Influence of Physicochemical Interactions on the Mechanical Behavior of Tropical Residual Gneiss Soils

M.M. Futai, W.A. Lacerda, A.P.S. Martins

Abstract. When soils are inundated with liquids other than water, a physicochemical interaction takes place and can alter the soil behavior. Depending on the type of soil and on the solution, the soil can become more compressible and lose strength (or the contrary). In this paper, tropical residual gneiss soils are used, namely lateritic and saprolitic soils. The solution used are a mixture of sodium hexametaphosphate and sodium carbonate. Solutions were prepared with different concentrations such that the pH value remained at 10.5. Sodium concentration was used to interpret the results. Oedometer and triaxial compression tests were carried out with samples permeated with these solutions. The lateritic soil behavior was found to be quite distinct from the saprolitic one. While the lateritic soil becomes much more compressible upon the increase in the concentration of sodium, the saprolitic soil swells progressively. However, the compression curve converges at more elevated stress levels. The stress-strain curve also alters in relation to the concentration. The lateritic soil loses strength and its stiffness is greatly reduced with the increase in concentration.
Keywords: physicochemical, tropical soil, lateritic soil, saprolitic soil.

1. Introduction

Physicochemical interactions often have a damaging impact on natural soils, such as excessive settlements and expansion, failures due to piping associated with dispersive clay soils, the contamination of underground water by the migration of contaminants, etc. Furthermore, in these situations, the knowledge of physicochemical properties constitutes an important tool for diagnosing and for solving problems. Physicochemical interaction can turn soils not previously presenting engineering problems into problematic soils. For example, non-expansive soils can swell or non-collapsible soils can be deformed through collapses caused by the infiltration of liquids that alter the soil structure.

Tropical soils have quite a different chemical and mineralogical composition as compared to temperate soils, as they have a dominance of minerals with a variable charge as well as distinct electro-chemical behavior. Consequently, research is needed to expand the knowledge of the mechanisms and factors related to physical and chemical interaction processes and their impacts in terms of structural changes and geo-mechanical behavior.

In the literature, various experimental works were found referring to the physicochemical interaction of different liquids (salt, acid, base, organic) with the soil. The studies in question investigated permeability, (Anandarajah, 2003), compressibility (Bolt, 1956; Abdullah *et al.*, 1997; Alawaji, 1999; Chen *et al.*, 2000; Brancucci *et al.*, 2003 and Sivapullaiah & Manju, 2006) and shear strength (Moore, 1991; Anandarajah & Zao, 2000 and Brancucci *et al.*, 2003). The works cited used predominantly clayey or pure clay soils and a mineralogical composition consisting of illite, kaolinite, montmorillonite or mixtures of these minerals. The samples were prepared through remolding or compaction. Chen *et al.* (2000) studied the influence of different liquids on the compression of soils and used the dielectric constant to compare the influence of different fluids. Anandarajah & Zao (2000) did the same with triaxial tests. Sivapullaiah & Manju (2006) used sodium hydroxide (NaOH) in different concentrations to study the compressibility of kaolinite. The pH of a solution with NaOH is known to vary according to the concentration, while Sivapullaiah & Manju (2006) also found that NaOH transforms kaolinite into zeolite; in other words, it attacks the clay chemically.

Our aim is to verify the physicochemical interaction in the behavior of tropical soils with a base solution containing sodium. The chemical and mining industries frequently use sodium hydroxide (NaOH) and, as a result, produce Na concentration effluent. NaOH significantly increases pH and, for this reason, the dispersion of clay is attributed to the increase in the basic pH. We used a combined solution of sodium hexametaphosphate and sodium carbonate which has a physicochemical interaction similar to that of NaOH. The proportion of this mixture allows the pH to be controlled so that even when the concentration of sodium varies, the pH remains constant. Therefore, the aim is to investigate the mechanical and physicochemical interaction of the sodium concentration in a basic environment with a principal content. Whenever the influence of the

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concentration of Na is mentioned in the text, it should be understood that this refers to a basic environment of pH = 10.5.

Physicochemical interactions influence various properties of clayey soils, including Atterberg limits, compressibility, permeability and shear strength (Mitchell, 1976). To understand the mechanical behavior of clayey soils, the nature of antiparticle forces must be examined. The most important antiparticle forces are Born's repulsion force, Van Der Waals' forces of attraction and the double layer repulsion force. Most studies involving the influence of physicochemical interactions in the behavior of clayey soils concern sedimentary soils and take into account only double layer repulsion forces, due to the complexity of the quantification of the other forces (Mitchell, 1976). The theory of the electrical double layer (EDL), first developed by Gouy (1910) and Chapman (1913) and later improved by Stern (1924), describes, from both the qualitative and quantitative viewpoints, physicochemical phenomena on surfaces with electrical charges. Although this theory is still commonly used and is still unanimously accepted, it should be noted that in real soils there are fractions with different grain sizes, hindering the effects of the electrical double layer. In common soils, this theory functions for soils which have clay minerals as their predominant fraction.

The repulsion created by the double layer and the electromagnetic attractions resulting from Van Der Waals' connections combined result in the force that defines the tendency towards approximation or distancing of soil particles. Repulsion energy is sensitive to changes in electrolytic concentration, cation valence, dielectric constant, and pH, while attractive energy is only sensitive to changes in the dielectric constant and temperature (Mitchell, 1976).

2. Material and Methods

The tests were performed with tropical gneiss lateritic and saprolitic soil. A chemical solution was used to understand its influence on mechanic behavior. This item describes the characteristics of solutions and of the soil, the methodology used in the oedometer and triaxial tests. All the tests were carried out in a room kept at 20 °C.

2.1. Characteristics of solutions

To simulate real situations in laboratory, in which the soil is percolated with different chemical substances, the interstitial fluid was replaced with a solution used on a daily basis in soil laboratories, with a simple stable chemical composition that can be dissolved in water capable of inducing structural changes without dissolving the clay minerals in the soil. Solutions containing sodium hexametaphosphate $(NaPO_3)_n$ and sodium carbonate (Na_2CO_3), with predefined concentrations and pH = 10.5, were selected. The pH value was adopted to guarantee chemical stability, avoiding the reversal of sodium hexametaphosphate to sodium orthophosphate. The dissolution of the sodium hexametaphosphate in distilled water provided a solution with pH of around 6, with the addition of sodium carbonate (Na_2CO_3), making it necessary to raise the pH to 10.5. The characteristics of the solutions used in the tests are given in Table 1.

The solutions herein will always be identified by the total concentration of sodium ions (Na^+) expressed in g/L. In addition, the solutions chosen to interact with the soil were verified not to corrode the aluminum and latex components used in the tests. In the case of the triaxial tests, the possibility of the interstitial fluid ions in the test samples flowing to the water chamber through molecular diffusion was investigated. A diffusion test was carried out by Martins (2005), and this type of flow was found not to occur.

The treatment of the soils studied with sodium hexametaphosphate $(NaPO_3)_n$ provides sodium cations (Na^+) for the double layer on the larger side of the clay minerals. The phosphate anion $(PO_3)^-$ is absorbed by the smaller side (the edge), while the effect of this adsorption is the transformation of the edge, through the coverage of a mono phosphate -layer, from a positive charge to a negative one. Side-edge and edge-edge interactions are destroyed, and the soil structure becomes more disperse (Santos, 1975). Equation 1 presents the chemical reaction associated with the addition of $(NaPO_3)_n$:

Table 1 - Characteristics of the solutions used in the tests.

Concentration $(NaPO_3)_n$	Concentration (g/L)				Total concentration Na^+(g/L)	pH
	$(NaPO_3)_n$	Na^+(*)	(Na_2CO_3)	Na^+(**)		
0.001 N	0.102	0.023	1.52	0.66	0.68	10.5
0.01 N	1.02	0.23	1.38	0.60	0.83	10.5
0.1 N	10.2	2.29	12.4	5.38	7.67	10.5
1 N	102	22.95	74.7	32.42	55.37	10.5

Note: N - normal state.
Na^+(*) - concentration of sodium in $(NaPO_3)_n$.
Na^+(**) - concentration of sodium in (Na_2CO_3).

$$(NaPO_3)_n \xrightarrow{H_2O} nNa^+ + nPO_3^- \quad (1)$$

The addition of sodium carbonate (Na_2CO_3) can be better understood through the main associated chemical reactions (2) and (3):

$$Na_2CO_3 + 2H_2O \rightarrow 2NaOH + H_2CO_3 \quad (2)$$

$$H_2CO_3 \rightarrow CO_2 + H_2O \quad (3)$$

The hydrolysis of sodium carbonate generates a strong base (NaOH) and a weak acid (H_2CO_3). The presence of hydroxyls in the pore solution, associated with the formulation of sodium hydroxide (NaOH), causes the dissociation of hydrogen (H^+) from the SiOH, AlOH and FeOH groups existing on the edges of the clay minerals, resulting in an increase of negative surface charge of particles and the consequent increase in the repulsion forces of the clay-water system (dispersive effect). Concomitantly, the sodium added by the treatment dislocates the hydrogen and/or aluminum adsorbed by the soil, which go to the pore solution to neutralize the hydroxyls, resulting in a stabilizing effect on pH (buffer effect). At elevated pH conditions, the tendency for dissociation of the hydroxyl (OH) exposed on the sides and edges of the clay minerals is increased. The higher the pH, the greater the tendency of H^+ to go to the pore solution, the greater the negative charge of the particle, the greater the repulsion force associated with the double layer.

