

Unsaturated soils in the context of tropical soils

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Article

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Abstract

The practice of geotechnical engineering in tropical climate regions must consider the use of unsaturated soil concepts. However, these concepts must also take into account the specific behavior traits of tropical soils, particularly those related to soil aggregation, pore structure, and mineralogy. This paper will initially present considerations on the typical properties of unsaturated tropical soils as well as fundamental concepts. Throughout the article, several engineering problems will be presented alongside reflections on the complex interaction between the numerous variables involved in the modeling and engineering practice of tropical unsaturated soil behavior. The paper addresses issues related to soil formation, chemical and mineral composition, physical properties, tropical soil classification, and structural characteristics of soils. Issues related to compaction and the influence of weathering, geomorphology and bioengineering are also addressed.

1. Introduction

The engineering practice is generally based on the experience built over time, with new scientific and technological advances being introduced gradually. Critical thinking, the central pillar of engineering, is often set aside to prioritize the application of standards and regulations that, in most cases, are not mandatory. The lack of critical thinking may have greater consequences when dealing with soils that present complex soil behavior, such as unsaturated tropical soils. Unfortunately, standards do not consider the particular behavior of unsaturated and tropical soils, even when developed in countries where these types of soils are predominant. For instance, drying of specimens in preparation for soil characterization tests is recommended by most standards, but it may greatly affect testing results because of the potential degradation of the aggregates present in deeply weathered soils.

The books *Laterite Soil Engineering: Pedogenesis and Engineering Principles* (Gidigas, 2012) and *Tropical Residual Soils* (edited by Fookes, 1997) present a broad perspective on tropical soils, ranging from their formation and characterization to their behavior and uses. However, tropical soils have characteristics that remain poorly studied and that depend on the degree of transformation suffered during their genesis. It is important to note that the properties and

behavior of tropical soils bear a faint link with their origin, as illustrated the studies of Mortari (1994) and Cardoso (1995) on the behavior of tropical soils from the Federal District, Brazil. These authors showed that the particle-size distribution, the Atterberg limits, and the Skempton activity index of these soils depends on and the Claystone, Slate, and Metarrythmite formations from which these residual soils developed.

The experimental determination and the use of soil properties require the consideration of what they represent and the contextualization in time, space, and general environmental conditions. This is particularly true for unsaturated tropical soils. Static and non-contextualized interpretations of soil behavior generally lead to the adoption of simplifications and poor engineering decisions and planning.

Regarding the relevance of time effects, geotechnical engineering practice is frequently focused on the present and on the past geological periods. Little consideration is given to what will happen to construction materials in the future. In the case of unsaturated soils, temporal contextualization has a great relevance since soil moisture and consequently its behavior often varies over time and follows a cyclical pattern. These fluctuations impose changes in the physicochemical properties of the soil. For example, cyclical variations of water content can be of great relevance to the fatigue of

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pavement structures and to the development of erosive processes (Lima, 2003).

Regarding the spatial context, materials are generally studied under laboratory conditions that do not reproduce the dynamic balance with the environment, nor most of the geomorphological, biological, and geological factors, including structural geology and hydrogeology (Diniz et al., 2012; Jesus et al., 2012; Jesus et al., 2017; Oliveira & Ribeiro, 2017; Romão & Souza, 2017). For instance, the imposition of new drainage conditions on unsaturated soil due to the development of erosion processes or due to the construction of a road cut, imposes new hydraulic gradients that influence soil behavior (Lima, 2003).

Unsaturated and tropical soils can also be affected by intentional or unintended chemical changes in the soil itself or the environment in which they are found. An example of unintentional chemical changes occurs when executing concrete piles in situ in an unsaturated soil profile. The initial suction in the concrete, a porous material put in direct contact with the soil, is generally close to zero. The surrounding soil suction, being greater than zero, will result in the migration of chemical elements and compounds from the concrete into the soil. This may result, in the case of deeply weathered tropical soil profiles, in textural degradation over time (Wanderley Neto, 2020). As an example of intentional chemical alterations, soil stabilization depends on the mineralogical characteristics significantly associated with the weathering profile and moisture fluctuations resulting from the soil-atmosphere interaction (Ayala, 2020).

Structural characteristics of soils from weathering profiles can also play an essential role in soil behavior. Chemicals introduced for soil stabilization, such as lime, cement, or ash, do not immediately penetrate the aggregates and microaggregates present in deeply weathered tropical soils or the clay packages present in slightly weathered tropical soils. In deeply weathered soils, ionic exchanges are combined with the solubilization of minerals, such as gibbsite, hematite, and goethite, affecting the soil textural stability. In slightly weathered soils, ionic exchanges are predominant, interfering with the interactions between particles. The effects on highly weathered soils were shown by Ayala (2020), who studied soils stabilized with hydrated lime. Pérez (2018) showed that agricultural fertilizers also provoke changes in soil aggregates and microaggregates. It is also important to note that studies on the influence of suction on the hydromechanical behavior of soils are almost always based on analyzes of matric suction; however, when introducing chemical effects, osmotic suction becomes relevant (Pérez, 2018, Ramírez et al., 2017).

The several issues described herein highlight the importance of understanding the properties and behavior of tropical unsaturated soils and their impacts on the performance of geotechnical structures. A broader view is required, considering the role of soil suction, structural stability, and macro and microaggregate interactions. In this context,

this paper presents the analysis of physical, chemical, and mineralogical properties in the context of the behavior of unsaturated soils, with particular emphasis on tropical soil behavior. The particular behavior of natural and compacted soils will be considered. Finally, the temporal and spatial impact on the weathering process and behavior of unsaturated tropical soils will be discussed.

2. Properties of tropical soils

2.1 Mineralogy of weathering profiles of tropical regions

Weathering profiles formed in tropical regions depend on factors such as climate, microclimate, geology, structural geology, hydrogeology, geomorphology, and drainage conditions. Therefore, an assessment in the broad sense is necessary (Gusmão Filho, 2002). This particularity limits the validity for tropical soils, especially for deeply weathered ones, of existing correlations between physical properties and behavior developed for soils with different characteristics.

Figure 1 exemplifies a tropical weathering profile typical of the Federal District, Brazil, presenting the mineralogical composition based on data obtained by Rodrigues (2017). The gibbsite content, which is higher near the ground surface, remains constant between 2 m and 4 m in depth and then decreases with depth. The opposite behavior is observed for kaolinite. This pattern occurs because gibbsite comes from the weathering of kaolinite (Cardoso, 2002). Kaolinite, in this case, is probably originated from the weathering of muscovite. It should be noted that in recently deposited sedimentary soils formed from erosive processes acting on weathered tropical soils that formed over centuries and millennia, the mineralogical profile shown in Figure 1 is generally inverted (Santos, 1997).

Figure 1 shows also that there is great similarity between the quartz and the gibbsite contents, along the entire profile. That similarity can be attributed to the fact that the quartz

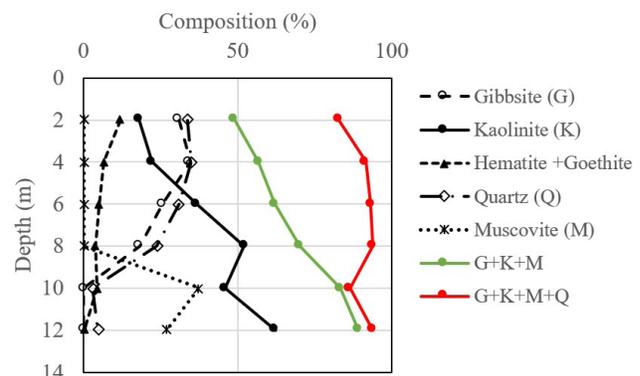


Figure 1. Mineralogy of a soil profile from the Federal District, Brazil.

is neoformed, as explained by Senaha (2019). In this case, quartz would be formed from silicon released when kaolinite is weathered, producing gibbsite. Such neoformation also occurs during the formation of kaolinite from clay minerals 2:1, as indicated by the parallel profiles of kaolinite and quartz content obtained for Manaus, Brazil (Lima, 1999).

In the neoformed condition, quartz is present in significant quantities inside the aggregations, as observed in laterites of the Federal District (Figure 2a). Phyllosilicates preserved inside these laterites were also observed (Figure 2b). The minerals present in the soil under these conditions do not influence the hydromechanical behavior of the soil, which relativizes the importance of mineralogical composition in the study of the behavior of unsaturated tropical soils and the definition of the soil-water characteristic curve itself.

Leaching processes result in changes in the soil properties and in the mineralogical composition along the profiles of tropical soils. Figure 1 shows that the sum of the fractions of gibbsite, kaolinite, muscovite, and quartz results in quantities that are smaller at 2 m and 10 m in depth. The near ground surface region is affected by the infiltration of rainwater, generating the migration of the gibbsite formed at a depth of 2 m. The soil in the region near 10 m in depth is less porous and less permeable, resulting in the accumulation of water during the rainy season, which is subsequently exfiltrated during the dry season, thus causing the gradual migration of kaolinite to lower depths.

The mineralogy of tropical soils has significant impacts on the selection of adequate chemical stabilization techniques. Its consideration must be integrated into the structural analysis, as the presence of compounds such as iron and aluminum oxyhydroxides directly impact the aggregation status of these soils. The increase in soil pH produced by

stabilizers such as lime and Portland cement enables the solubilization of gibbsite, making the aggregates present in deeply weathered soils fragile, as shown by Rezende (2003) and Ayala (2020). Delgado (2007) showed, when studying tropical soils subjected to chemical stabilization, that lime affects the shape of the soil-water characteristic curve and the soil's mechanical behavior. The influence of chemical stabilization depends on the level of weathering suffered by the soil, on the conditions in which that weathering process took place, on the soil mineralogy, and on the level of aggregation (Rezende, 2003; Pessoa, 2004; Aguiar, 2014). Such findings imply the need for a detailed analysis when dealing with chemically stabilized tropical soils.

Testing methodologies used to investigate the mechanical behavior of tropical soils subjected to chemical treatments or contamination must be carefully designed. In general, contaminated mixtures or soils are not subjected in the laboratory to the same water flow conditions imposed by the unsaturated conditions and variations that occur in the field. For example, oxide-hydroxides of aluminum and solubilized iron can be carried by unsaturated seepage, affecting the mechanical behavior and the soil-water characteristic curve of the soil. These effects were observed by Ayala (2020) when comparing results obtained for laboratory curing conditions and those found in situ.

When studying the properties and behavior of tropical soils, whether saturated or not, it is necessary to understand the particularities of behavior. For example, scattering in testing results may have specific causes and not simply imply in testing errors. Freitas (2018) shows that mineralogy can cause unexpected results. In his dissertation, he shows that the simple compressive strength of a tropical soil stabilized with the addition of rice husk ash and Portland cement, when

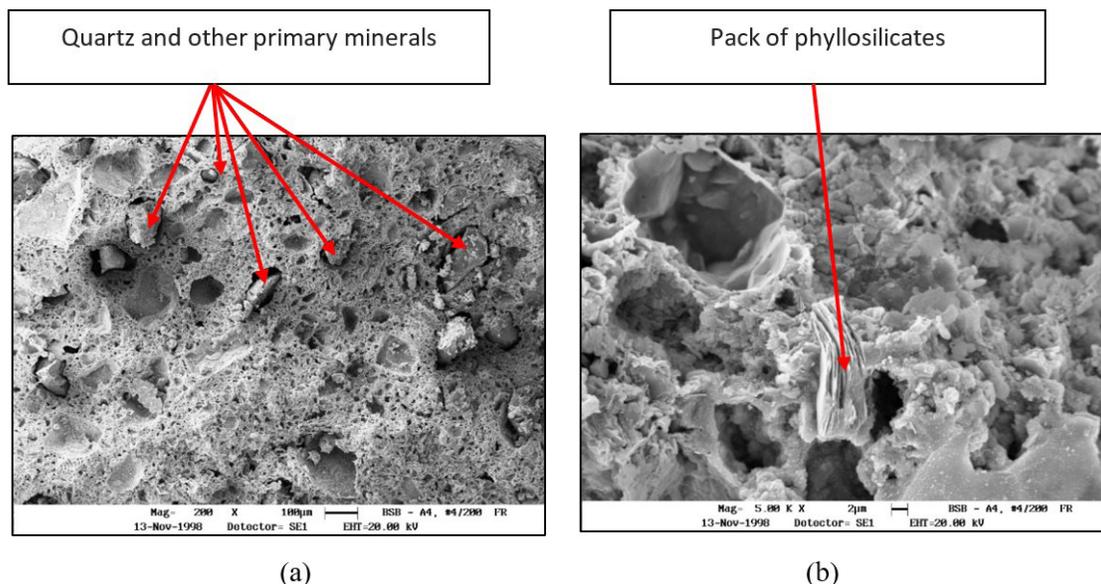


Figure 2. Microstructure of the interior of a laterite from the Federal District, Brazil.

plotted as a function of the degree of saturation, showed a highly scattered result. However, when plotted as a function of the saturation degree divided by the sum of the hematite and goethite contents, these same results led to a good correlation.

