for its applicability in geotechnical works using improvement and stabilization techniques.

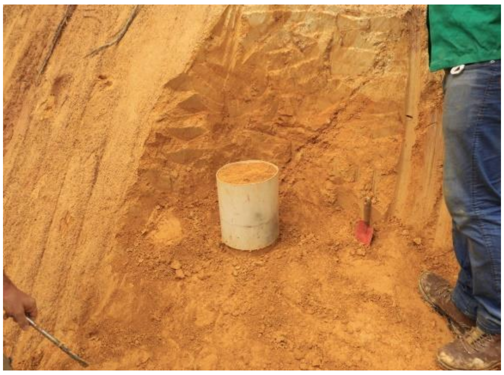
The information in Table 1 refers to soil characterization tests. Table 1 shows the type of test, the standards followed (in Brazil and its equivalent in the United States of America), and the number of times the test was repeated for greater precision according to the corresponding standard.

Table 1. Soil's characterization tests

Test	Number of repetitions
Granulometric	1
Water content	4
Liquid Limit	1
Plasticity Limit	1
Specific Gravity (Gs)	12
Compaction	1
One-Dimensional Consolidation	1
X-ray fluorescence (XRF)	1
Electron Microscopy (SEM) analysis	1
Energy-dispersive X-ray spectroscopy (EDX)	1

The undisturbed samples were collected for tests of unconfined compressive, split tensile, field dry specific gravity, and one-dimensional consolidation, all in their natural state. The soil in its natural state was found to have hygroscopic moisture of 40% and a specific dry weight of 11.60 kN/m^3. As can be seen in Figure 3, yellow soil was found in the second layer, with other layers, such as ash, considered the deepest of the Guabirotuba Formation (up to 50 m) according to official data from Mineropar in the State of Paraná. Undisturbed samples were collected according to Figure 3b. After field collection, the samples were cut with the utmost care to preserve their natural state during testing (Figures 3c-d).


(a)


(b)

(c)

(d)

Figure 3. Soil collection and characterization steps: (a) Road slope where the soil was collected. (b) Collection of undisturbed samples. (c) Undisturbed sample preparation for CIU triaxial tests, unconfined compressive and split tensile. (d) Type of rupture of an undisturbed sample after an unconfined compressive test

3. RESULTS AND DISCUSSIONS

The results of the soil characterization tests are presented in Table 2. The silt is the most considerable portion of the soil granulometry, with 60%. The actual density of the grains was calculated as 2.62. The predominant color of the soil is yellow. Soils with yellow color, in turn, indicate the absence of hematite and the highest occurrence of hydrated oxidized iron. The differences between the reddish or yellowish colors of the soils are often associated with the different types of iron oxides present in the soils.

Similarly, a nail (which has iron) also turns reddish or yellow when rusting. Red-colored soils may indicate large amounts of iron oxides (hematite) as the first layer of soil visualized in Figure 3a. Studies carried out by (Pereira, 2004)in reddish Guabirotuba Formation soils indicate a high percentage of Fe_2O_3 and hematite.

Since the soil has unsuitable mechanical properties to receive a specific type of request or undertaking, two options are possible. The first is the removal and replacement of the material, while the second consists of improving its properties with the addition of alternative material through stabilization processes. The first option is more expensive, mainly due to the amount of equipment and work teams. The improvement of soil properties is economically and environmentally favorable, considering that residues are applied that do not have a good destination in many cases, which makes their acquisition low-cost, and the application of alternative materials avoids their inappropriate disposal in the environment.

Soils are generally ordered as sands, silts, clays, and those composed of their different fractions; in this case, the predominant material is called first in the nomenclature, as is the case with clayey or silty clay sites. The main factors responsible for the soils are their rock of origin, the magnitude of climatic variations (rainfall frequency, wind and temperature changes), and anthropic actions. The process of soil formation is continuous and dynamic, thus resulting in an arrangement of non-homogeneous layers of material in the environment. For this reason, it is common for a slope cut to have two or more types of soil. This factor is decisive in the choice and design of foundations and the execution of earthworks, mainly due to the non-homogeneity of the soil layers and its influence on the responses to the various requests to which it is submitted.