2.2. Characterization of soils

The specimens were collected in the municipality of Ouro Preto in the southeast of Brazil. The geotechnical profile is typical of a residual gneiss soil in a tropical environment. Futai *et al.* (2004) summarize the conventional data of the physical index and the granulometric composition of this location (Fig. 1). The surface layer is a lateritic soil, while the lower layer is a saprolitic soil. The soil samples were collected at 1 m and 5 m depths to represent both types of soil. In this paper, results of geotechnical tests with chemical solutions will be presented and only conventional tests were performed by Futai *et al.* (2004).

The physical index, the Atterberg limits and the grain size analysis results are given in Table 2. The 1 m soil depth is more weathered than the 5 m soil depth, with a lower natural specific weight and a greater void ratio due to the weathering process to which it was submitted. The difference in the specific gravity of soil solids is associated with differences in the mineralogical composition. The level of

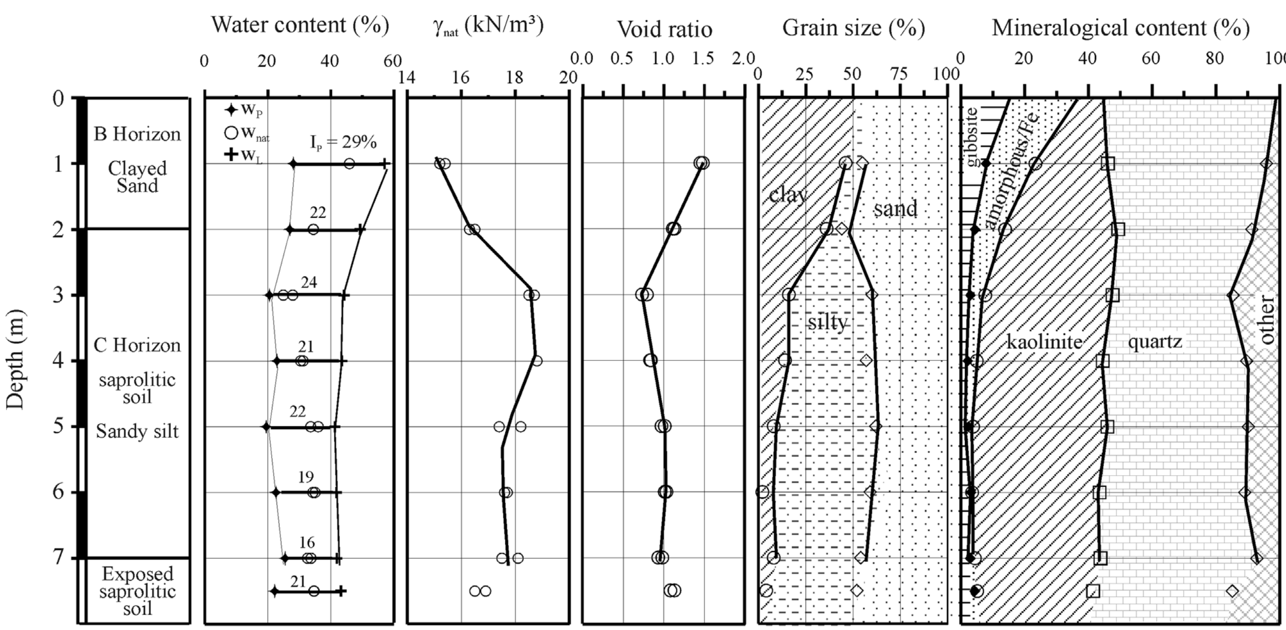


Figure 1 - Site characteristics (Futai *et al.*, 2004).

Table 2 - Physical indices, consistency limits and grain size analysis of the soils studied.

Depth (m)	γ_{nat} (kN/m^3)	w_{nat} (%)	E	G_s	S (%)	w_L (%)	w_P (%)	I_P (%)	Clay (%)	Silt (%)	Sand (%)
1	15.4	45.9	1.45	2.635	83.4	57.1	28.1	29.0	50* (0)	9* (37)	41* (63)
5	17.4	33.6	1.01	2.675	89.0	41.3	19.5	21.8	6 (0)	60 (64)	34 (34)

*according to the Brazilian standard and in brackets: (without deflocculant and without mechanical dispersion).

clay is greater in horizon B, resulting in higher Atterberg limits due to higher clay and oxide content. The degree of saturation demonstrated the unsaturated condition of the profile. The study of the unsaturated behavior of these soils was presented by Futai & Almeida (2005).

The X-ray diffraction (DRX) results are presented in Fig. 2. The soil was sifted in sieve #200. The sample preparation technique was the orientation of the particles of the glass plate method. Apart from natural soil, samples treated with the solutions were also prepared.

The mineralogical composition is essentially constituted of quartz and kaolinite (around 40%), although there is also an important presence of iron oxides and hydroxides and aluminum for the 1 m soil and illite and mica for the 5 m soil. The granulometric composition of saprolitic soil is silt, yet the largest part of this fraction is kaolinite. These data and oxides content explain the plasticity of a soil with a low level of clay. The cationic exchange capacity is less than 2.9 meq/100 g, a low value compatible with the dominant clay mineral (kaolinite). The pH of the soils in water is acid, with a value of approximately 5. The mineralogical composition of the soils determined by DRX (Fig. 2) confirms that 1 m soil depth is more weathered than 5 m soil depth.

The treatment of soils with solutions of sodium hexametaphosphate $(NaPO_3)_n$ and sodium carbonate (Na_2CO_3) did not dissolve the constituent minerals. DRX tests carried out on the fine fraction of the soil treated with the solutions showed (Fig. 2) that there is no change in the mineralogical composition when soils interact with the solutions. Cation exchange capacity tests (Table 3) and selective chemical analyses for sulfuric attack (Table 4) showed that the chemical composition changed little when the results for the natural soil are compared to soil treated with solutions. Thus, the solution used has the same effect as NaOH, although it allows the pH to be kept constant in relation to variations in the Na concentration in the solution.

Scanning Electron Microscopic, SEM, sweep tests show that the intact microstructure of the lateritic soil (1 m depth) is characterized by the aggregation of clay particles caused by the presence of cementing materials (iron oxides and hydroxides and aluminum) with significant porosity (Figs. 3a and 3b). The SEM micrographs of the intact saprolitic soil (5 m depth) showed an interlocking arrangement of the constituent minerals with kaolinite, mica plates (silt size) interwoven with quartz grains and a small amount of clay aggregate. (Figs. 4a and 4b).

Samples were prepared, remolded and treated with a solution corresponding to 7.67 g/L of Na to observe the structure in SEM. The treated body was molded into a ring and was submerged in a solution for twenty-four hours. The remolding of the lateritic soil (1 m) broke the aggregations of connectors, while the rounding and corners disappeared (Figs. 3c and 3d). There was a change in the form and distribution of the pores, which became more uniform. The treatment of the lateritic soil with the solution altered the struc-

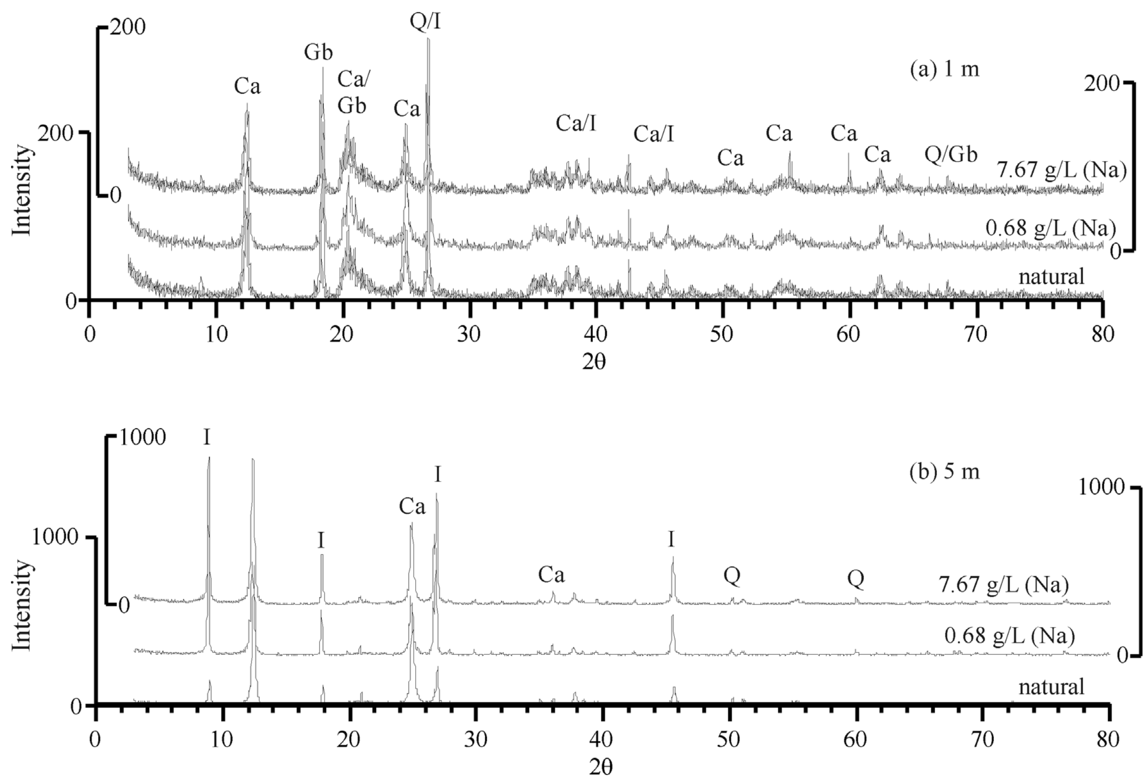


Figure 2 - X-Ray analysis: (a) 1 m depth and (b) 5 m depth.

ture (Figs. 3e and 3f) without any mechanical action taking place. The cementation was broken, making the soil more homogenous and more similar to the remolded soil. However, there was a difference in relation to the form of dispersion, since the physicochemical action is more effective than the mechanical remolding.