2.2 Structural properties of weathering profiles in tropical regions

Figure 3 shows typical microstructures of soil profiles submitted to the process of tropical weathering. Microstructures of a deeply weathered soil (Figures 3a, 3b, 3c), of a soil with an intermediate degree of weathering (Figure 3d), and of a slightly weathered soil (Figures 3e, 3f) are illustrated. It is noteworthy that the profile of tropical soil corresponding to Figure 3 did not present a water table in subsurface exploration drilling up to 13 m in depth.

Figure 3a shows that the soil collected at 2 m in depth is predominantly composed of aggregates, with macropores between them. These aggregates have micropores, as shown in Figures 3b and 3c. At 5 m in depth (Figure 3c) aggregates are still present but the macropores between them are relatively smaller. In the transitional soil present at 8 m in depth (Figure 3d) the aggregates decrease in size and independent particles and primary minerals are found. At 10 m in depth, the slightly weathered soil horizon is reached (Figure 3e), presenting clay packs that appear to replace the aggregates found in the deeply weathered soil. In deeper layers corresponding to the saprolite the chemical-mineralogical weathering is relatively small, with significant fractions of primary minerals being found (Figure 3f). The laterites may (Figure 4a) or may not (Figure 4b) have internal pores, and these may vary from micro to macropores. This microstructural analysis combined with the mineralogical analysis exemplified in the previous section shows that in tropical weathering profiles, mineralogical and structural transformations go hand in hand.

The structural characteristics that are present in most tropical weathering profiles result in unconventional behavior. For this reason, caution is necessary when analyzing the behavior of these soils and the correspondence between testing results and field monitoring data. For example, the results presented by Guimarães (2002) show measured N-values in standard penetration tests for depths from 1 m to 6 m that range from 2 to 4. These low N-values are due to the fact that the drilling and penetration procedures lead to alterations in the soil structure. Although the highest N-values were obtained for the dry period, when the suction is higher, the results are not consistent with the actual behavior of the soil, leading to estimations of load capacity based on the N-values that are lower than the results from load tests, as shown by Guimarães (2002).

Figure 5 shows load test results versus estimated load capacity values calculated using three methods, two of which use the N-values from SPT tests (Décourt & Quaresma Filho, 1978; Aoki & Velloso, 1975) and a third method that uses the maximum torque in standard penetration tests

(Décourt, 1996). Load tests and SPT tests were carried out at different times of the year (Guimarães, 2002). The results obtained for concrete piles immediately after concreting and 15 days after concreting are also shown in Figure 5. Despite the differences between the values estimated by the different methods, the results show that the load test results were higher when the values calculated from the N-SPT values were lower. The load test result obtained for the concrete pile immediately after concreting was superior to that obtained 15 days after concreting. In addition to the influence of the soil structure change generated during the SPT sampler penetration, these two sets of results indicate that the higher the suction acting on the soil, the greater the uptake of concrete chemical elements by the soil, resulting in strength loss. Ayala (2020) observed similar behavior when treating the same soil with lime.

Figure 6a shows the N-SPT values versus the sum of the logarithm value of suction in pF and of the vertical stress, also in pF, divided by the void ratio. Figure 6b shows the results of the maximum torque measured after the SPT sampler penetration versus the same variable used in Figure 6a, with exception of the use of horizontal stresses. The normalizations using the void ratio are based on the principles proposed by Camapum de Carvalho & Pereira (2002). Considering that the maximum torque was measured after driving the SPT sampler, its similarity with the N-SPT results show that in this test the soil structure is also affected. The larger scatter in Figure 6a is attributed to a lower level of soil structural change compared to the conditions imposed in the torque test (Figure 6b). The points excluded from the trend are located in the transition zone, between the slightly weathered soil and the highly weathered soil. It should be noted that the heterogeneity indicated in this figure is usual, as the N-SPT and maximum torque results were obtained at different times of the year. Thus, the temperature (Lima, 2018) and water content (Guimarães, 2002; Mascarenha, 2003) throughout the soil profile do not remain constant for the same depth. The corresponding changes in soil suction affect not only the soil shear strength but also its susceptibility of structural change during sampler driving.

Load tests carried out on Straus piles, precast, and excavated with mechanized and manual augers with approximately the same diameter (30 cm) and the same length (8 m) present different results (Figure 7), with the worst results being those obtained for precast and excavated by hand auger. The lower results for the precast piles are due to the destruction of the soil structure by the blows required to drive the pile. The lower results for the hand drilled pile may be attributed to the fact that water is used during the excavation process. An intermediate result was obtained for the Straus pile. The pile excavated with a mechanized auger showed the highest bearing capacity. In summary, it is observed that breaking the soil structure and increasing the water content of tropical soils decrease their mechanical strength.

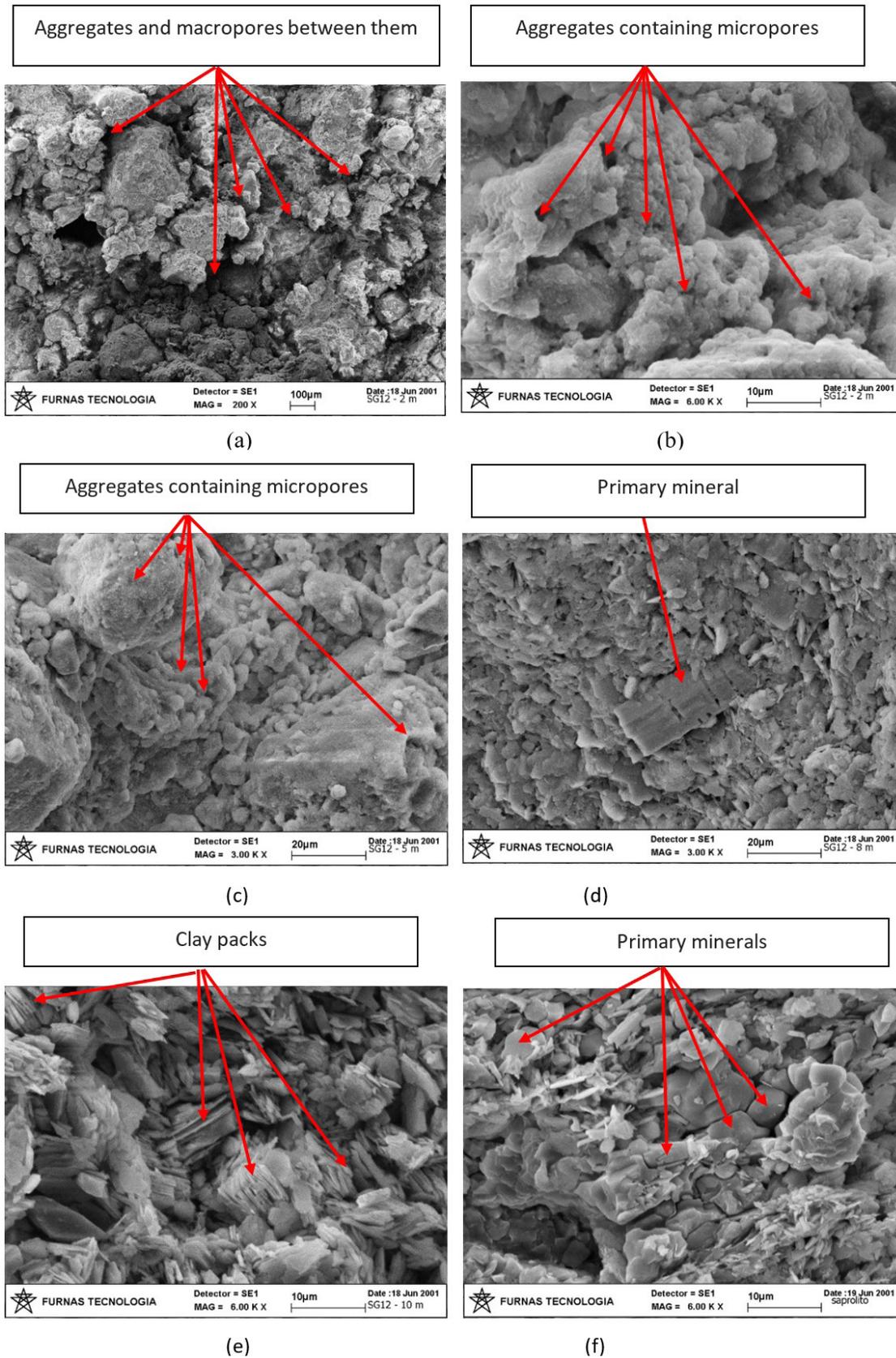


Figure 3. Microstructure of soils along a weathering profile: deeply weathered soil (a, b, and c); moderately weathered soil (d); slightly weathered soil (e and f).

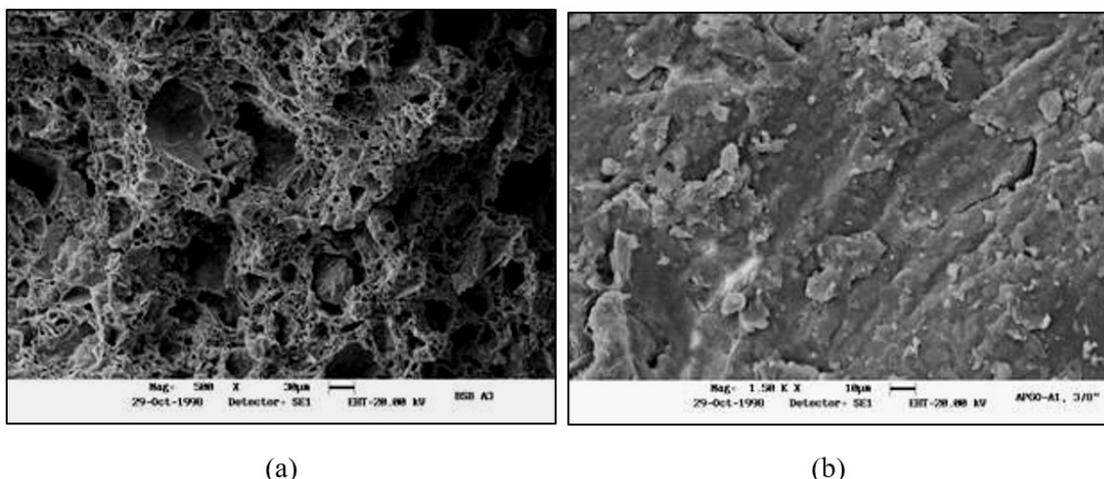


Figure 4. Lateritic aggregates from the Federal District and Goiânia, Brazil: (a) laterites with pores; (b) laterites without pores.

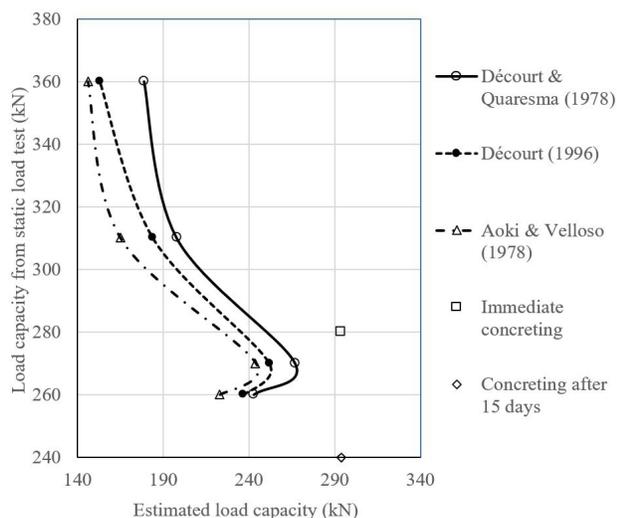


Figure 5. Estimated load capacity versus load test results on collapsible tropical soils in the Federal District, Brazil.