The process of soil formation is generally diversified because of the numerous factors that influence such occurrence. Therefore, it is common in several areas of engineering the need to deal with soils that do not meet the design requirements. In these cases, an action to replace the material or improve its properties is necessary.

The mechanical behavior of soils results from the influence of several parameters that permeate from its Formation, degree of weathering, type, and shape of particles, presence or absence of clay minerals, environmental disposition, and history of tensions, to the partial or total amount of water present in its structure. A soil mass is composed of solid particles, air, and water. The variation of these results in several other parameters that determine the behavior of the material

Table 2. Soil's properties

Properties	Value	Standard
Atterberg's limits		
Liquid Limit (LL) %	50,82	(ASTM, 2010)
Plasticity limit (LP) %	35,96	
Plasticity index (IP), %	14,86	
Granulometric		
Coarse sand (0,6 mm< diameter <2 mm), %	5	(ABNT, 1995)
Medium sand (0,2 mm< diameter <0,6 mm), %	12	
Fine sand (0,06 mm< diameter <0,2 mm), %	18	
Silt (0,002 mm <diameter<0,06 mm), %	60	
Clay (diameter< 0,002 mm), %	5	
Efect (d_{10}), mm	0,003	
Medium diameter (d_{50}), mm	0,038	
Uniformity coeficient (C_u)	12,88	
Coeficient og curvature (C_c)	0,88	
Other properties		
Specific Gravity	2,62	(ASTM, 2014)
Activity of Clay, A [A=IP/(%< 0,002 mm)]	2,97	(SKEMPTON, 1953)
Color	Yellow	
Classification (SUCS)	MH	(ASTM-D2487-17; ASTM, 2011)
Strength properties		
q_u- undeformed, kPa	104,58	(ASTM, 2003)
q_t- undeformed, kPa	16,62	(ABNT, 2011)
index q_t/q_u- undeformed	0,16	
Compaction properties		
OMC (standard effort), %	26,5	(ABNT, 2016a)
MDD (standard effort), kN/m^3	13,72	
OMC (intermediate effort), %	20,50	
MDD (intermediate effort), kN/m^3	15,43	
OMC (modified effort), %	14,50	
MDD (modified effort), kN/m^3	16,75	

The granulometric soil curve is shown in Figure 4. Particles smaller than 0.15 mm were measured by laser, and by sedimentation; the two coincide. Because of this, only the laser result was plotted. The diameter of the particles corresponding to 10%, 30%, 50%, 60% and 90% of fines (or passing) were measured as: d_{10} = 0.003 mm, d_{30} = 0.01 mm, d_{50} = 0.025 mm, d_{60} = 0.038 mm, and d_{90}=0.3 mm (see Figure 4). Additionally, the coefficients of uniformity, Cu, and curvature, Cc, were measured as C_u=12.88 and Cc = 0.88. Additionally, the soil was characterized as highly compressible silt with the presence of sand according to the Unified Soil Classification System [ASTM 2487 (ASTM, 2011)].