In the saprolitic soil (5 m), the remolding destroyed the kaolinite silt particle piles, stimulated the homogeniza-

Table 3 - Cation exchange capacity tests.

Depth (m)	Concentration Na (g/L)	Cation exchange capacity (cmol/kg)						
		$Ca^{2+} + Mg^{2+}$	K^+	Na^+	S*	Al^{3+}	H^+	T**
1	0	0.7	0.04	0.05	0.8	0.0	1.8	2.6
	0.68	0.6	0.01	1.22	1.8	0.0	0.0	1.8
	7.67	0.6	0.06	5,6	6.3	0.0	0.0	6.3
5	0	0.8	0.01	0.01	0.8	1.4	0.7	2.9
	0.68	0.7	0.03	1.36	2.1	0.0	0.0	2.1
	7.67	0.7	0.06	0.82	1.6	0.0	0.0	1.6

*S = ($Ca^{2+} + Mg^{2+} + K^+ + Na^+$). **T = ($S + Al^{3+} + H^+$).

Table 4 - Selective chemical analysis for sulfuric attack.

Depth (m)	Concentration Na (g/L)	Selective chemical (%)						
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O	Ki	Kr
1	0	13.8	22.8	3.7	0.40	0.17	1.03	0.93
	0.68	13.5	23.4	5.3	0.21	0.15		
	7.67	13.3	25.1	5.5	0.44	0.14		
5	0	22.3	18.2	2.7	0.30	1.22	2.08	1.9
	0.68	18	21.7	6	0.07	0.82		
	7.67	27.5	16.3	3.9	0.39	1.45		

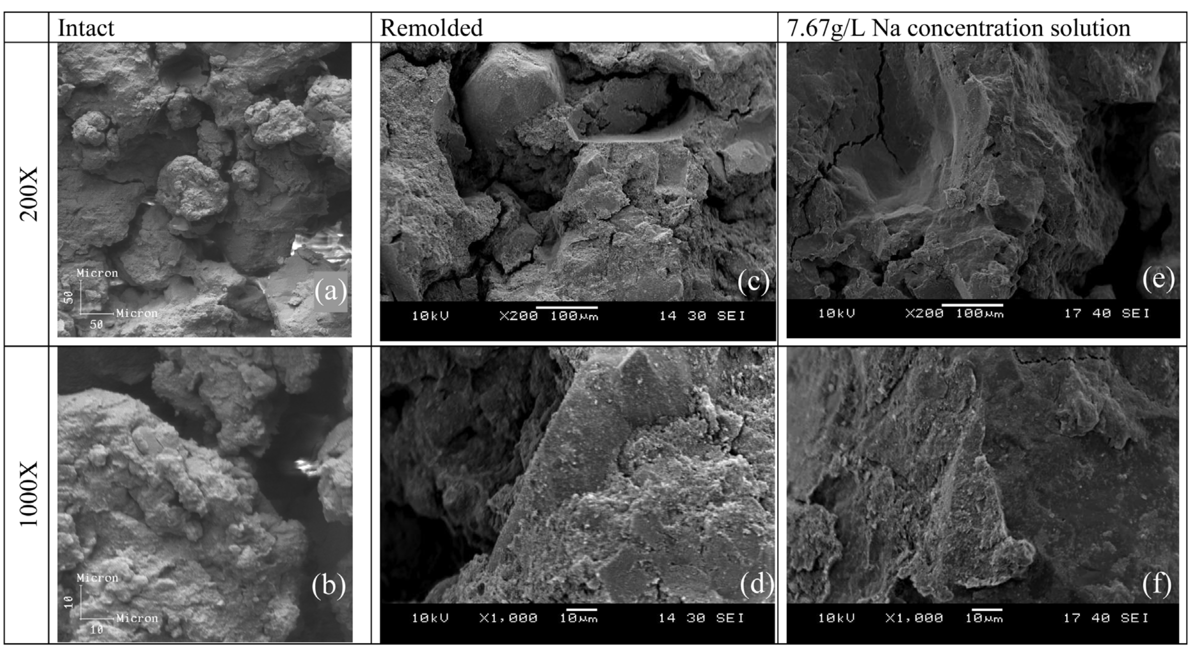


Figure 3 - SEM image of lateritic soil.

tion of voids and a small content of clay remained aggregated (Figs. 4c and d). The reorientation of particles could also be seen due to remolding. Compared with Fig. 4e (or Fig. 4f), in which the sample was treated with the solution, the alteration of the structure was verified not to be as striking as that of remolding.

The Atterberg limits and grain size analyses of both types of soil were obtained using the solutions detailed in Table 1, with the results presented in Figs. 5 and 6. Atterberg-limit values decreased with the increase of the concentration for the 1 m depth (Fig. 5). For kaolinite clays, sodium reduces the rigidity of the adsorbed water, reducing the connection force exercised by this layer, thus facilitating interparticle movement. Consequently, it reduces the water content necessary to reach the limits. Sodium may tend to displace molecules that otherwise satisfy the net negative charge of the clay particles. For the saprolitic soil (Fig. 5), the results did not indicate an influence of concentration. The accuracy of the method did not permit effective conclusions. The low clay fraction influences these observations. Additionally, the soil structure can be compared to explain the difference between two soils due to chemical interaction: the micropores of the 1 m soil depth retain more water than the 5 m soil depth; however, the disaggregation has more influence on the 1.0 m soil depth and the plasticity decreases. The conventional grain size analyses were performed according the Brazilian Standard (NBR 7181) and the tests with solutions (or water) were performed without mechanical dispersion. The results of the grain size analysis for the lateritic soil (Fig. 6a) showed a significant increase in the clay content with an increase in the total concentration of sodium, and the consequent reduction in the sand

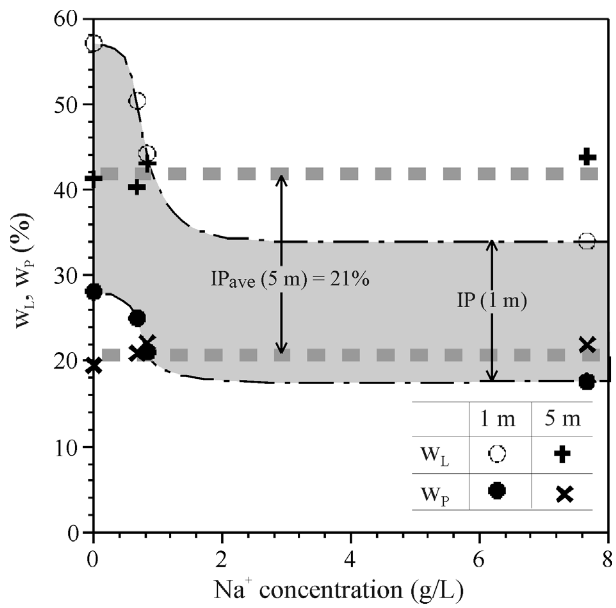


Figure 5 - Atterberg Limits using solutions, 1.0 and 5.0 m depths.

and silt fractions to compensate this increase. The saprolitic soil (Fig. 6b) presented different behavior in relation to the grain size analysis, with the clay, silt and sand fractions varying little with the increase in the total concentration of sodium. This is because the clay aggregation content is low, but it remains after treatment. When the soils were tested without deflocculant and without mechanical dispersion, the clay fraction was null. After the comparison with the results of the methodologies with and without chemical deflocculant, it indicated that the clay fraction is flocculated in the *in situ* condition.

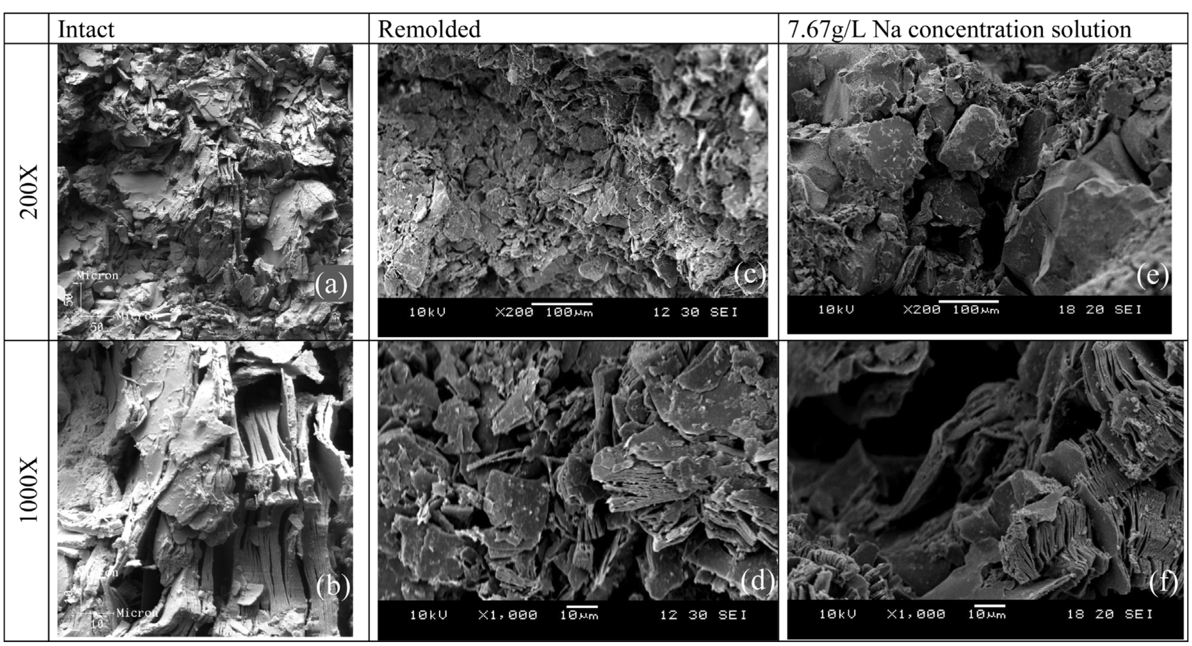
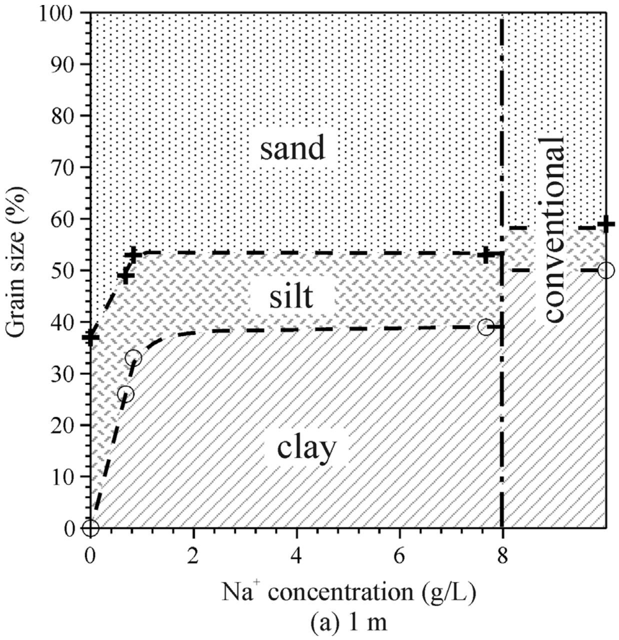