The shear strength envelopes of tropical soils under unsaturated conditions may, in some cases, present particular behavior that can be interpreted based on the structural behavior of the soil. Camapum de Carvalho (1981) showed typical results, such as strength increased due to prior drying of the soil and ascending envelopes, with increasing friction angles. In cases where the strength of the cementing bridges between the aggregates is constant, it is common to obtain a shift of the envelope at higher stresses while maintaining its slope approximately constant (Figure 8, CS1). That shift occurs due to the breakage of the cement links, implying a loss of cohesion. However, when the resistance of cementing links in the soil changes with the level of confining stress, a curved envelope is observed (Cardoso, 2002). In direct shear tests, when the contact surface between particles is augmented as a result of the structural collapse of the soil

with the increase of the confining stress, the shear strength also increases, which when divided by a constant area reflects in a pseudo-increase in the shear strength since the effective contact area is not corrected (Figure 8, CS2). This behavior can be better understood through the model presented by Camapum de Carvalho & Gitirana Junior (2005). Lateritic soils with a low degree of cementation in and between aggregates (Figure 8, LS) and saprolitic soils (Figure 8, SS) tend to present linear shear strength envelopes.

Cardoso (2002) showed that in moderately weathered soils significant dispersion in shear strength results could occur as a function of confining stress. This is due to the greater heterogeneity of these soils (Figure 8, TS). It is important to note that the shear strength envelopes shown in Figure 8 can be shifted as a result of changes in the degree of saturation and in the matric suction. Eventual changes in the friction angle can occur as a result of the loss of strength of the aggregates due to the reduction of matric suction or by chemical actions.

2.3 The soil-water characteristic curves of tropical soils

Before discussing unsaturated tropical soils' physical properties and behavior, it is relevant to present typical shapes of soil-water characteristic curves (SWCC) generally found when studying these soils. Figure 9 shows the types of SWCC behavior most commonly observed for fine-grained lateritic soils (TLS), saprolitic soils free of expansive clay minerals (SS), saprolitic soils containing expansive clay minerals (SSE), well-graded laterite gravel (WGG), uniform laterite gravel (UG) and gap-graded laterite gravel (GOG). It is noteworthy that the curves shown in Figure 9 are only general models of behavior and may vary from soil to soil.

The general shape of the SWCCs, their air-entry values (AEVs), and the slopes of the SWCCs depend on the particle-size distribution, on soil mineralogy, and on soil porosity. However, soil structure and microstructure

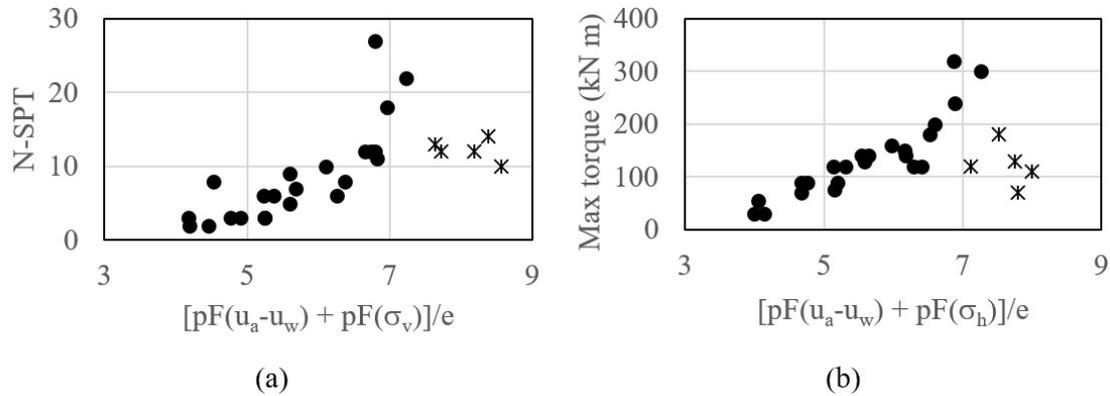


Figure 6. Effect of normalized stress state variables on: (a) NSPT; (b) maximum torque.

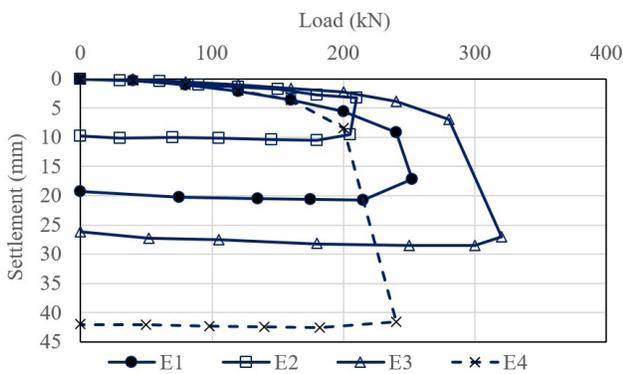


Figure 7. Results of static load tests on piles (modified from Rodrigues et al., 1998).

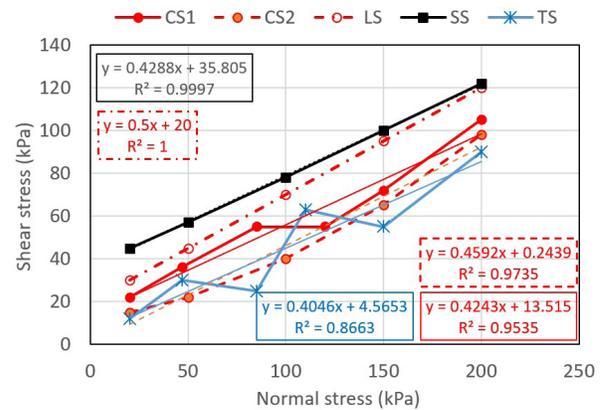


Figure 8. Shear strength envelopes of tropical soils.

also play a significant role. In the case of the three gravely materials (i.e., WGG, UG, and GOG), the AEVs of the macropores indicated in Figure 9 are followed by a plateau. The existence of this plateau will depend on the occurrence of these macropores in significant amounts, which is linked to the level of particle aggregation and soil porosity. The AEVs for the micropores of the three gravely soils are also shown, followed by the residual water content region. This behavior is observed for microstructures of aggregates similar to the one in Figure 4a. However, it is not observed when the microstructure assumes the characteristics of Figure 4b. For the gap-graded lateritic gravel (GOG), the SWCC often presents an AEV at an intermediate level, corresponding to mesopores arising from the loss of continuity in the grain size distribution and, consequently, in the pore-size distribution.

The typical SWCC for lateritic soils shown in Figure 9 has a bimodal shape, with the first drainage section corresponding to the macropores and the second to the micropores (Camapum de Carvalho & Leroueil, 2004). This behavior is generally attributed to aggregated materials. Multimodal curves are sometimes observed and can be modeled by extending existing fitting equations, such as that proposed by Gitirana Junior & Fredlund (2004).

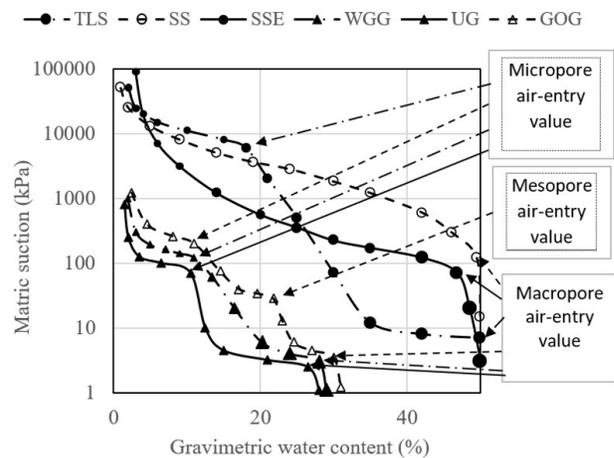


Figure 9. Typical soil-water characteristic curves of soils from tropical weathering profiles.

It is interesting to note that in the macroporosity zone, where matric suction is relatively low, the aggregates' volume tends to be relatively constant. However, when entering the residual zone of the macropores, the amount of aggregate volume change will depend on the level of

internal cementation. The solubilization of these cementing agents due to the chemical action of the medium may also provoke volume change of aggregates. The slope of the SWCC in the macropore's residual zone will depend on the variation in pore-size between aggregates and between non-aggregated particles.

Aggregates lose saturation when their AEV is reached. From a practical point of view, this observation has great relevance. It is current practice in geotechnical engineering to air dry the soil in preparation of soil characterization and even hydro-mechanical testing of remolded/compacted soils. When the water content of the air-dried sample becomes lower than that corresponding to the AEV of the micropores, the aggregates tend to remain unsaturated when the soil is subsequently wetted. The forced drying of soil aggregates results in differences between laboratory testing and field conditions. The excessive drying of samples may also produce micro-cracks in the aggregates, compromising their textural stability. In summary, great attention is required in terms of the representativeness of sample preparation methods of soils with aggregations.

Suction values that produce drainage in the microporosity zone, although generally very high, have a decreased effectiveness in contributing to the improvement of the mechanical behavior of the soil. In this stage, suction starts to act predominantly inside the aggregates, thus reducing its contribution to the state of stress between the aggregates, and, consequently, to the mechanical behavior of the soil as a whole. Figure 10 illustrates this behavior and indicates that the maximum values of the simple compressive strength (SCS) and of the tensile strength (TSDC) correspond to the AEV of the micropores (Valencia et al., 2007; Valencia et al., 2019).

The typical SWCC for saprolitic soils free of expansive clay minerals follows a pattern commonly found in sedimentary soils, because in this case the particles are dispersed or flocculated, but not aggregated (Camapum de Carvalho, 1985; Camapum de Carvalho et al., 2002a). The AEV and the slope of these curves will depend on the soil porosity, particle-size distribution, pore-size distribution, and soil

mineralogy. Typically, these soils do not show significant compressibility with increased suction after AEV.

Finally, considering the typical SWCC of saprolitic soils containing expansive clay minerals, attention is drawn to its loss of linearity after air entry. This loss of linearity may be attributed to the change in hydration of the expansive clay minerals, causing the volume of the particles to vary and, consequently, generating changes in soil porosity. This behavior is not observed in soils with low content of expansive clay minerals and when such minerals do not have a relevant structural function.

Studies analyzing SWCCs of expansive soils have generally focused on bentonite materials. However, these studies should be extended to tropical saprolitic soils containing expansive clay minerals. Barreto (2019) proposed a method for considering the effect of soil porosity of expansive non-tropical soils. Tripathy et al. (2014) present a study of SWCCs of three clays, designated as MX80 bentonite, Yellow bentonite, and Speswhite kaolin. In defining the SWCCs as a function of the void ratio, the authors considered the values of specific gravity obtained for the dehydrated minerals, respectively, 2.80, 2.84, and 2.61. Such consideration leads, in the case of expansive clay minerals, to high void ratio values. However, in these cases, it is critical to define the interparticle water content. Interparticle pores and the corresponding water content control the hydromechanical behavior and even other properties, such as the Atterberg limits. This interpretation of the relevant water content was also presented by Chen et al. (2019), when analyzing the hydraulic conductivity of a unsaturated compacted bentonite. The literature has treated the pore space corresponding to the basal interplanar distance as "microporosity" (Sedighi & Thomas, 2014; Navarro et al., 2015; Chen et al., 2019). However, when analyzing the properties and behavior of tropical soils, it is suggested to reserve the term microporosity only for the intra-aggregate pore space. In special cases, depending on the pore size, pores existing outside the aggregates and between independent particles may also be referred to as micropores.