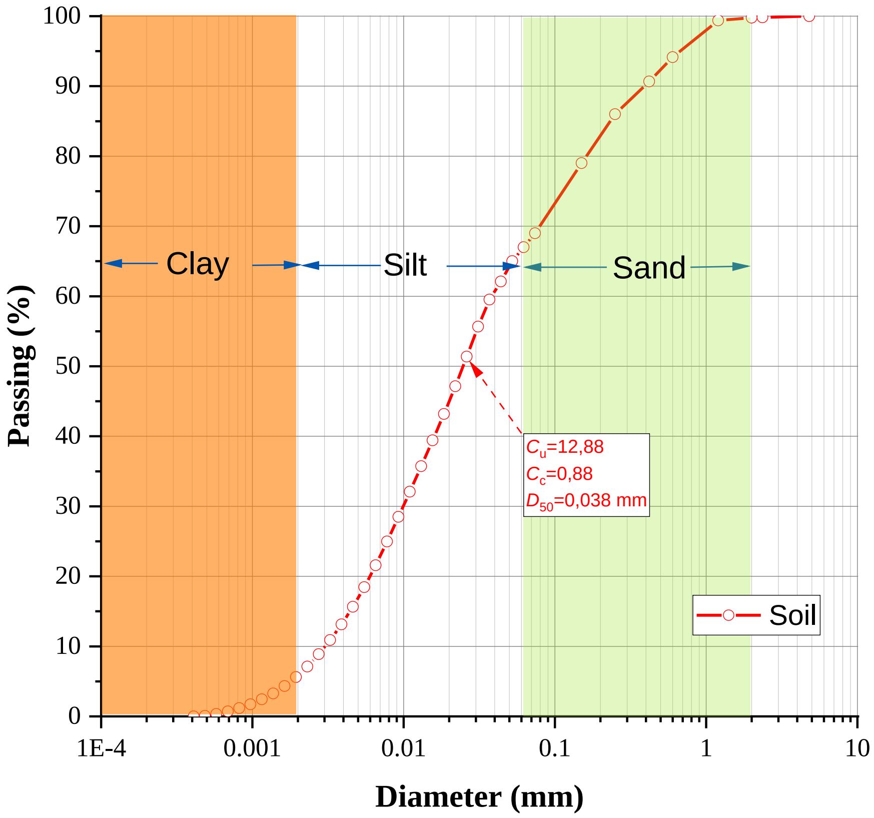


Figure 4. Granulometric curve

Figure 5 shows the compaction curves at the three soil energies. The 80% and 100% saturation lines were plotted. The compaction curves calculated the maximum dry specific weight ($\gamma_{d\text{-}max}$) and optimal moisture content (ω_o) at the three energies. The results of γd-max and ω_o are presented in Table 2. The optimal moisture content was reduced by increasing the compaction energy, and the apparent dry specific weight was increased. The optimal compression line is close to 70% saturation.

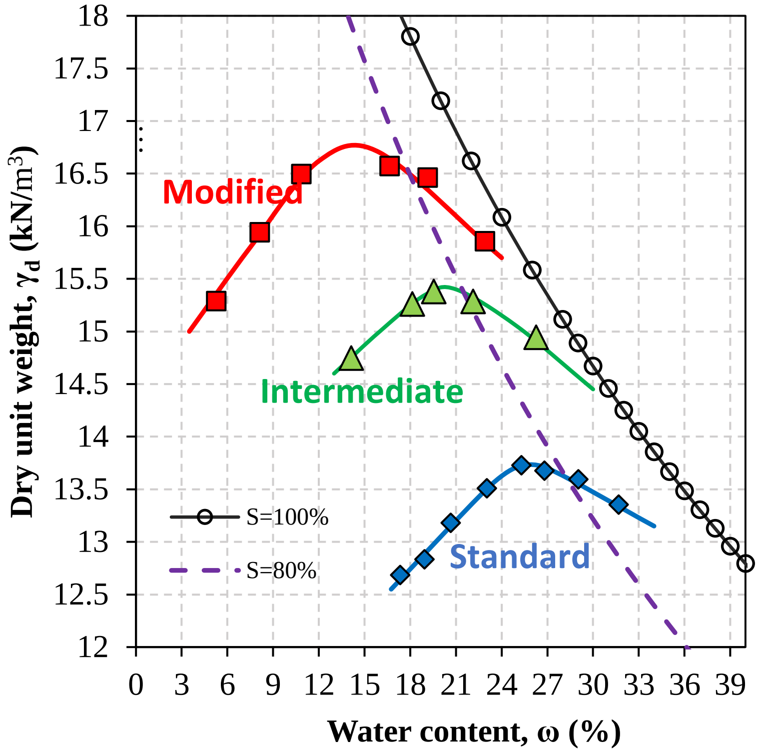


Figure 5. Compaction curves of the soil at standard, intermediate and modified effort, accompanied by 80% and 100% saturation lines.

The total quantitative chemical composition of the soil sample was investigated by X-ray fluorescence (XRF) and energy dispersive spectroscopy (EDX) at the position marked in Figure 6, corresponding to scanning electron microscopy (SEM) of the soil. Table 3 shows the results of the chemical composition of the soil sample using XRF. Mainly SiO_2, Al_2O_3, and Fe_2O_3 were found, which are usually found in sedimentary soils and actively participate in the chemical stabilization process of Guabirotuba soils (Baldovino et al. 2019c).