Figure 4 - SEM image of saprolitic soil.



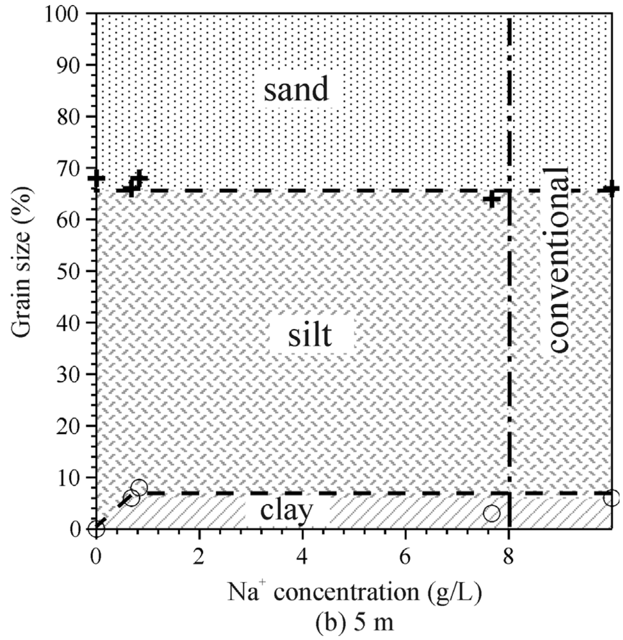


Figure 6 - Grain size analysis using solutions, 1 and 5 m depths.

2.3. Oedometer compression tests

Conventional oedometer tests were carried out on inundated samples of lateritic and saprolitic soils, which were intact, remolded and permeated with solutions containing sodium at concentrations of 0.68 g/L; 0.83 g/L; 7.67 g/L and 55.37 g/L. The samples were inundated with distilled water or with solutions after the stabilization of the settlement corresponding to the 3.125 kPa stage (settlement load). The increases in load stages maintained the ratio $\Delta\sigma_v/\sigma_v = 1$. In the tests with the solutions, after the stabilization of the deformations corresponding to the inundation with solution, the samples were percolated with a volume of the solution equal to twice their void ratio. The duration of each loading stage was sufficient to allow for the stabilization of deformations.

The soil parameters were obtained using conventional methods. The pre-consolidation stress was determined by the Casagrande method and was called vertical yield stress, σ_{vy}.

2.4. Triaxial tests

The objective of the triaxial tests was to study the influence of physicochemical interactions on the stress-strain behavior and on the shear strength for the lateritic soil sample. Tests were carried out in the saturated condition, both drained and undrained, using remolded soil at approximately the liquid-limit, and permeated with solutions with total sodium concentrations of 0.68 g/L and 7.67 g/L. The results of these tests were compared with those of the intact soil. The test samples (diameter 50 mm; height 100 mm) were saturated by back-pressure saturation, and the B coefficient was considered to be satisfactory when greater than 0.96. The strain rates of tests were determined in accordance to Head (1986). For the 1 m depth, they were 0.011 and 0.04 mm/min for the drained and undrained tests, respectively. The strain rate adopted in the drained tests was justified by the relatively elevated permeability of the soil, resulting from its aggregated microstructure, and from the fact that primary consolidation occurred almost instantaneously. In the test with the solutions, before the saturation stage, a volume of the solution was percolated through the sample equal to twice the void ratio of the samples (approximately 220 mL). The percolation was carried out with an upwards flow, applying back-pressure of 10 kPa at one extremity of the test sample and collecting the percolated solution at the other extremity, open to atmospheric pressure. Simultaneously to the application of the back-pressure, a confining pressure of 15 kPa was applied to the cell to guarantee the integrity of the sample. The percolation required extremely variable times from 30 min to around 12 h, while these times were not related to the sodium concentrations in the solutions. This heterogeneous behavior may be associated with the dispersed effect of the percolating fluid, causing the dragging of fine particles and the blocking/unblocking of flow paths.

3. Results and Discussion

This item will presented results of the oedometer test for 1 m end 5 m depth with solutions described in the methodology. The results of the triaxial test carried out for 1.0 m depth are provided.

3.1. Oedometer tests with the lateritic (1 m depth)

The void ratio of the lateritic soil varies a lot due to its heterogeneity. Various tests were carried out with the same solutions, as shown in Fig. 7, and the compressibility parameters are presented in Table 5. The vertical deformation could not normalize the compression curves. For the samples with the highest void ratio and in the same test conditions, the greater the void ratio, the lower the vertical yield stress was observed.

To facilitate the interpretation of the influence of the solutions used in the compressibility, the results were organized according to the void ratio intervals, as shown in Fig. 8.

The results of the alteration in structure are shown in Fig. 3 and the dispersion of clay in Fig. 6 can also be seen in the compressibility of the lateritic soil. The greater the concentration, the more compressible the soil becomes. In Fig. 8c (samples with the highest void ratio), the tests with concentrations of 7.67 g/L and 55.37 g/L of Na present high compression with the first load.

The compression curve of the remolding soil depends on the initial water content (or void ratio) in which the sample was prepared. Three tests were carried out with different initial water content (Figs. 8b and 8c). It was not possible to prepare remolded samples with e = 1.0, since at

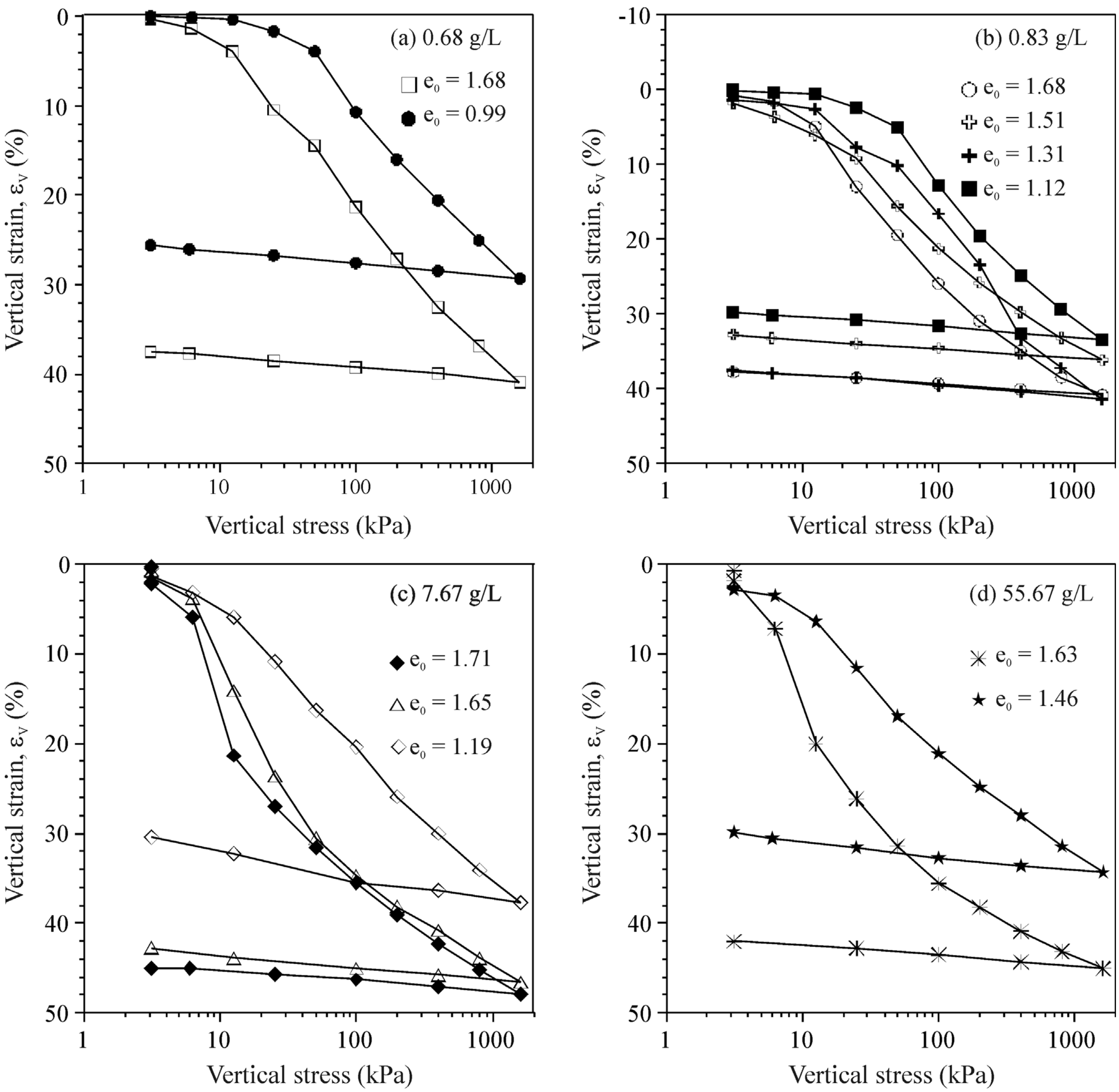


Figure 7 - Compressions curves of lateritic soil (1 m depth): void ratio influence.

this level there was too much water content below the liquid limit.