2.4 Physical characteristics of tropical soils

The physical characteristics generally considered in studies of tropical soils are the specific weight of the particles, particle-size distribution, pore structure, Atterberg limits, porosity, and gravimetric water content. From these characteristics, others can be calculated, such as the degree of saturation and the dry unit weight. However, when interpreting these characteristics, little attention is paid to the pore structure and effects of hydration or dehydration. Emphasis will be placed here on the study of the specific weight of particles and particle-size distribution and their impacts on the analysis of soil porosity. The interference of these studies on the properties and behavior of unsaturated soils will also be considered. A great focus will be placed

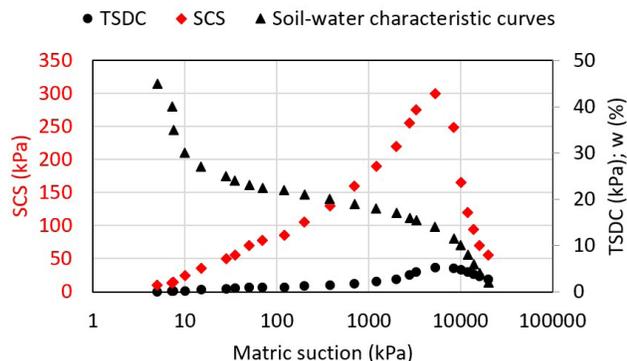


Figure 10. Suction influence on the behavior of aggregated tropical soils (modified, Valencia et al., 2007, 2019)

on the peculiarities of tropical soils that distinguish them from sedimentary soils.

2.4.1 The specific weight of particles

The specific weight of particles corresponds to the chemical-mineralogical composition of the soil. This association is particularly relevant in deeply weathered tropical soils (i.e., lateritic soils) and must consider their texture. The specific weight of the particles also changes with the hydration level of expansive clay minerals, which are often present in slightly weathered tropical soils (i.e., saprolitic soils). It should also be taken into account that aggregates and micro aggregates present in deeply weathered tropical soils have internal pores that are not connected to the external environment, thus generating a decrease in the value of the specific weight of the particles (Palocci et al., 1998).

The concept of an “apparent” specific weight of the particles is useful in the interpretation of the behavior of deeply weathered soils containing voids inside the aggregates, including their SWCCs and their general hydromechanical behavior (Camapum de Carvalho & Pereira, 2002; Camapum de Carvalho et al., 2002a, b; Camapum de Carvalho, 2017). This concept and the corresponding modeling approach are presented in Camapum de Carvalho et al. (2015a) and are based on the concepts shown in Figure 11. The model for the

interpretation of soil behavior was based on tests carried out on soils from Goiânia, Brazil (Figure 11a) and the Federal District, Brazil (Figure 11b). In this conceptual model, iron spheres were used to symbolize iron concretions, and glass spheres were used to represent aluminum concretions. The iron spheres were hypothetically assigned a relative density of 5. In the case of glass, a relative density equal to 2.5 was considered. This model will also be used, due to its simplicity, when dealing with other physical indices.

Figure 11a shows a compact laterite without pores in its interior, except for those corresponding to cracks, which are represented by spheres. In this case, both the mechanical behavior and the SWCC will be influenced by the pores existing between the aggregates and/or between the microaggregates. In Figure 11b, the aggregates have internal voids. According to Figure 11b, these voids may or may not be connected to the external environment, between the aggregates. The communication between the pores in deeply weathered tropical soils influences the material's behavior and its SWCC (Figure 9). The connected internal voids impact soil water content, global void ratio, and degree of saturation but do not interfere with the soil properties and behavior, as shown by Camapum de Carvalho et al. (2002b) when analyzing the collapse of a soil profile from the Federal District, Brazil. Camapum de Carvalho et al. (2002a), when analyzing the transformation model of the SWCC proposed

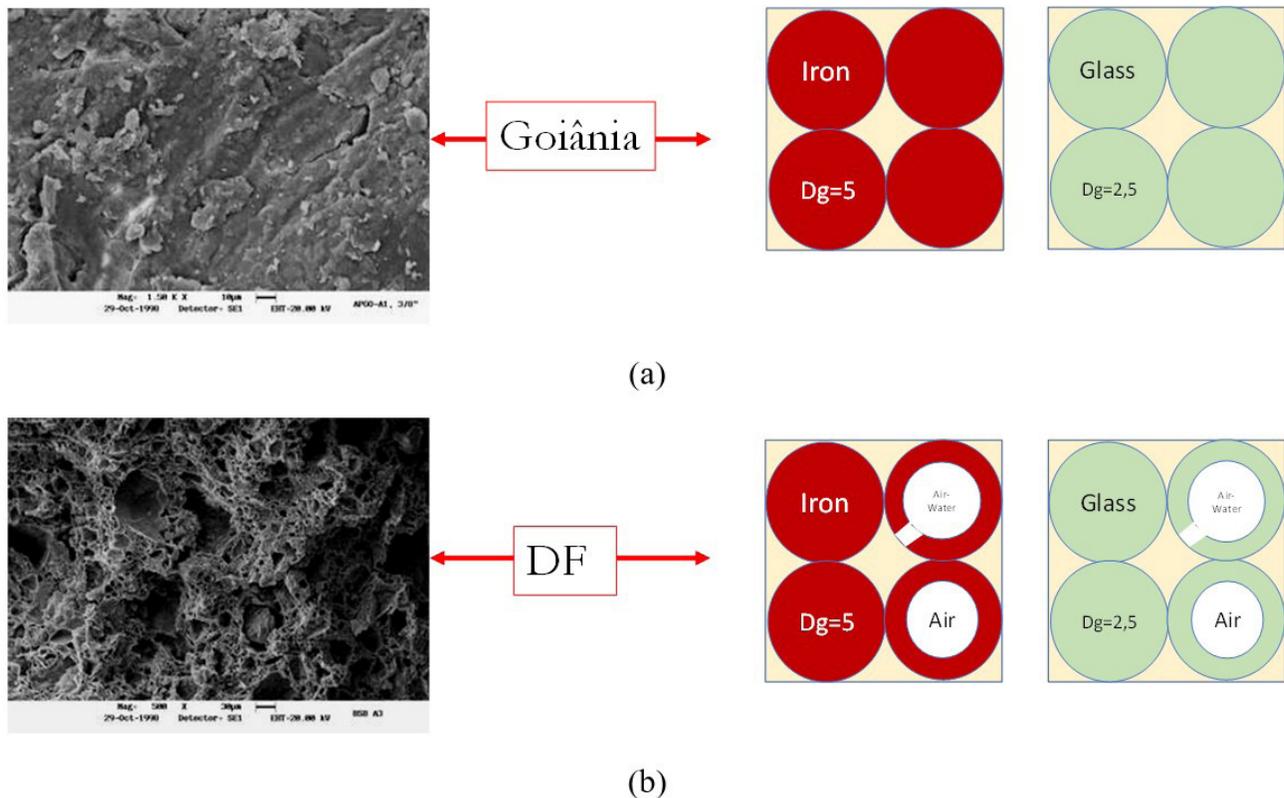


Figure 11. Model of pore-volume distribution in laterites and lateritic soils: (a) concretion from Goiânia, Brazil; (b) concretion from the Federal District (DF), Brazil.

by Camapum de Carvalho & Leroueil (2004), demonstrated the need to consider the pore structure in this analysis.

Slightly weathered tropical soils without expansive clay minerals may present expansion only of structural nature (i.e., increase in the distance between particles). In this case, the analysis of soil properties and behavior under unsaturated conditions may follow standard procedures. However, for slightly weathered tropical soils with expansive minerals, the swelling of these soils can be both structural and mineralogical (i.e., swelling of the particles themselves). Figure 12 shows that with the expansion of clay minerals, the volume of solids expands according to the increase in the interplanar basal distance (Camapum de Carvalho et al., 2019). In this case, it is necessary to consider the volume change of the expansive clay minerals and their impacts in the relative density of the particles. It is also important to realize that structural volume changes directly affect the void ratio, while mineralogical volume changes do not. Therefore, since the hydromechanical behavior is a function of the void ratio, it will not directly correspond with the global volume variation in the case of soils containing expansive clay minerals. Due to the difficulties in separating the two types of volume change, studies generally do not make such a distinction (Consoli et al., 2020). In studies applied to the analysis of bentonites, mineral expansion due to increased basal interplanar distance has generally been considered as a variation of soil microporosity (Sedighi & Thomas, 2014; Navarro et al., 2015; Chen et al., 2019) that does not necessarily interfere with the hydromechanical behavior.

To summarize, the analysis of the specific weight of the particles and its influence on the mechanical behavior of soils requires several considerations:

- a) It is necessary to consider the weathering profile and the variation of its chemical-mineralogical composition;
- b) Any analysis of deeply weathered tropical soils considering the void ratio requires attention towards the effect of the pore structure;
- c) Any analysis of slightly weathered tropical soils with expansive clay minerals requires attention towards the hydration or dehydration of clay minerals, with important impact on physical indexes;
- d) The definitions and analyses of the SWCCs obtained of deeply weathered tropical soils require considering the pore structure;
- e) The definitions and analyses of the SWCCs of slightly weathered tropical soils require considering, when present, the hydration or dehydration of the expansive clay minerals.

Adequate interpretation of the specific weight of the particles is essential in dealing with practical engineering problems and in the interpretation of laboratory testing data. For example, Camapum de Carvalho et al. (2019) showed, when analyzing the particle-size distribution curve of a bentonite obtained in hydrometer tests, that it is essential to consider the specific weight of the particles in a hydrated state. The same authors, when analyzing the relationship

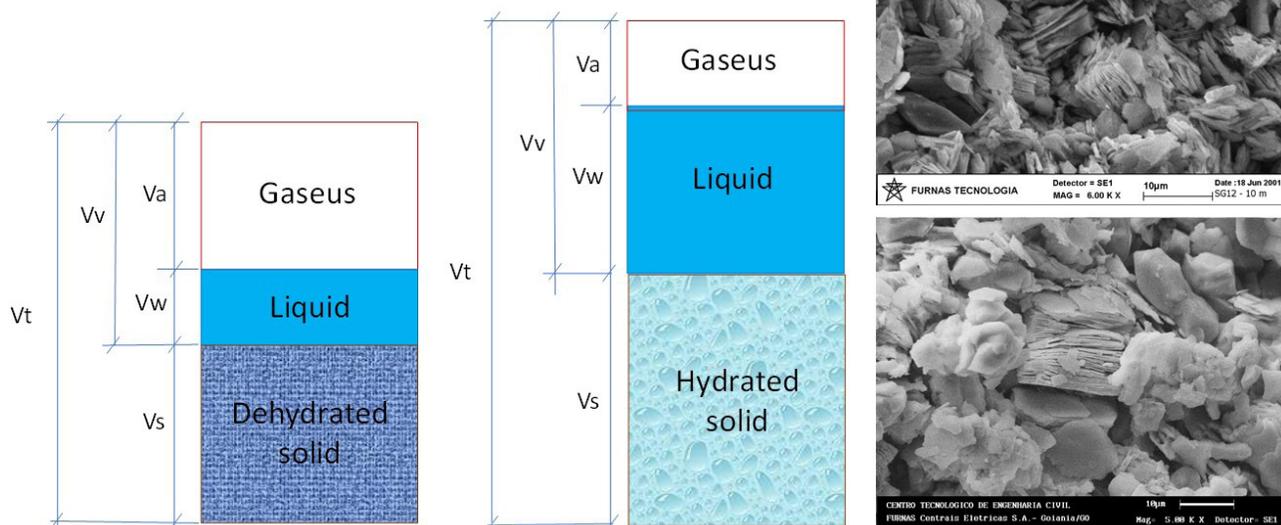


Figure 12. Impact of mineral expansion on the volume of solids.

between the void ratio corresponding to the liquid limit with the Skempton activity coefficient, found that meaningful results are only obtained if the particle-size distribution used is computed considering the specific weight of the particles in the hydrated state.

2.4.2 Particle-size distribution

Important information regarding the structural characteristics of tropical soils that affect their behavior may be obtained from the particle-size distribution (PSD). Particle-size analysis methodologies and the interpretation of results must consider the use of the soil, active suction, and temporal dynamics. Figure 13, obtained for a deeply weathered and aggregated soil (lateritic soil) shows that the PSD can be highly dependent on the sample preparation method (Roseno & Camapum de Carvalho, 2007). For this reason, PSD analyses of tropical soils must always include tests with and without the use of ultrasound and/or deflocculants. The PSDs obtained without dispersion offer information regarding the in-situ state of the soil. In situations where the soil is subjected to chemical stabilization (e.g., pavement structures) or the flow of contaminants (e.g., landfill covers and liners), the impact of these elements on the texture and aggregation must be investigated. In the event of disaggregation effects from soil treatment, it becomes relevant to include the use of deflocculant in the analyses. Obviously, changes in osmotic suction may take place and need to be accounted for.