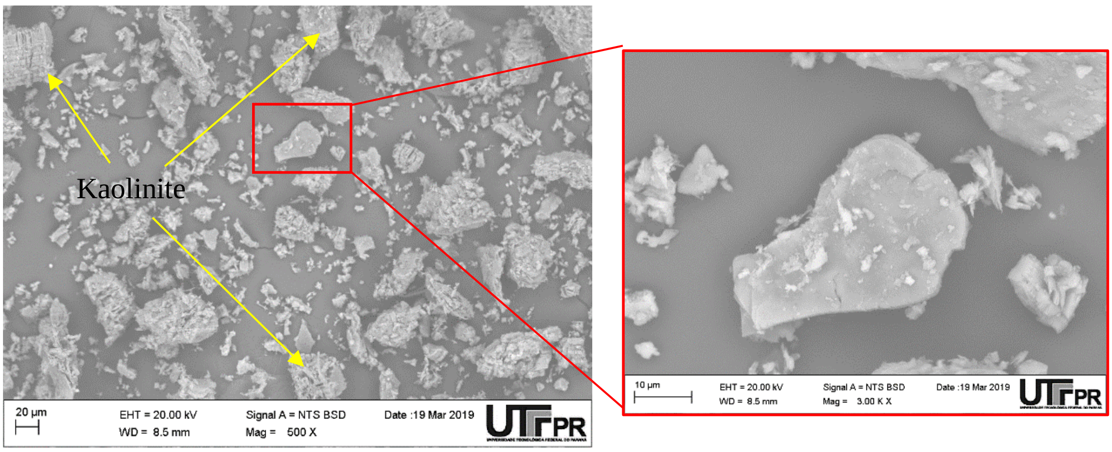


Figure 6. Micrograph (SEM) of a soil sample and position of the EDX study area.

Table 3. Soil chemical composition using XRF

Compost	Concentration by weight (%)
SiO_2	48,78
Al_2O_3	44,51

Fe_2O_3	0,61
K_2O	0,84
TiO_2	0,92
SO_3	4,12
LOI	0,22

Through EDX analysis in a soil particle (see Figure 6), the following elements were detected: aluminum (9.50%), silica (9.71%), iron (1.48%), oxides (59.02%), and carbon (20.29%). These elements are equivalent to those found using FRX. In Figure 6, the morphology of the particles can also be seen. Note the presence of kaolinite and planar particles, which are very characteristic of the fine soils of the Guabirotuba Formation (Pereira 2004). The presence of kaolinite in the soil can be reinforced with the XRD plot of the soil presented in Figure 7. In XRD three minerals were detected mainly: kaolinite, quartz, and smectite. The largest kaolinite and quartz peaks were found at 12° and 25°, representing a more significant amount of these minerals above 65% by weight. Finally, it should be noted that smectite can attribute expansive properties to the soil, as found in previous studies (J. A. Baldovino et al., 2018; J. de J. A. Baldovino et al., 2019; Pereira, 2004).

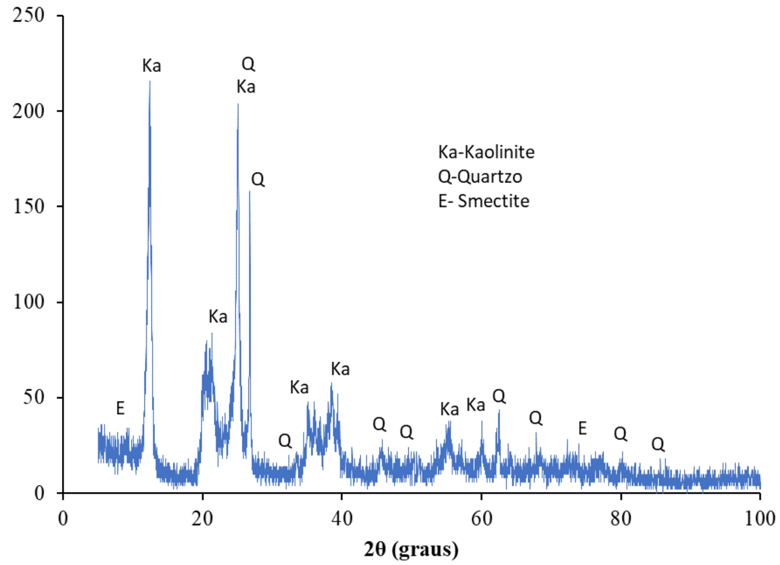


Figure 7. DRX of soil sample

Undisturbed samples were also used to determine the compressibility properties of the silt in its natural state. The test results are plotted in Figure 8. The test was performed using an automatic press.