Figures 8b and 8c allow verifying that the compression curve of the intact soil is positioned above the curve of the remolded soil, a behavior typical of structured soil, in accordance with the models proposed by Vargas (1953) and Vaughan (1988 and 1992). The presence of cementation due to iron oxides and hydroxides and aluminum allows the intact soil to maintain void ratios higher than the remolded soil.

3.2. Oedometer tests with the saprolitic soil (5 m-depth)

Figure 9 shows the results of the oedometer compression tests for the saprolitic soil, while the compressibility curves were also obtained (Table 6). Some tests were carried out in duplicate (Figs. 9a, 9b and 9c) to investigate the heterogeneity of the soil and the repeatability of the tests. The compression curve of the intact soil is positioned below the curve for the remolded soil at the liquid limit, a characteristic that is typical of soils that are not structured by cementation (Vaughan, 1988 and 1992). The 5 m-depth has this structure due to the interlocking arrangement of its constituent materials, and is similar to a highly over-consolidated soil. This aspect was visualized with SEM sweep tests (Fig. 2), as reported above, in relation to the soil description. In Fig. 9d, compression tests were selected with initial vacuum levels between 0.9 and 1 in order to compare the results without the interference of heterogeneity. When the soil was tested with solutions, the results were in an intermediate position between those of intact soils and remolded soils. The greater the concentration, the greater the initial swelling; for higher stresses, the curves are convergent (Fig. 9d). The parameter C_c for $\sigma_v > 500$ kPa is practically the same; *i.e.*, concentration and remolding do not exert an influence, as shown in the detail of Fig. 9. This was limited to a vertical stress equal to 30 kPa and included the volumetric strain due to swell. The intact soil did not swell when inundated with distilled water, while inundation with the solutions caused significant expansions of up to 5% (Fig. 10). The vertical yield stress σ_{vy} is reduced with the increased concentration of Na. This occurs due to the initial swelling which raises the initial part of the curve. The data in Table 6 show that the recompression index did not practically vary for the different conditions tested, while remolding caused the breaking of the mineral arrangement, resulting in destructured soil.

3.3. Comparison of oedometer-testing parameters

The variation in the compressibility parameters with concentration can be seen in Fig. 11. In this figure, the parameters referring to the tests presented in Figs. 8c and 9d were used.

There is a rapid reduction in the vertical yield stress with the increase in the concentration of Na both for the lateritic and the saprolitic soil (Fig. 11a). This behavior is

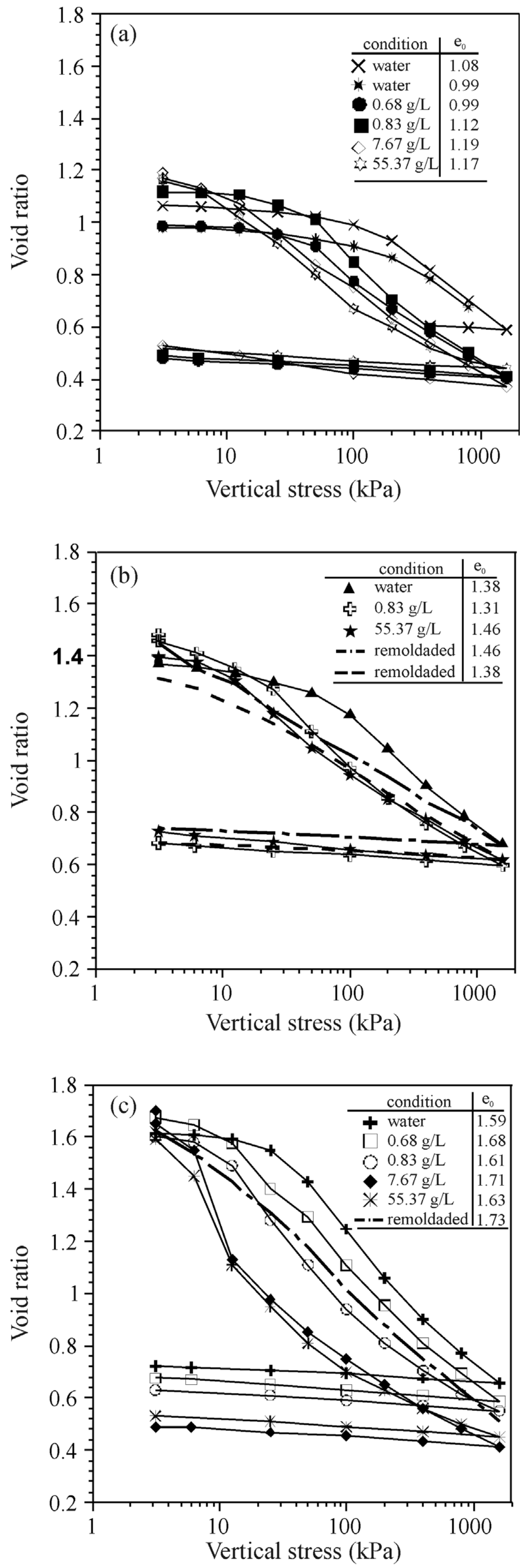


Figure 8 - Compressions curves of lateritic soil (1 m depth): Na concentration influence.

Table 5 - Oedometric compression parameters and initial void ratios, lateritic soil.

Soil condition	Pore fluid	Conc. Na (g/L)	e_o	σ'_{vy} (kPa)	C_c	C_s	C_r
Intact	Water	0	1.62	65	0.51	0.02	0.03
		0	1.38	75	0.42	0.02	0.03
		0	1.08	180	0.37	0.02	0.03
		0	0.98	260	0.35	0.02	0.03
	Solution	0.68	1.68	19	0.47	0.02	0.03
		0.68	0.99	38	0.32	0.02	0.03
		0.83	1.61	9	0.46	0.02	0.05
		0.83	1.50	30	0.41	0.02	0.16
		0.83	1.31	22	0.48	0.02	0.05
		0.83	1.12	45	0.39	0.02	0.03
		7.67	1.71	5	1.36 (5 kPa < σ_v < 15 kPa) 0.29 (50 kPa < σ_v < 1600 kPa)	0.02	0.18
		55.37	1.63	4	0.49 (5 kPa < σ_v < 15 kPa) 0.23 (50 kPa < σ_v < 1600 kPa)	0.02	0.45
		55.37	1.46	9	0.29	0.02	0.05
Remolded	Water	0	1.38	-	0.29	0.02	-
		0	1.46	-	0.32	0.02	-
		0	1.74	-	0.42	0.02	-

not repeated for the compression index. In the lateritic soil, C_c is reduced with the increase in the concentration of Na; however, it practically does not influence the values of C_c in the saprolitic soil (Fig. 11b). The recompression index, C_r, of the lateritic soil is significantly affected by the concentration of Na. In the highest concentrations (7.67 g/L and 55.37 g/L of Na), the values of C_r were greater than C_c (Fig. 11c). This is the result of the occurrence of an abrupt change in the structure under a low load level. Figures 11b and 11c contain a schematic drawing that illustrates this behavior. On the other hand, the values of C_r for the saprolitic soil vary little with the concentration.

Figure 10 shows that the saprolitic soil is significantly influenced by the initial swelling and this is also confirmed in the swelling index, C_s (Fig. 11d). The tendency of C_s increases with the concentration of sodium in the case of the saprolitic soil, but there is practically no influence on the lateritic soil. Figures 7c and 8d show that the compression curves of the lateritic soil are located more to the left as the concentration of Na increases. Conversely, the compression curve for saprolitic soil is found more and more above and to the right according to the increase in the concentration of Na.

Table 6 - Oedometric compression parameters and initial void ratios, saprolitic soil.