Ayala (2020), when studying a lateritic soil stabilized with hydrated lime, determined PSDs using hydrometer tests considering: a) the pure soil (SP); b) the soil stabilized with 4% hydrated lime one day after mixing (4% 1D); c) soil obtained from crumbling a compacted cylindrical specimen prepared without the addition of lime (SP 1A); and d) soil from another crumbled specimen mixed with 4% of lime (4% 1A) and kept buried in situ for a year. Figure 14a shows that

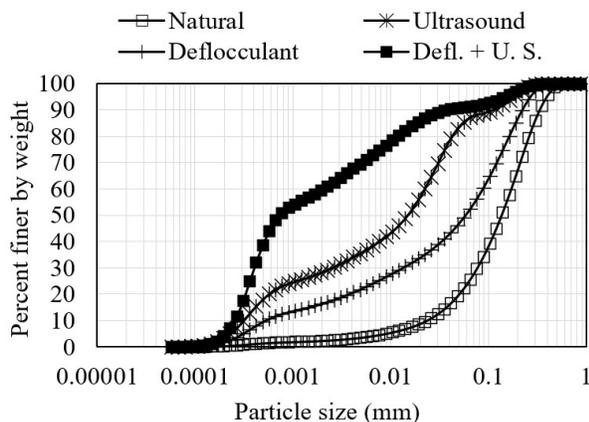
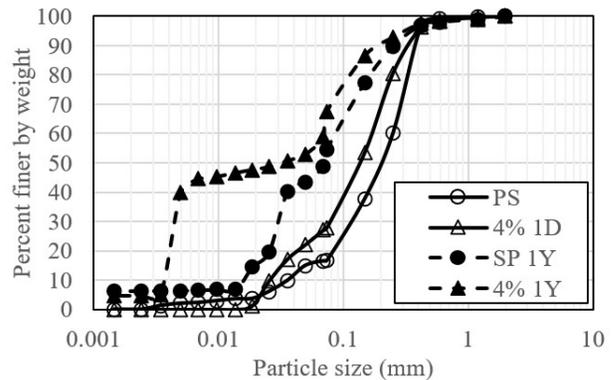


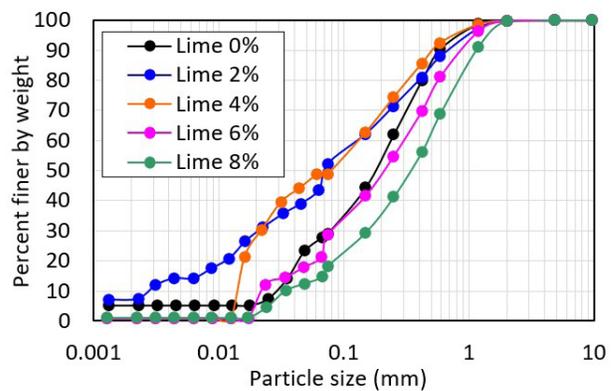
Figure 13. Particle-size distribution curves of a highly weathered soil collected at 4 m in depth, Federal District, Brazil (Modified from Roseno & Camapum de Carvalho, 2007).

the presence of lime affected the textural stability of both treated and untreated soils. Figure 14b, obtained for a soil studied by Delgado (2007), shows that depending on the lime content added to the soil, it can promote its disaggregation or aggregation. The addition of 2% lime disaggregated the soil. In the case of 6% lime content, it practically did not affect the stability of the aggregates or, more likely, it increased disaggregation and aggregation. Finally, with 8% lime, the soil suffered aggregation. These results show the importance of understanding the properties and behavior of tropical soils subjected to chemical stabilization or placed in contact with chemical products, common situations in geotechnical works such as the construction of pavement structures, embankments, dams, foundations, and retaining walls.

Rezende (2003) showed for a lateritic soil treated with 2% of lime that the chemical affected the textural stability and altered the SWCC (Figure 15). The influence of lime on the SWCC obtained by Rezende (2003) was, however, different from that verified in the study carried out by Botelho (2000), thus indicating that the chemical agent can act to



(a)



(b)

Figure 14. Particle-size distribution curves of lateritic soils treated with lime: (a) modified from Ayala (2020); (b) modified from Delgado (2007).

aggregate or disaggregate the soil, depending on soil and the chemical agent itself.

Concrete placed in contact with the unsaturated soils can also be considered a contamination source, as shown by Wanderley Neto (2020), based on direct shear tests were performed on concrete-soil interfaces. The specimens were molded using concrete and a semi-statically compacted lateritic soil. Water content and void ratios corresponded to that of the soil found in the field. Matric suction was measured using the filter paper technique. Direct shear tests were carried out after 10, 14, 28, 60, and 90 days of curing. For the curing time equal to zero, the matric suction in the soil was equal to 4.1 kPa and in the concrete equal to zero. Figure 16 shows the results obtained by Wanderley Neto (2020) for the lateritic-concrete soil interfaces and the suctions measured using the filter paper technique on the soil surface and on the concrete surface. The results show that both cohesion and friction angle increase up to 60 days of curing, decreasing thereafter. The suction in the soil and the concrete increases until 60 days of curing, tending to equalize and stabilize after that time. As deteriorations occurred in the soil-concrete interface between 60 and 90 days, it is useful to analyze the destabilizing effect of the aggregates. Figure 17 presents shear stress results as a function of cure time for different vertical stresses. For the lowest confining stress (50 kPa), there is already a decrease in strength when passing from 28 to 60 days of cure, which demonstrates the loss of stability of the aggregates.

The instability of aggregates verified by Ayala (2020) and Wanderley Neto (2020) may be explained by the penetration of chemical compounds in the aggregate. Under favorable pH conditions, iron and aluminum oxide hydroxides are solubilized. Another example of the instability of aggregates was observed by Silva et al. (2008) when analyzing, 32 years after its construction, a tieback wall built on lateritic soil. Soil volumetric collapse resulted in excessive residual deformations (Figure 18) and the low residual stresses of the ground anchors. It was observed that the collapse was

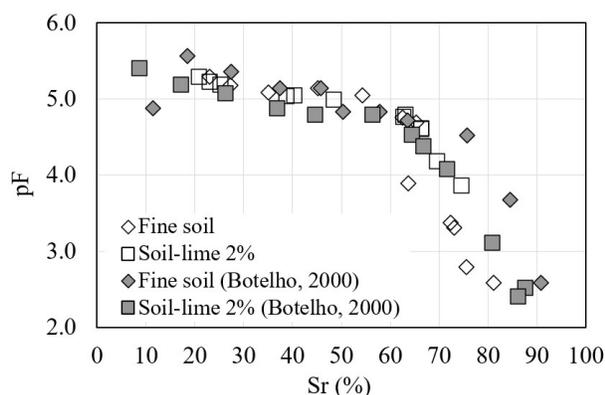


Figure 15. Soil-water characteristic curves of pure lateritic soils and stabilized soils with lime (modified from Rezende, 2003).

due to the loss of stability of the aggregations, as a result of chemical migration from the concrete into the aggregates.

2.4.3 Atterberg limits

The atterberg limits of tropical soils are strongly affected by the state of soil aggregation, chemical composition, and mineralogy. Figure 19 shows the plasticity chart containing data of the tropical weathering soil profile shown in Figure 3. These liquid limits and plasticity indices were originally

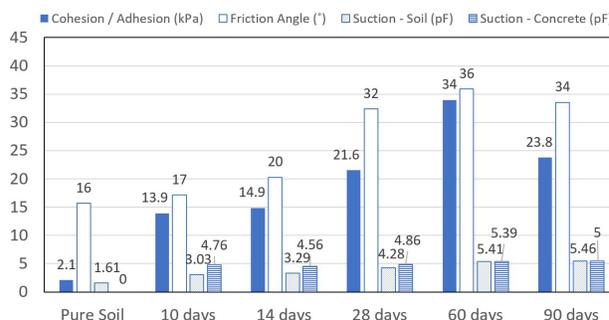


Figure 16. Soil-concrete interaction (Wanderley Neto, 2020).

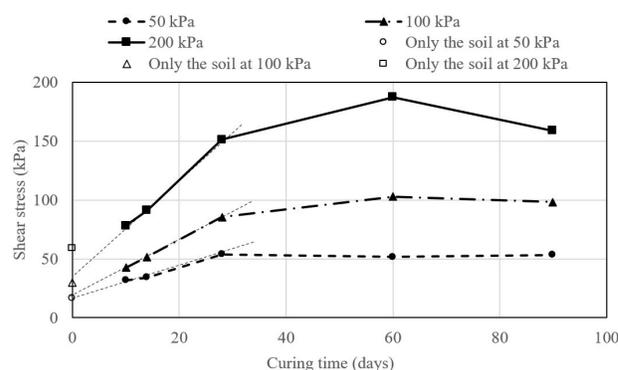


Figure 17. Shear strength in the soil - concrete interface as a function of curing time (Wanderley Neto, 2020).

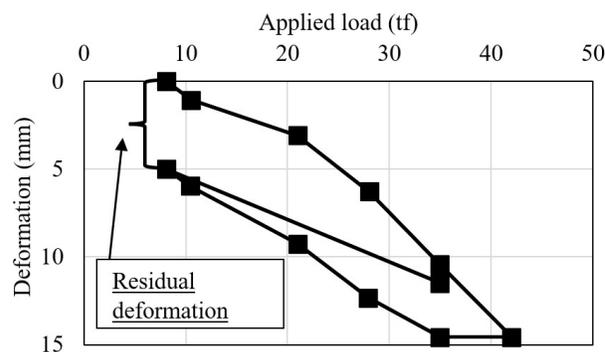


Figure 18. Load test on a ground anchor (modified from Silva et al., 2008).

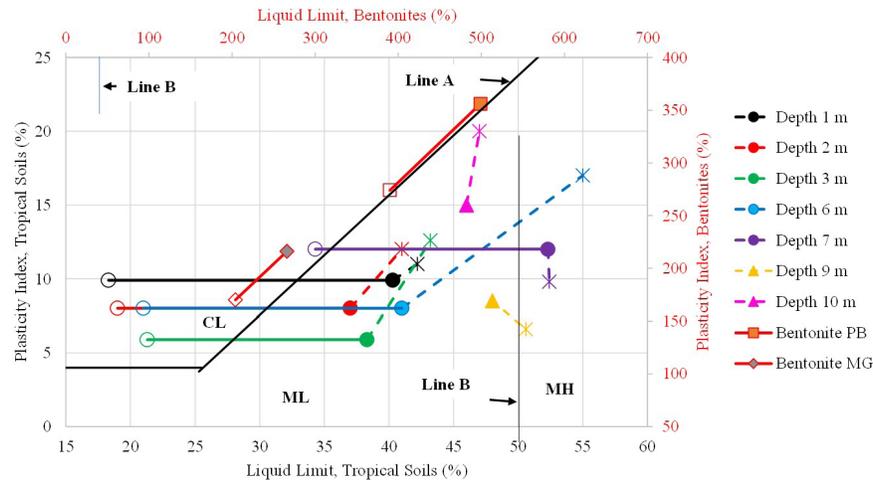


Figure 19. Plasticity chart and tropical soil's data under several conditions.

obtained by Carvajal et al. (2005). The data is presented for: a) the natural soil (filled markers); b) the soil disaggregated using ultrasound (“x” markers); and c) values adjusted by subtracting the intra-aggregate saturation water contents (empty markers). In the latter case, the intra-aggregate water content was estimated considering the content of aggregates and the water content corresponding to the micropore AEV, according to the bimodal SWCC model presented by Camapum de Carvalho & Leroueil (2004). The volume of micropores of aggregates was considered constant when going from the liquid limit to the plastic limit. However, depending on the stability of the aggregates, some volume change may occur. The results from Figure 19, combined with the plasticity chart by Vargas (1977), show that the weathered tropical soils (1 m to 7 m deep) move from the silt-clay classification to soils containing sand, which is more consistent with the soil texture in a natural state (Guimarães, 2002).