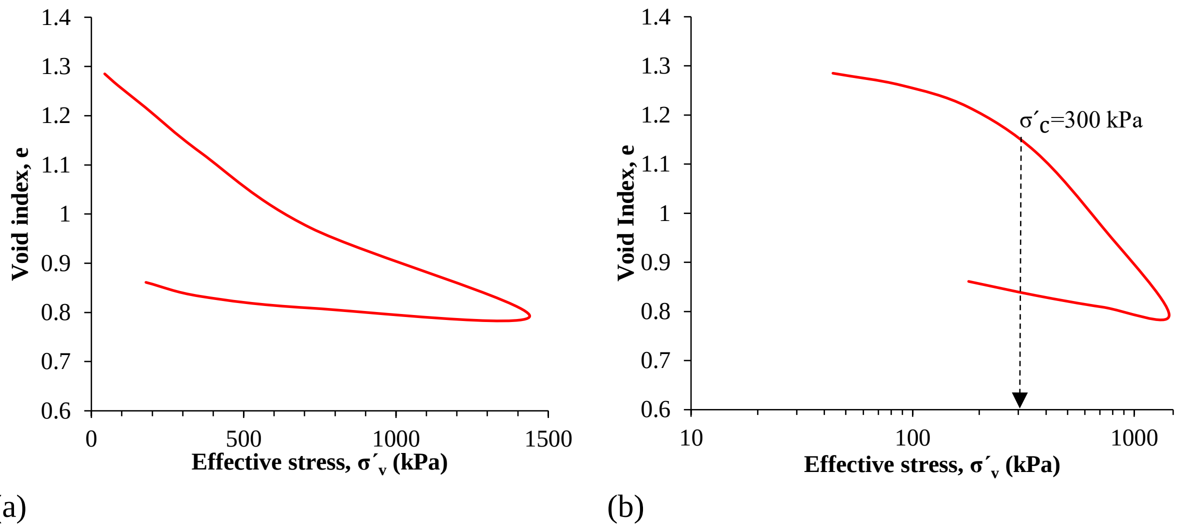


Figure 8. Result of the soil oedometric test in (a) natural scale and (b) semi-log scale

In Figure 8a, the soil consolidation test results were plotted in full scale, and in Figure 8b, they were plotted in semi-log scale. According to the American standard, the pre-consolidation stress (σ'_c) was calculated as 300 kPa. Furthermore, following the same standard criteria, the consolidation coefficient (C_v) was measured as 0.02 cm^2/s. Each type of soil has different geotechnical characteristics, typical of its formation process and the different variations (climatic, chemical, mechanical, and anthropic) to which it has been submitted until the present moment. The magnitude of the occurrence of these variables is decisive in the main mechanical properties of soils as in their shear strength, compressibility, permeability, and carrying capacity.

4. CONCLUSIONS

– The city of Curitiba and its metropolitan region are located on a sedimentary basin characterized by the geological unit called Guabirotuba Formation. It is predominant in its composition of silty clays and clayey silts; the occurrence of granular materials is possible. Due to its physical-mechanical properties, low bearing capacity, high compressibility, and erodibility, sedimentary soils often cannot be used as a base and sub-base material for pavements, stabilizing slopes and slopes, or even to support surface foundations.

– The results showed that pre-consolidation stresses are higher in undisturbed samples than in compacted samples.

– The consolidation coefficients showed less variation in the undisturbed samples of pure soil concerning the compacted soil samples, having their origin in the stress histories of the samples.

– The samples submitted to Proctor compaction tests showed an increase in the dry apparent specific weight of the soil with the variation of the compaction energy.

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