Soil condition	Pore fluid	Concentration Na (g/L)	e_o	$e_{after\ swell}$	σ'_{vy} (kPa)	C_c	C_s	C_r
Intact	Water	0	0.92	0.92	280	0.35		0.07
		0	0.87	0.87	320	0.35	0.04	0.12
	Solution	0.68	0.91	0.96	200	0.35	0.07	0.09
		0.68	0.77	0.80	350	0.35	0.07	0.05
		0.83	1.00	1.06	85	0.37	0.1	0.1
		0.83	0.98	1.03	100	0.35	0.1	0.07
		7.67	0.94	1.03	120	0.36	0.12	0.1
		55.37	0.92	0.99	170	0.35	0.1	0.09
Remolded	Water	0	1.22	1.22	0	0.37	0.09	-

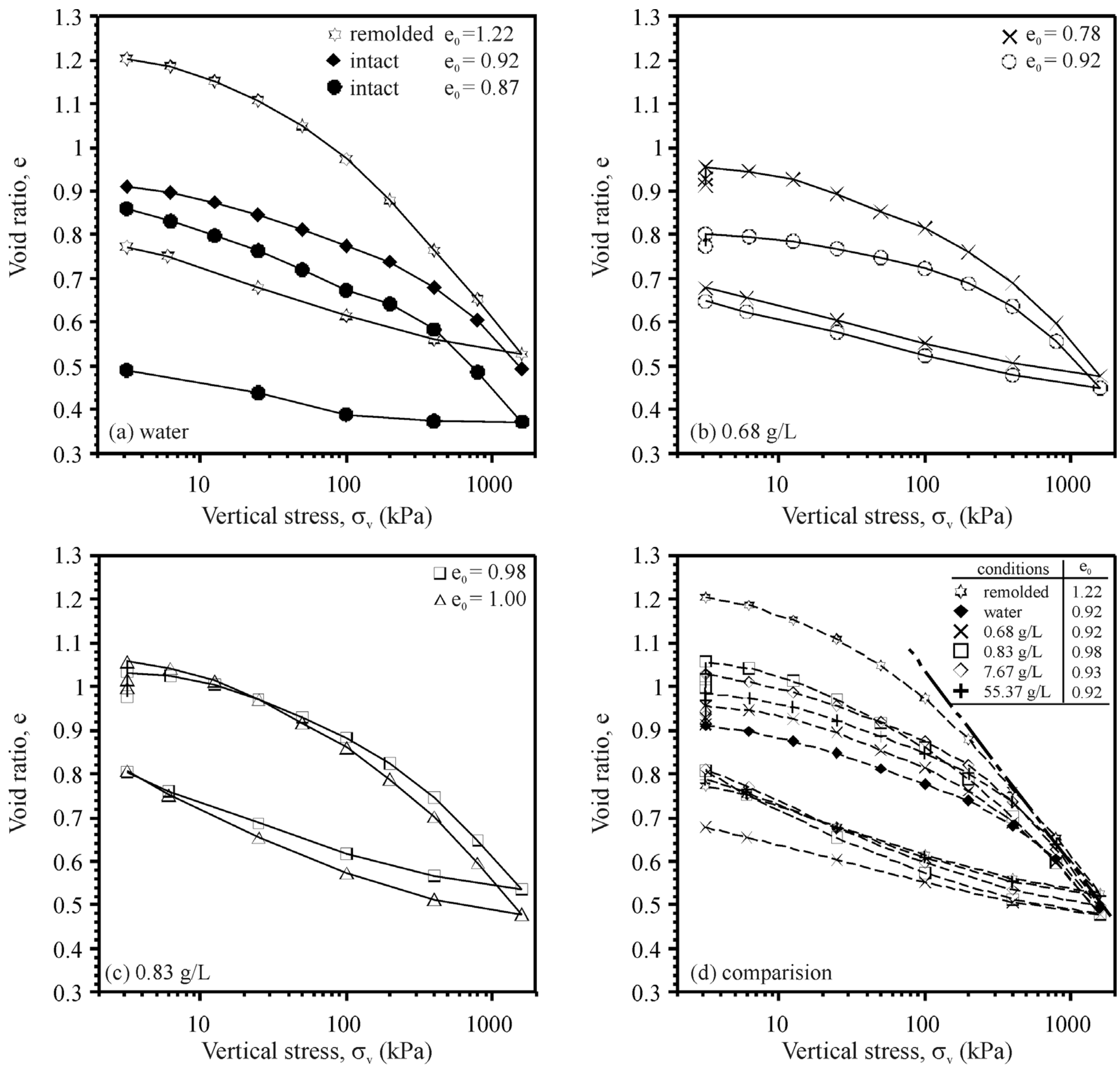


Figure 9 - Compressions curves of saprolitic soil (5 m depth).

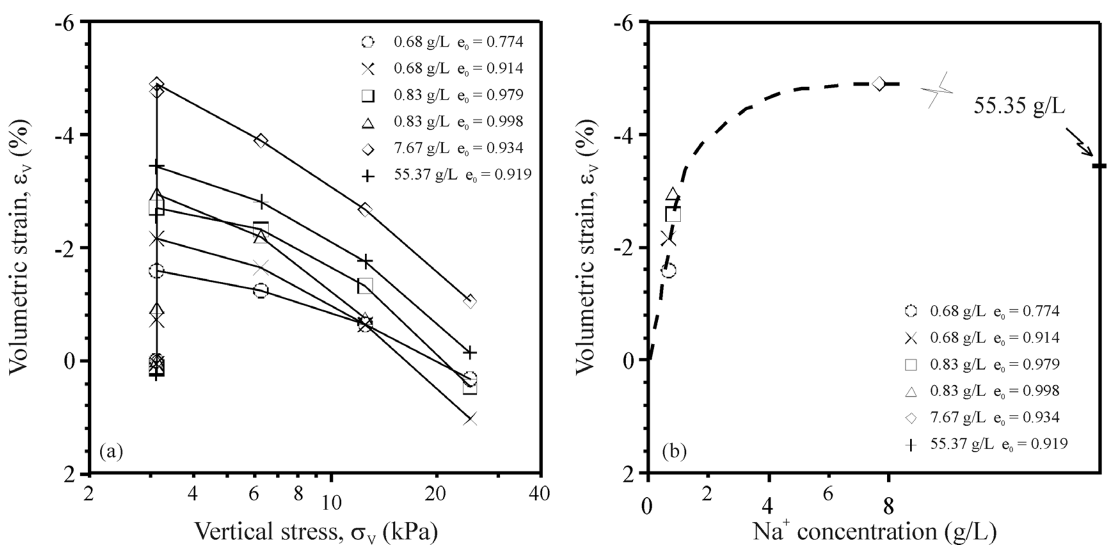


Figure 10 - Initial swelling of saprolitic soil.

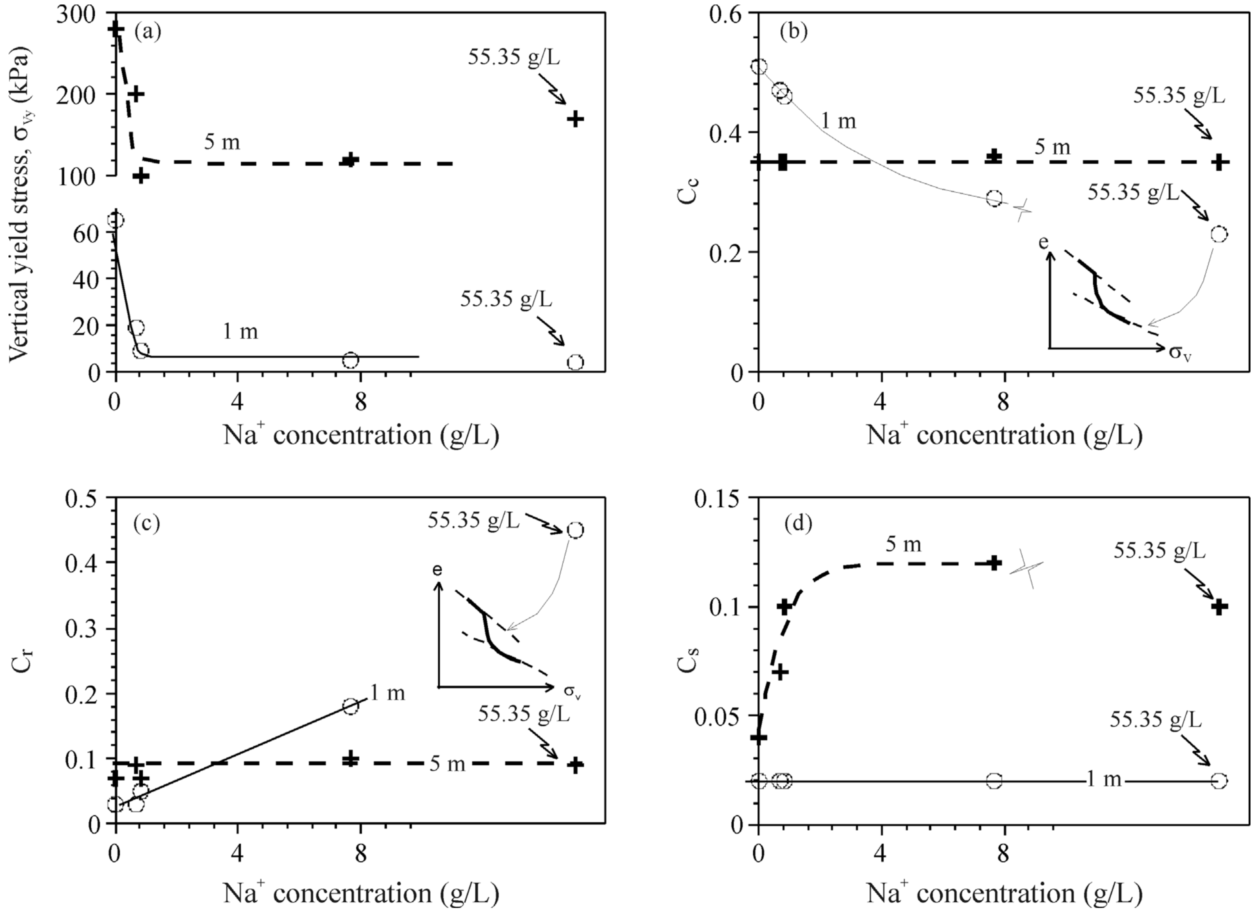


Figure 11 - Compressibility parameters.