Figure 19 shows that disaggregation leads to higher liquid limits and plasticity index values. It is noteworthy that the samples collected at 9 m and 10 m in depth correspond to slightly weathered soils that do not present aggregations. These soils contain clay packages that are easily destroyed by ultrasound. Figure 19 also demonstrated that soil disaggregation releases active particles that can interact with water. These results indicate that the intra-aggregate water content does not contribute to the soil properties measured by the liquid limit and plastic index. Balduzzi & Mayor (1981) reached similar conclusion, based on studies carried out at the Federal University of Paraíba, towards better classification of tropical soils. According to these authors, tropical soils present superior mechanical properties when compared to soils from temperate climate regions with similar plasticity. As explained herein, the water content that effectively defines soil behavior is lower than the global water content (Camapum de Carvalho, 2017; Camapum de Carvalho et al., 2002b). As a result, Balduzzi & Mayor (1981) point out that the plastic limits of tropical soil

can vary significantly depending on the method of sample preparation. This finding may be extended to a greater or lesser degree, depending on the soil, to other tests aimed at evaluating the hydromechanical behavior of tropical soils.

The data presented by Campos et al. (2008) for a bentonite from the state of Paraíba, Brazil ($w_L = 499\%$, $PI = 356\%$), and for a bentonite from the state of Minas Gerais, Brazil ($w_L = 266\%$, $PI = 216\%$) are also shown in Figure 19. To estimate the amount of water occupying the basal interplanar distances, the model presented by Camapum de Carvalho et al. (2019) was used. The results presented in Figure 19, subtracting from the global moisture the water occupying the basal interplanar distances (empty markers), show significant variations in the liquid limits and the plasticity index value. Global void ratios were calculated assuming a saturated state and considering the total water content or only the free water (i.e., subtracting basal interplanar water). For the bentonite from Paraíba, the void ratios corresponding to the liquid and plastic limits went from 13.37 and 3.83 to 5.68 and 1.74, respectively. For the bentonite from Minas Gerais, the same values went from 6.83 and 1.285 to 3.20 and 0.60, respectively. These results underscore the importance of disregarding interplanar basal water content in the interpretation of properties and behavior of expansive clay minerals.

Additional factors must be considered in the case of deeply weathered tropical soils and slightly weathered tropical soils containing expansive clay minerals. Considering the results presented by Carvajal et al. (2005), Fleureau et al. (1993), Guimarães (2002) and Khalili et al. (2004), Figure 20 presents correlations between the liquid and plastic limits and the product of the void ratio and the macropore AEV in pF. The soil data from Guimarães (2002) indicate that superior correlations are obtained when subtracting from w_L and w_p the water content present inside the aggregates and taking only the void ratio corresponding to the inter-aggregate pores, as proposed by Camapum de Carvalho et al. (2015a). Figure 20 show also

that when considering only interparticle moisture and porosity in the analysis of expansive soils, the data points present a superior fit to the trends originally proposed by Camapum de Carvalho et al. (2017) and Bigdeli (2018). This fact highlights the need for such consideration when slightly weathered tropical soils have expansive clay minerals.

In order to highlight the importance of the chemical-mineralogical composition of tropical soils, Figure 21 shows correlations between the aggregate contents determined in the studies carried out by Lima (2003) and the activity coefficients determined according to Skempton (1953) and according to the EMBRAPA (2006) methodology, with the latter being based on the cation exchange capacity (CTC). Superior correlations are obtained using the EMBRAPA (2006) methodology, indicating the need to review how the Atterberg limits of deeply weathered tropical soils (aggregate

soils) are determined and highlighting the importance of chemistry composition for the state of soil aggregation. The data presented in this section corroborates the analyzes shown in Figure 19 and demonstrates the need for further studies on the impact of aggregations and the corresponding structure of pores in the case of deeply weathered soils and of the effect of the presence of expansive clay minerals in slightly weathered soils.

2.5 Soil classification

Soil classification is an important element in Geotechnical Engineering. Its purpose is not to precisely define the hydromechanical behavior of the soil but to indicate the expected general behavior. Design based on parameters estimated from classification indexes should be completely avoided in the case of tropical soils, due to their particular characteristics, properties, behavior, and temporal dynamics. The adoption of theoretical models for estimating SWCCs also requires attention, since it depends on the pore-size distribution, pore structure, and on the chemical-mineralogical characteristics. In this context, there is a need to establish a link with the specific behavior and properties of tropical unsaturated soils.

Deeply weathered soils, fine-grained lateritic soils, and lateritic gravels require the consideration of aggregate porosity and stability against the environment and construction-related loads. The slope of the dry branch of the compaction curve (defined by Nogami & Villibor, 1995) and its relevance for soil classification deserves further analysis, including the behavior of coarse-grained soils. The slope of the dry branch may be linked to variations in suction and/or breaking of aggregates, which depends on the compaction water content. The mass loss immersion test, used to evaluate soil erodibility, may also serve to identify the presence of soil expansion when the soil detaches from the mold. The detachment occurs by shear in the contact plane between the part of the specimen extracted from the mold.

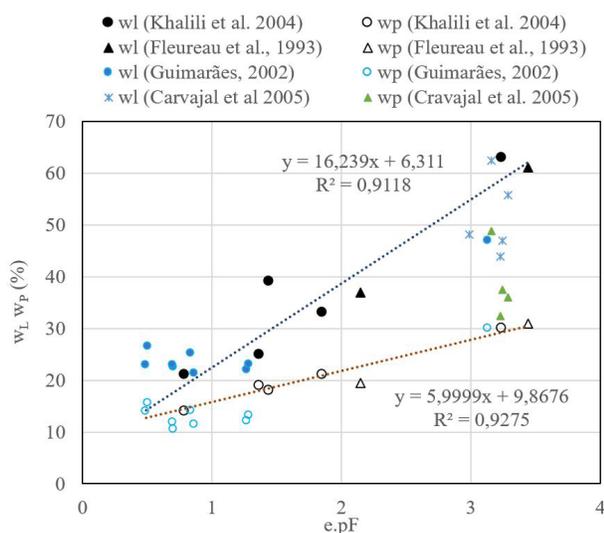
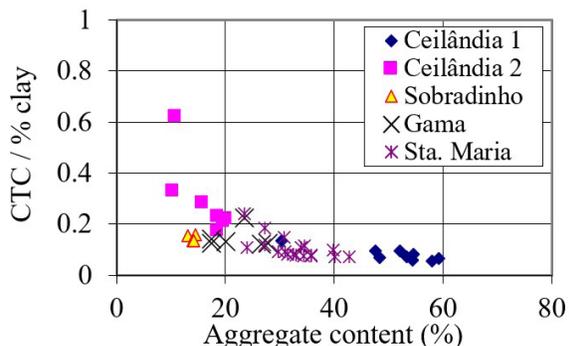
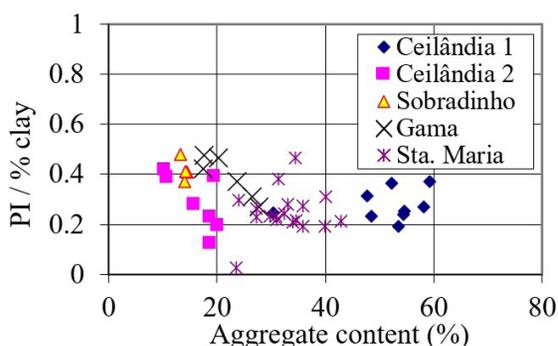


Figure 20. Relationship between the air-entry value transformed by the void ratio and the corrected plastic and liquid limits (modified from Camapum de Carvalho et al., 2017)



(a)

(b)

Figure 21. Aggregate content as a function of: (a) plasticity index; (b) cation exchange capacity (modified from Camapum de Carvalho et al., 2015b).

In traditional classification models, the use of texture as a classification element must be combined with analyzes related to aggregate stability and the distribution of pores in the soil. In this sense, considering the shape of the SWCC (e.g., Figure 9) is relevant for understanding the properties and behavior of tropical soils and for adopting classifications that are more integrated to engineering practice. Another aspect to be analyzed, in the specific case of coarse-grained tropical soils, is the potential PSD discontinuity that may lead to piping erosion (Camapum de Carvalho et al., 1999).

The use of the Atterberg limits in traditional classification systems applied to tropical soils requires two important factors to be considered: a) if the soil is in an aggregated state (i.e., lateritic soil), it is necessary to subtract from w_L and w_p the water present in the interior of micro-aggregates; b) if the soil is slightly weathered and has expansive clay minerals (i.e., saprolitic soils), the water integrating the hydration of these clay minerals must be subtracted from w_L and w_p , it is important to note that these two factors still need further study. The approach presented here aims to encourage researchers to further these studies.

3. Compaction of tropical soils

The compaction of tropical soils requires the understanding of unsaturated and saturated behavior. As the water content is increased, the dry unit weight in the dry-of-optimum branch increases due to: a) the lubricating effect of water, an effect not always preponderant; b) the reduction of suction and the corresponding decrease in the resistance to the compaction process, with effects that depend on the presence of inter-aggregate water (Camapum de Carvalho et al., 2012); c) particle breakage, which is common in aggregate materials such as laterite gravels. Further increase in the water content will lead to the occlusion of the air phase, generating positive pore-water pressures during compaction, and reducing the effective compaction energy. These are the mechanisms that result in the wet-of-optimum compaction conditions.

Given the particularities of tropical soils, some points deserve to be highlighted:

- due to the presence of different levels of aggregation and aggregate stability, deeply weathered soils may present compaction curves with two dry unit weight peaks;
- the crushing of aggregates during the compaction process affects the distribution and structure of pores, the resulting SWCC and suctions acting on the soil, and the dry unit weight;
- in deeply weathered soils (i.e., lateritic soils), where the compaction water content partially fills the macropores, suction is relatively small. As a result, little effect of suction is observed in the compaction

and mechanical behavior of the soil (Camapum de Carvalho, 2004; Parreira et al., 2004);

- in slightly weathered soils (i.e., saprolitic soils), the SWCCs are generally unimodal. The influence of suction on the compaction process and on the soil behavior will depend on the size and distribution of the pores;
- Lambe's theory regarding the influence of water content and compaction energy on the soil structure is only applicable to saprolitic soils. Particle orientation does not occur in highly weathered tropical aggregated soils;
- when a tropical soil is stabilized with asphalt emulsion, the compaction curve must be represented as a function of the fluid content and not the moisture content. The emulsion interferes with the effect of suction, interparticle lubrication, air phase occlusion, and pore-water pressure;
- when the soil has a significant amount of expansive clay minerals, the hydration water content of these clay minerals must be subtracted from the global water content. The weight of these hydrated particles must be taken into account in the calculation of the dry unit weight.

The characteristics of tropical lateritic and saprolitic soils define the shape of the compaction curve and the mechanical behavior of the soil, as illustrated by Nogami & Villibor (1995) in Figures 3.8 and 3.9 of the book "*Pavimentação de baixo custo com solos laterítico*".

Guimarães et al. (1997) showed that the disintegration of the soil using a chemical agent promotes the increase in maximum dry unit weight (Figure 22, black markers). Nevertheless, the mechanical behavior is worsened (Figure 22, red markers). The penetration resistance curves obtained for the natural and disaggregated soil are affected by the different

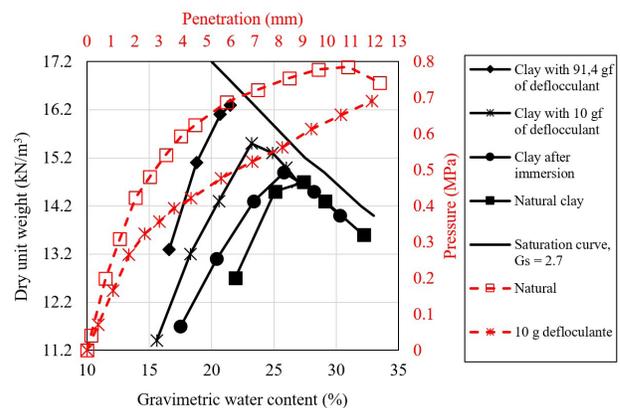


Figure 22. Influence of dispersion on the compaction and resistance of a lateritic soil (modified from Guimarães et al., 1997).

structures and aggregations present in the natural soil and by the dispersed particles in the disaggregated soil. In addition, the reuse of tropical soil and its prior drying can affect the compaction results (Aquino et al., 2008).

The aggregates in deeply weathered tropical soils are affected by the chemical actions of the environment. Therefore, it is necessary to consider the quality of the water used in compaction. The composition of the water used in laboratory studies is often different from that of the water in the field. The solubilization and, in some instances, the leaching of chemical compounds such as iron and aluminum oxides and hydroxides can promote textural and structural instability in deeply weathered soils (Farias et al., 2002).

Figure 23 shows the impact of water quality on the compaction curves of a deeply weathered soil collected at 5 m in depth and of a slightly weathered soil, collected at 9 m in depth (Coelho et al., 2016). The stream water used for compaction was contaminated by domestic sewage. These results show that, in slightly weathered soil, the water quality affects the optimum water content, but has little effect in the maximum dry unit weight. This finding indicated the potential influence of the osmotic suction. For the deeply weathered soil, there is an increase in the dry unit weight when using polluted stream water, indicating the occurrence of instability of the aggregates. These results show the importance of using, in the laboratory investigations, the same water that will be used in the field.

The method of sample preparation can also affect the compaction curve of tropical soils. Figure 24 presents Proctor compaction results obtained for four soils from Urucu, AM, Brazil (Pessoa, 2004). Filled markers correspond to the air-dried soil and the empty markers correspond to testing results using samples that were not air-dried. For the studied soils, air drying resulted in higher optimum water contents and lower dry unit weights. Different results can be obtained for other soils, depending on the sensitivity of its structure to drying.

It is suggested that when studying the compactability of a tropical soil, one should pay attention to variations in the specific weight of particles in situ, the aggregate stability, and the structural and/or mineralogical expansion of the soil. Finally, incorporating iso-suction curves into the compaction curve constitutes important complementary information that allows evaluating how the suction is varying depending on the compaction condition (Camapum de Carvalho & Leroueil, 2004; Camapum de Carvalho et al., 2012).

4. Effective water content and porosity

The study and analysis of the properties and behavior of tropical soils require consideration of the “effective porosity” and “effective water content”, as these are the effective parameters that define the hydromechanical behavior of the soil. The void ratio (e) and global water content (w) are based on the weight and volume of solids dried at 105 °C. The effective void ratio (e') and the effective water content

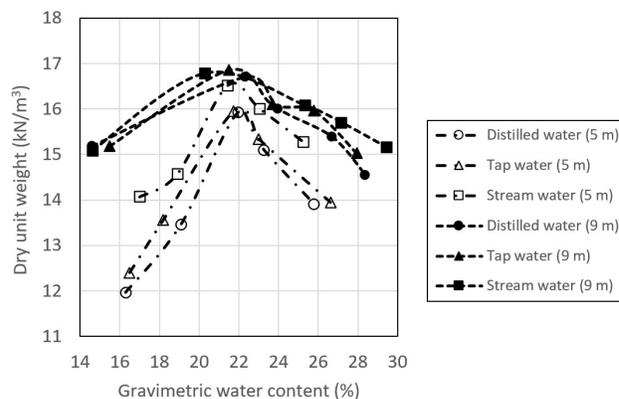


Figure 23. Influence of water quality on the compaction curve of tropical soils (modified from Coelho et al., 2016).

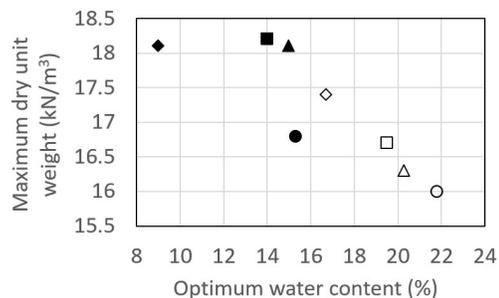


Figure 24. Influence of sample drying on the optimal compaction condition (modified from Pessoa, 2004).

(w') may be computed based on the following methodology: a) for soils with aggregations, only the inter-aggregate voids and water content must be considered. Depending on the water contents and suction, aggregates may be assumed to be saturated and the water contained in them may be incorporated in the weight and volume of solids; b) for active clay minerals, the volume of voids and the water content corresponding to the hydration water must be excluded, thus reducing their densities. Additional assumptions are required. The basal interplanar distance equation shown in Figure 25 (Camapum de Carvalho et al., 2019) was adopted for the calculations of smectite hydration and corresponding specific density presented herein. The data shown in Figure 25 corresponds to a material from the same region were the bentonite studied by Consoli et al. (2020) was collected. Smectites may be assumed to have an average number of layers of 10 and an average diameter of 1 mm.

Figure 26 presents the analysis of compaction curves where the dry unit weight was replaced by the void ratio (regular and effective). The data corresponding to a lateritic soil compacted in normal Proctor conditions (LSPN-e) and intermediate Proctor energies (LSPI-e) was originally presented by Delgado (2002). The dataset for the mixtures of bentonite (B) with kaolin (K) in the proportions 10%B

/ 90%B and 50%B / 50%B was originally presented by Consoli et al. (2020). That bentonite is composed of 70% of smectite, approximately. The slightly weathered tropical soil studied by Delgado (2002) and the bentonite-kaolin mixtures studied by Consoli et al. (2020) present some common minerals. Slightly weathered tropical soils often present 5% to 10% of expansive clay minerals and kaolinite is also often created during weathering. Quartz is also frequently present in tropical weathering profiles, either as a residual mineral or as a newly formed mineral (Senaha, 2019). These common mineral occurrences have motivated the comparisons presented herein. Figure 26 shows the significant difference between the values of global and effective void ratio and moisture contents.

This analysis approach can also be applied to other materials, with varying degrees of aggregation, such as construction waste (Camapum de Carvalho 2017) and sandy-quartzose soils (Machado and Vilar, 1998; Camapum de Carvalho & Pereira, 2002). The effective parameters e' and w' have also been used in the analysis of the SWCC and of the volumetric collapse of tropical soils (Camapum

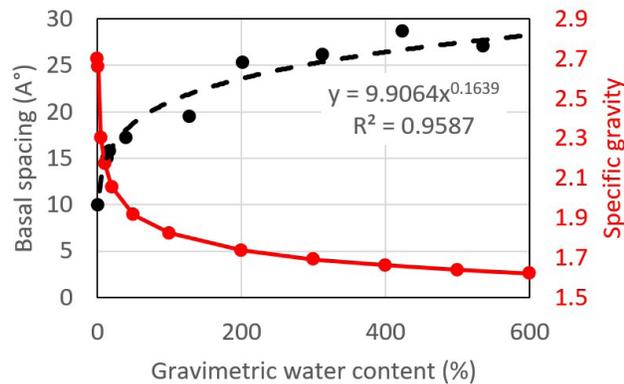


Figure 25. Effect of gravimetric water content on basal interplanar distance and on density of a bentonite (modified from Camapum de Carvalho et al., 2019).

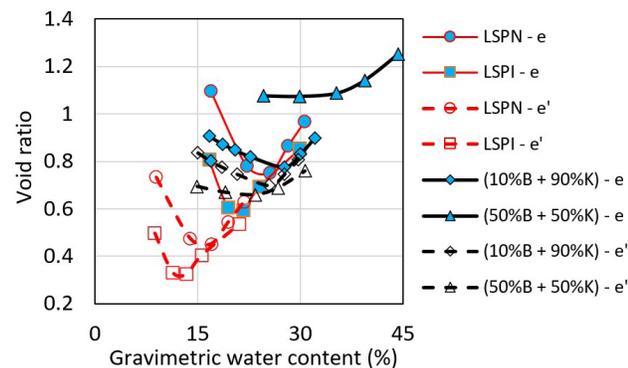


Figure 26. Compaction curves (modified from Delgado, 2002; Consoli et al., 2020)

de Carvalho et al., 2002a; Camapum de Carvalho et al., 2002b). Finally, when studying chemical stabilization, the cation exchange capacity and exchangeable ions should be considered.

The swelling results presented by Consoli et al. (2020) for mixtures of kaolin, bentonite, and Portland cement were analyzed using the effective parameters e' and w' . Figures 27 was obtained considering that swelling is directly proportional to the smectite content and inversely proportional to the Portland cement content, water content, and void ratio. Smectite content was used in the normalization attempt, to isolate the effect of mineralogical expansion and to disregard kaolinite structural expansion (Mielenz & King, 1955 apud Grim, 1962). Figure 27 shows that no clear trend is found when considering global parameter e and w . Swelling is better defined in terms of the effective parameters e' and w' . The need to include the Portland cement fraction should also be recognized. Figure 27 shows also that the transition zone, before the relatively constant swelling behavior, corresponds to a global water content that matches a minimum basal spacing shown in Figure 25. In summary, the use of effective void ratio and effective water contents allows the establishment of meaningful relationships between the state variables.

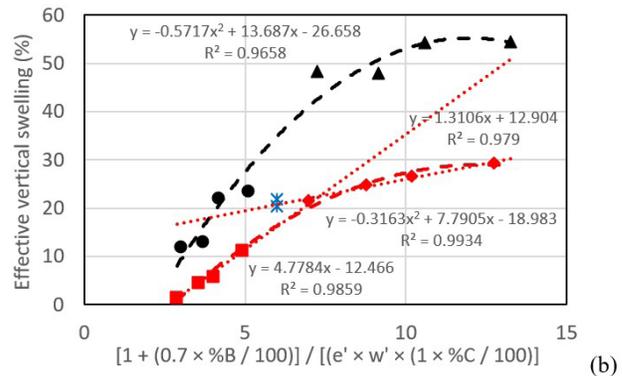
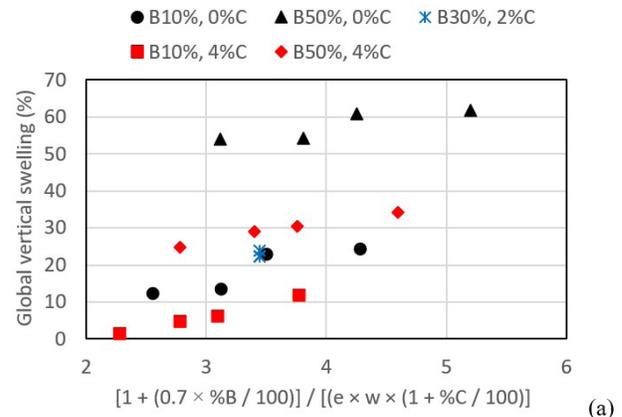


Figure 27. Analysis of swelling considering: (a) global parameters; (b) effective parameters.

5. Temporal and spatial aspects

The impact of time and terrain morphology on tropical soil behavior is related to the level of weathering, mineralogical and chemical composition, structure and physical state, climate, geomorphology, and anthropogenic effects. Therefore, treating engineering problems that involve tropical soils as being static in time is an inadequate approach. Results from Lima (2003), obtained during studies of erosion gullies in the Federal District, Brazil, illustrate the effects of geomorphology and time. Figure 28a shows that the clay content increases when approaching the face of the erosion slope. These findings reveal the degradation of clay aggregates over time, as the gully gradually exposes the soil to the weather conditions. In connection with the change in texture, the sum of the iron and aluminum oxide/hydroxides increases when approaching the erosion edge. Figure 28b shows SWCCs determined by Lima (2003) for undisturbed specimens taken from the same gully erosion location. Well 1 was located 3 m from the edge of the erosion slope and well 2 was located 20 m from the edge. The accelerated weathering observed in the specimens from well 1 modifies the retention properties of the soil, increasing the AEV.

Table 1 shows the data obtained from direct shear indicating a slight increase in the effective friction angle and a significant reduction in effective cohesion when approaching

the erosion edge, despite the increase in clay content and the presence of iron and aluminum hydroxides. This means that the fine particles produced due to weathering have negligible interaction with the soil matrix. The decrease in cohesion is related to the leaching process that occurred in the original structure due to the flow towards the slope. Lima (2003) shows that the factors of safety for the gully slope (height of 15 m and slope angle of 70°) were higher when considering the shear strength parameters from specimens taken from well 2, when compared to the results based on well 1. These factors of safety show the significance of the accelerated soil weathering and degradation. To summarize, the study of erosion gullies in tropical soils clearly demonstrates temporal impacts on the behavior of the soil that should not be neglected.