The difference in behavior can be explained by the granulometric composition (the lateritic soil is more clayey and the saprolitic soil is more silty), degree of weathering, mineralogy and by the structure seen in SEM (lateritic soil with weakly cemented aggregations of clay and a saprolitic soil organized by the piling of kaolinite particles).

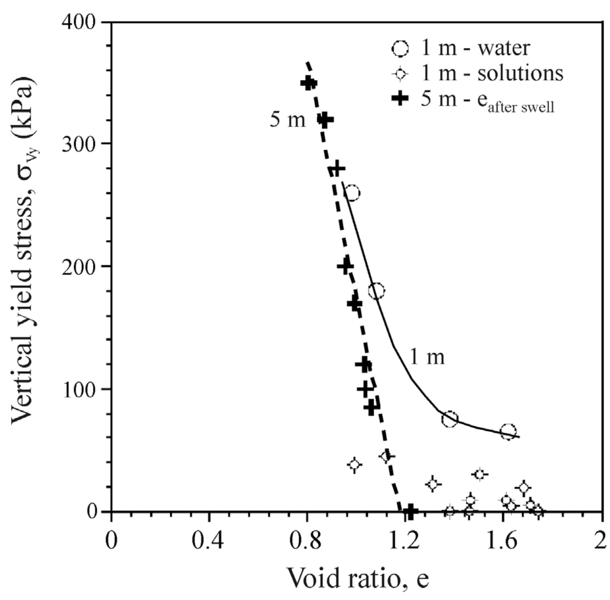


Figure 12 - Vertical yield stress and void ratio relationship.

Putting e: σ_{vy} into a graph (Fig. 12), some differences between the lateritic soil tested with distilled water and the soil tested with solutions with different concentrations can be verified, the data of which are shown in Table 6. It can also be observed that there is a relationship between e and σ_{vy} in the lateritic soil tested with distilled water; the same cannot be said for the other tests carried out using solutions.

The void ratio for the saprolitic soil used in Fig. 12 contains values after the initial swelling. There is a direct relationship between the void ratio and the vertical stress yield. Therefore, the saprolitic yield stress depends on the initial swelling.

Bolt (1956), Abdullah *et al.* (1997), Alawaji (1999), Chen *et al.* (2000), Brancucci *et al.* (2003) and Sivapullaiah & Manju (2006) tested compacted soils. It is difficult define a general aspect of physicochemical influence on natural soil such as presented in this paper, because it will depend on the soil, on the solution and on their interaction.

3.4 Triaxial tests

The results of the triaxial tests carried out on the lateritic soil sample and the low confining stress (σ'_c = 25 kPa) can be seen in Fig. 13. Based on the results presented in Figs. 13(a) and (b), the maximum deviator stress was verified not to be well defined in the drained tests, except for the test with intact soil, which presented a discrete peak obtained by an axial deformation (5%). The peak formation demonstrates the influence of cementing on the intact soil when tested with confining stress lower than the vertical yield stress obtained in the oedometer test, σ'_{vy} = 60 kPa. The remolded soil obtained a maximum deviator stress close to that of the intact soil, yet it required a greater level of axial deformation, *i.e.*, approximately 20% greater. The interaction of the soil with the solutions caused its dispersion, with a reduction in soil strength regarding the intact soil. This reduction was approximately 30% for the most diluted solution and of approximately 60% for the most concentrated solution. All the test specimens exhibited compressive behavior during the drained shearing. Futai (2002) explained this soil does not dilate because the porous structure is maintained by lateritic processes. Taking an axial deformation level of around 20%, volumetric deformations of around 1.5%, 11.5% and 7% were obtained for sodium concentrations equal to zero (intact soil), 0.68 g/L and 7.67 g/L, respectively. The volumetric strains at the consolidated stage were 0.5%, 1.1% and 10.5% were obtained for sodium concentrations equal to zero (intact soil), 0.68 g/L and 7.67 g/L, respectively, these results explain why the 0.68 g/L presented lower volumetric strain than 7.67 g/L at the compression stage.

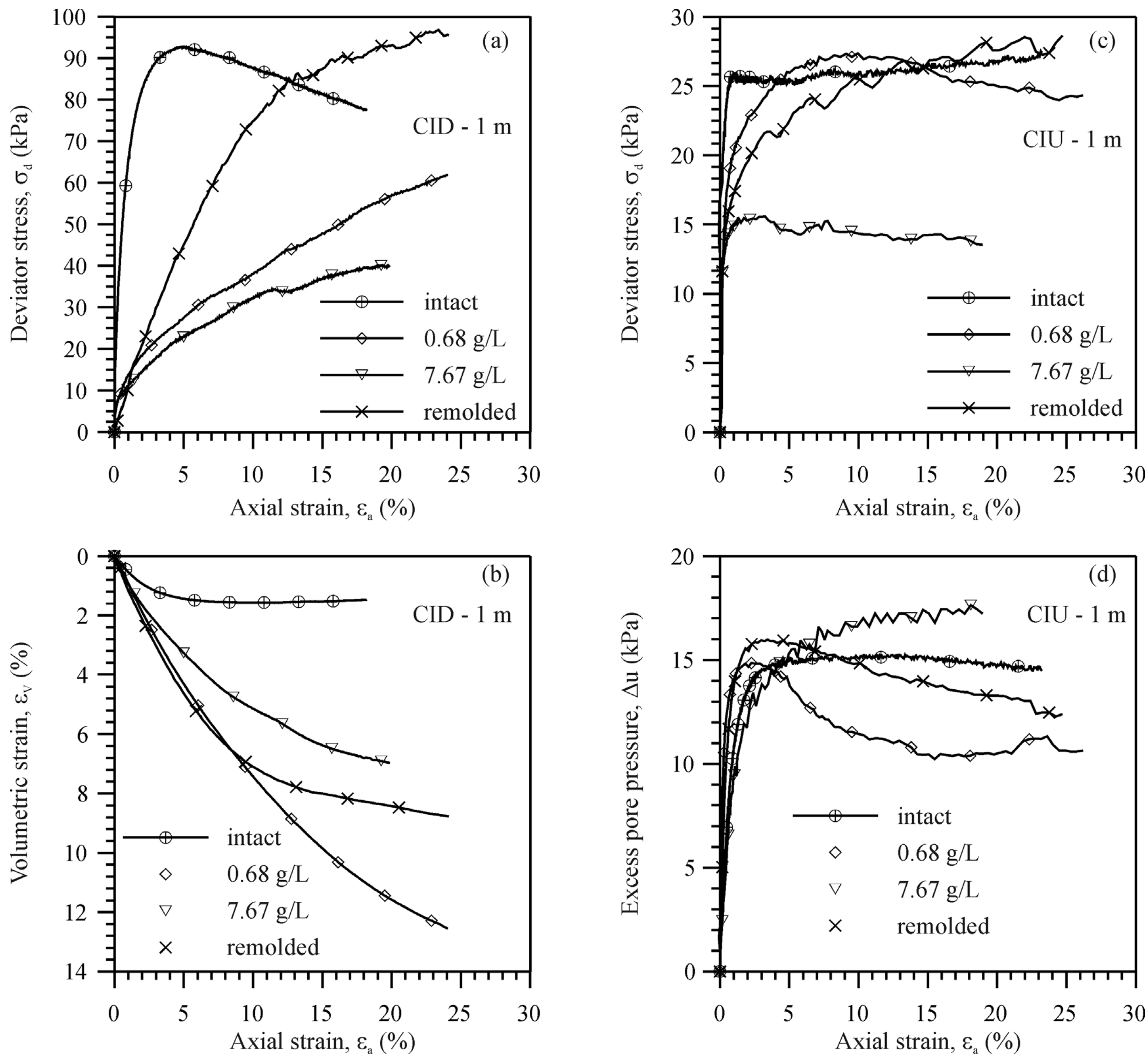


Figure 13 - Results of triaxial tests σ'_c = 25 kPa.

The stress strain behavior of the soil under undrained-testing conditions can be seen in Figs. 13(c) and 13(d). For the 7.67 g/L sodium concentration solution, there was a reduction of peak strength of approximately 45% regarding the intact soil. Positive excess pore-water pressures were generated during the undrained test. When the most diluted solution was employed, excess pore-water pressures generated increased up to 2% of the axial deformation, after which it decreased. This behavior was different from that obtained in the test with the most concentrated solution in which the excess pore pressure always increased.

The 1 m depth was also tested with a higher confining stress (σ'_c = 400 kPa), the results of which are presented in Fig. 14. Analyzing the curves presented in Figs. 9(a) and (b), the increase in the confining stress was found to reduce the differences in the stress-deformation behavior. There was a tendency towards the stabilization of the deviator stress associated with the stabilization of volumetric deformations, while approximately 20-25% of the axial deformations resulted in rupture.

The remolded soil had greater strength and stiffness than the intact soil. For all the confining stresses tested, the remolded soil terminated the hydrostatic consolidation and achieved failure with lower void ratios than the intact soil, resulting in greater strength at the shear stage. The most accentuated effect of the soil solution interactions occurred with the sodium concentration solution of 7.67 g/L, with a reduction of peak strength of around 30% being found in relation to the intact soil. All the samples became elongated during shearing, while the remolded soil on which solutions had been used became deformed to a lesser extent than in the intact condition.