Another example of temporal effects arise from the analysis of geological data related to slope failures. During a recent conference organized in remembrance to the tragic slope failure events that occurred in 2011 in the state of Rio de Janeiro, Ana Carolina F. Campello (Universidade Federal do Rio de Janeiro) presented the dating of hillside failures that occurred over several past centuries. Figure 29 shows information presented on sediment accumulations over time and information from Marcott et al. (2013) on the temperature variations over the last 11,000 years. The plot shows that during the warming and cooling phases of the

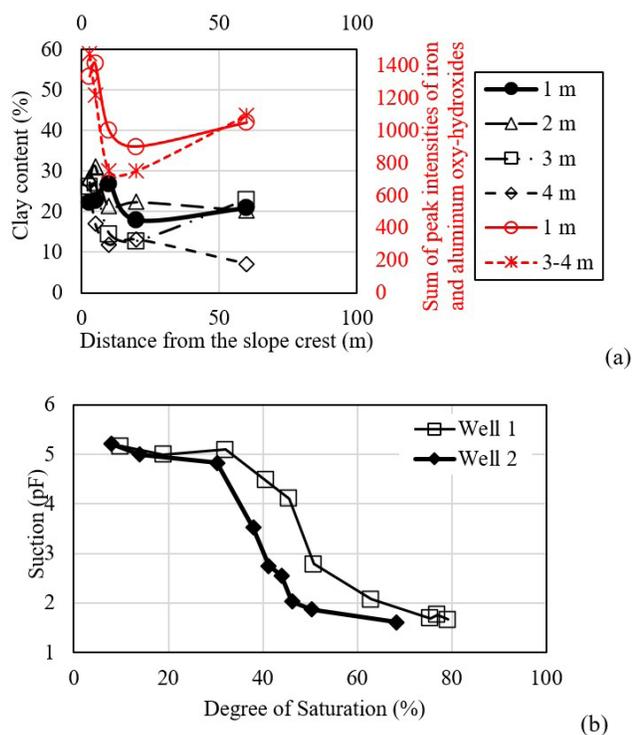


Figure 28. Temporal effects of weathering near an erosion gully: (a) soil composition; (b) soil-water characteristic curves (modified from Lima, 2003).

Table 1. Shear strength parameters from direct shear tests for wells 1 and 2 (Lima, 2003).

Depth (m)	Well 1, 3 m to the slope edge		Well 2, 20 m to the slope edge	
	c' (kPa)	φ' (°)	c' (kPa)	φ' (°)
1	2.2	23.9	4.2	20.8
3	8.7	27.7	23.5	26.1

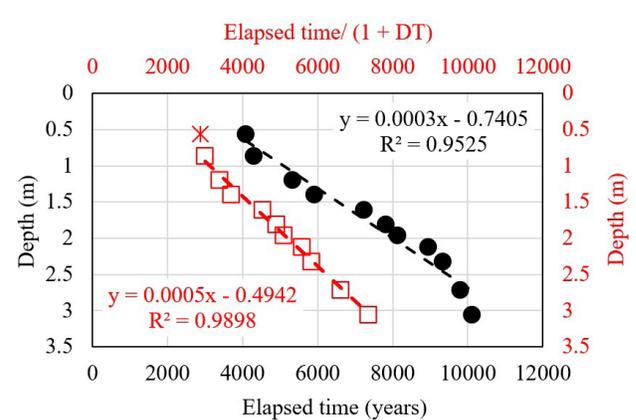


Figure 29. Accumulation of sediments as a function of the elapsed time and as a function of elapsed time normalized by the thermal variation.

planet there was an expansion of the soil profile in relation to time. Thermal variations in the time scale were introduced in Figure 29 by dividing the year of occurrence of the sediment accumulation by $(1 + DT)$, where DT is the thermal variations in the respective sediment accumulation periods. The data normalization led to the linearization of the results, except for the most recent years of accumulation of sediment. This shows the impact of extreme events, anthropic interventions, changes in the microclimate and in the quality of rainwater. This simple and brief analysis highlights the importance of the temperature in altering the soil, which indicates that factors such as insolation and wind must be considered, as they alter the hydrological conditions in the unsaturated media.

The unsaturated soils predominate in most geotechnical works in tropical climate regions and are influenced by weather and drainage conditions. In this context, subsurface and surface morphology plays a significant role. Camapum de Carvalho et al. (2007) present the analysis of a slope of a 12 m excavation that failed in 2005 (Figure 30a). The slide occurred on the concave side of a curved section. Other failures have been observed in the region, under similar conditions, such as the slide shown in Figure 30b. Numerical analyzes and physical modeling (Camapum de Carvalho et al., 2007; Jesus, 2013) demonstrated that the slope morphology influences not only the stress state, but also the saturated/unsaturated seepage conditions near the slope surface. Concave slopes present converging flow near the toe and higher water tables. The opposite effect is observed in convex slopes. The increase in the water table in concave slopes goes against the favorable effects of stress arching.

Some conclusions can be drawn from the analysis of these slopes failures. Terrain morphology must be considered, including its influence on saturated/unsaturated seepage.

The two-dimensional analysis of slope stability does not represent adequately concave and convex slopes. The region right next to the corner where two vertical slopes meet should be carefully analyzed, as it may be negatively influenced by a higher water table. It is expected that these effects of geomorphology will be accumulated over time.

6. Life in the soil and unsaturated behavior

Vegetation, insects, and microscopic organisms can affect the properties and behavior of tropical soils, by changing the characteristics of the environment (Bernardes & Gomes, 2012) and the physical state of the soil itself (Valencia, 2009; Gómez Muñetón, 2013; Guimarães et al., 2017). For example, plants promote the movement of chemical compounds in soils and generate organic matter that influences the aggregation and distribution of pores (Momoli et al., 2017). Termites affect the hydraulic properties of the soil and often incorporate substances that aggregate the particles (Conciani et al., 2009). Bacteria present in tropical soils can affect the cementation and distribution of pores (Valencia, 2009; Gómez Muñetón, 2013). Therefore, temporal, climatic, and geomorphological aspects must also be combined with the influence of living organisms. Figure 31 shows growing bacteria naturally occurring in a tropical soil from erosive processes in the Federal District, Brazil. Studies have been carried out on the use of bacteria to stabilize these erosive processes, by promoting soil cementation through crystallization of chemical compounds. This cementation provides a change in the matric suction acting on the soil and on its mechanical behavior (Figure 32).



(a)



(b)

Figure 30. Slope failures in excavations (Camapum de Carvalho et al., 2007).

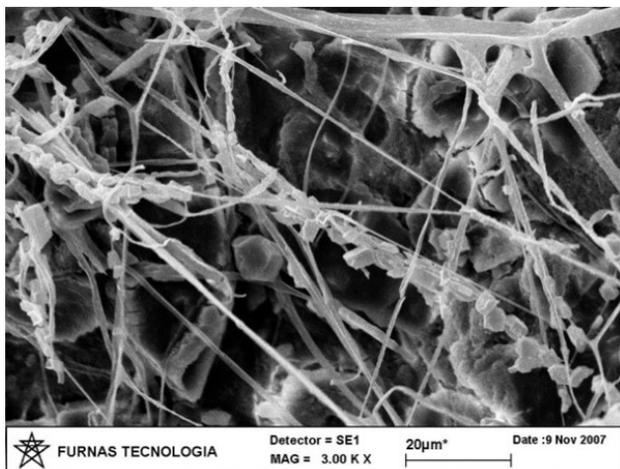


Figure 31. Formation of crystals by bacteria present in the soil (Valencia, 2009).

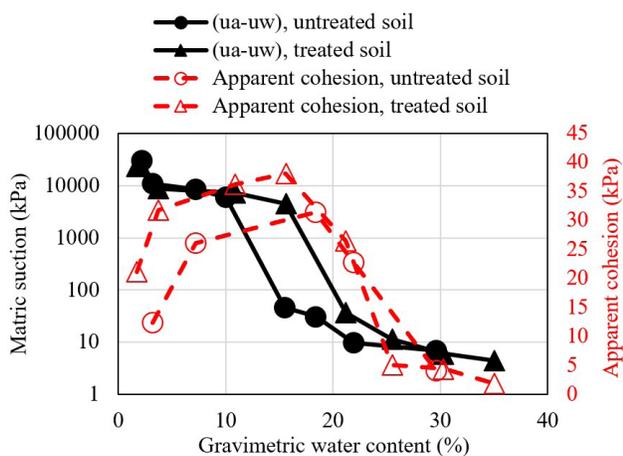


Figure 32. SWCC and apparent cohesion of a soil in a natural state and modified by the action of bacteria (modified from Valencia, 2009).

7. Final remarks

The practice of geotechnical engineering and the use of theories and concepts for unsaturated soils in tropical regions requires the consideration of the particularities of the weathering profiles and their temporal and spatial dynamics. Microstructure, chemical-mineralogical composition, pore structure and distribution, the chemistry of the environment, the geomorphology, and the climatic conditions need to be accounted for.

Classification systems and hydromechanical behavior models developed for sedimentary soils and temperate and cold climate soils are generally also applicable to slightly weathered tropical soils and saprolitic soils. However, its applications to deeply weathered tropical soils and lateritic soils require adaptations that were discussed in this article.

The comparison of the PSD obtained from test with and without the use of deflocculants and ultrasound provide important quantitative information on the soil pore structure, volume of aggregates, and aggregate stability. The representative particle size analysis will depend on the problem at hand. For example, problems where the soil is in contact with domestic sewage requires PSD analyses with and without deflocculants. The evaluation of pavement structures requires PSD tests with and without the use ultrasound. However, if this soil is subjected to chemical action, deflocculants and ultrasound are recommended. In problems involving the chemical stabilization of soils or the presence of fertilizers, it is recommended to evaluate the effect of these compounds on the PSD.

Studies and analyzes of the properties and behavior of natural and compacted unsaturated tropical soils require consideration of their sensitivity to the chemistry of the environment and their alterability as a function of climatic and spatial conditions. In many cases, the temperature has an immediate effect on tropical soils' behavior and on the SWCC. The paper also highlighted the importance of living organisms to the soil's behavior.

Given the complex temporal and spatial dynamics acting on the properties and behavior of tropical soils, it is often necessary to have simplified analysis approaches. The transformed SWCC model proposed by Camapum de Carvalho & Leroueil (2004) offers a useful alternative. However, in the case of aggregated soils, it is also necessary to consider the pore structure, as exemplified by Camapum de Carvalho et al. (2002a). When it comes to the analysis of the mechanical behavior, the use of transformation or normalization models of suction in relation to the void ratio is suggested, taking into account conditions where the parameter is directly proportional to porosity, such as in volumetric collapse (Camapum de Carvalho et al., 2002b), or inversely proportional, such as in shear strength (Camapum de Carvalho & Pereira, 2002). It should be noted that these models do not replace detailed laboratory studies and field monitoring.

Most of the topics discussed herein require further studies and a continuing advance in the understanding of the complex phenomena involving tropical unsaturated soils. The scientific research and engineering practice require consideration of the current State-of-the-Art and State-of-the-Practice, technical standards, the exercise of observation, and, especially, the reflection which is the philosophical basis of engineering. To put this perception into practice, it is necessary to exercise thinking that is free of ties to the norms, dogmas, and previously set knowledge. Past experience should not be neglected, but should be followed without losing sight that it is always evolving, especially in the complex field of geotechnical engineering.

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Declaration of interest

The authors declare that they do not have conflicts of interest that could have interfered with the contents of the paper.

Author's contributions

José Camapum de Carvalho: conceptualization, formal analysis, funding acquisition, writing – original draft; Gilson de F. N. Gitirana Jr.: formal analysis, writing – review & editing.

List of symbols

AEV	Air-entry value
CTC	Cation exchange capacity
c'	Effective cohesion
e	Void ratio
e'	Effective void ratio
PI	Plasticity index
G_s	Specific gravity
N-SPT	Number of blows
PSD	Particle-size distribution
SPT	Standard penetration test
SWCC	Soil-water characteristic curve
w	Gravimetric water content
w'	Effective gravimetric water content
w_L	Liquid limit
w_p	Plastic limit
ϕ'	Effective friction angle

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