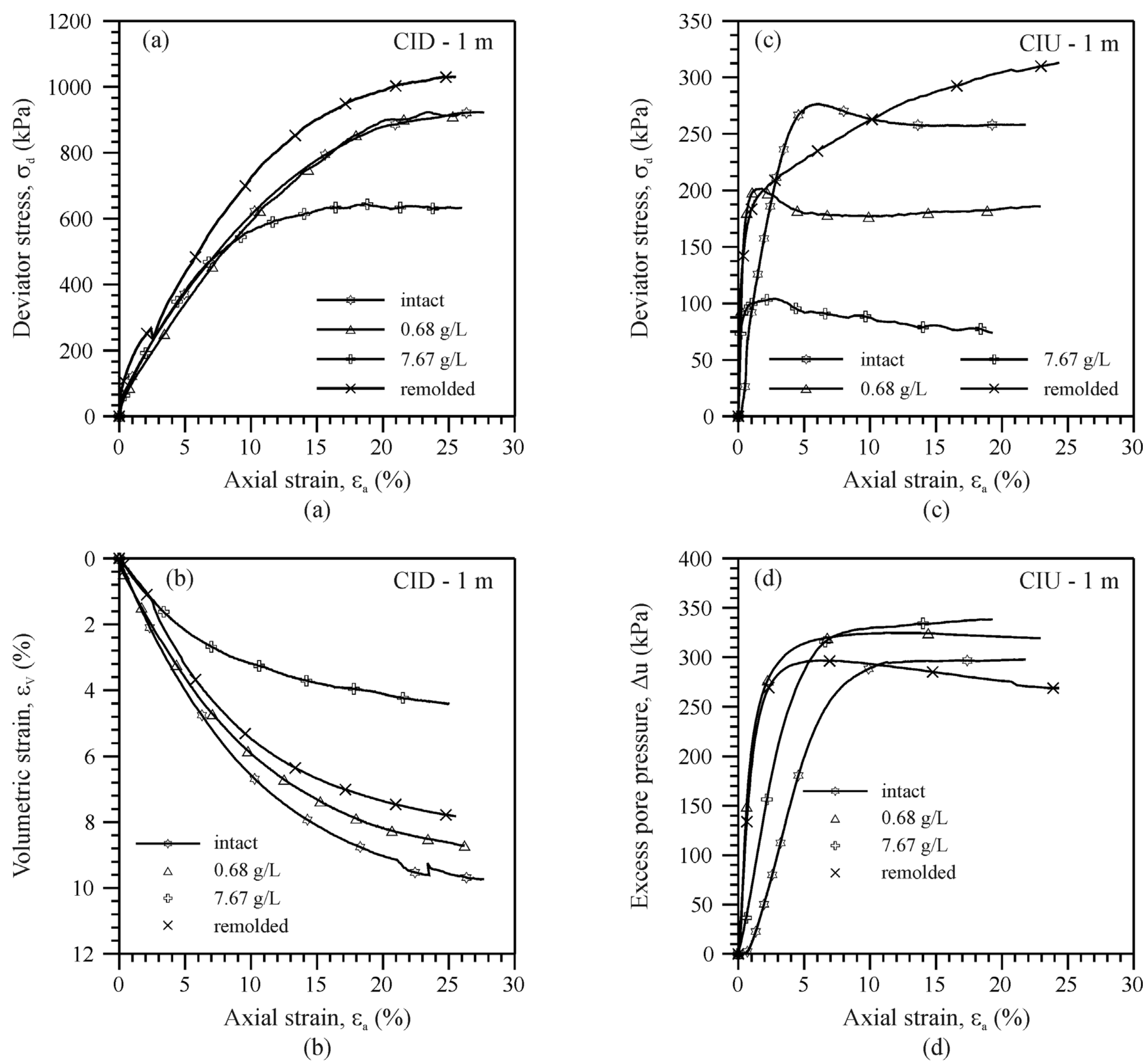


Figure 14 - Results of triaxial tests with σ'_c = 400 kPa.

Figures 14(c) and 14(d) indicate that, in the undrained tests, the intact soil and the soil with solutions had increasing deviator stress until their failure, followed by a decrease in resistance with the formation of a post-peak level, associated with the stabilization of the excess pore-water pressure. The peaks are not associated with the fall in the excess pore pressure generated. The remolded soil always had a rising deviator stress, while the maximum deviator stress adopted was 25% for axial deformation. The interaction with the solutions caused a reduction in resistance of around 30% to 60% for the sodium concentrations equal to 0.68 g/L and 7.67 g/L, respectively. All the test specimens developed excess positive pore pressure during shearing. In the intact conditions and with solutions, the standard stress-deformation behavior differed, although the responses in terms of excess pore pressure were similar. The remolded soil presented increasing excess pore pressure up to approximately 5% of axial deformation, which afterwards declined until the significant deformation condition was reached.

The physicochemical interaction changed the shear strength of the soil, as shown by Moore (1991), Anandarajah & Zao (2000) and Brancucci *et al.* (2003). The result could be increased or decreased of shear strength depending on the soil being flocculate, deflocculate, attacking the minerals or cement. However, the results presented herein only show the results of the tested soil with the used solution.

The effective stress paths and those around the undrained test peaks can be seen in Fig. 15(a), with the details for low confining stress also being presented in Fig. 15(b). The stress paths for the intact soil (Fig. 15) tend towards the left, and generally have an accentuated development of excess pore pressure. When the soil is tested with solutions (Fig. 15), the paths tend to curve towards the left, even though they are more constrained than the intact soil paths. The stress paths of the remolded soil (Fig. 15) are 'S'-shaped. Initially, they follow an approximately 45° direction, before bending to the left until they reach the envelope, which corresponds to the section in which the excess pore pressure is declining.

The peak envelope of the intact soil is a curve for lower confining stress than the oedometer vertical yield stress, σ'_{vy} = 60 kPa (Futai, 2002), even though a linear adjustment was used in order to obtain the strength parameters. The peak resistance parameters for the intact and remolded soil and the soil on which solutions were used are given in Fig. 15(a). When the soil is remolded or tested with solutions, the cementing is broken and the intergranular mechanical contacts are diminished; consequently, the cohesion intercept vanishes and the friction angle tends toward lower values. For sodium concentrations equal to zero (intact soil), 0.68 g/L and 7.67 g/L, the friction angle presents declining values, as shown in Fig. 16. Despite the large difference around the peak, all the trajectories follow the same direction for the critical states. The same occurs for the drained tests that reach the same line of critical states without a peak of strength and with large axial deformations.

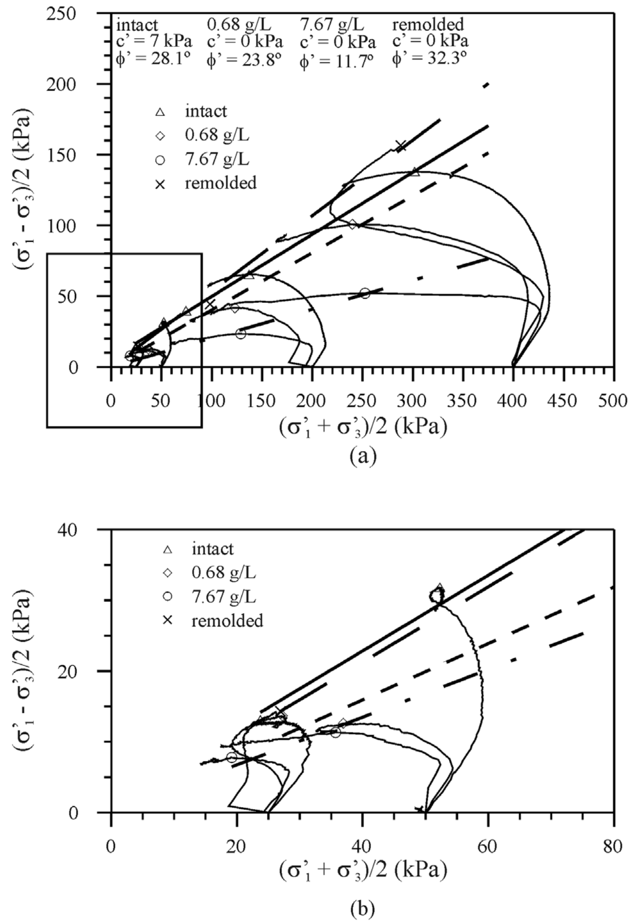


Figure 15 - Effective stress paths and peak envelopes, CIU tests, 1 m soil depth.

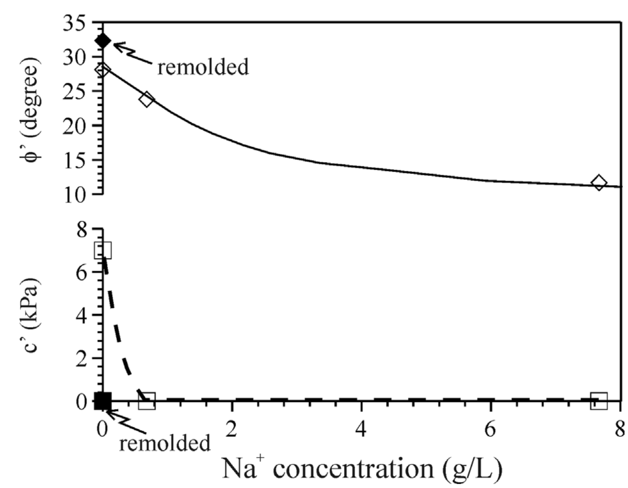


Figure 16 - Influence of the sodium concentration on strength parameters.

4. Conclusions

1) The dispersion of soils was the result of chemical reactions associated with salts $(NaPO_3)_n$ and (Na_2CO_3), and the pH value adopted (pH = 10.5), with an increase in the negative charge of clay mineral particles and the consequent increase in the repulsive particles associated with the electrical double layer. Since the pH value was kept constant, the influence of the concentration of sodium void ratio, mineralogy and degree of weathering on the mechanical behavior of the soil was analyzed.
2) The effect of the physicochemical interactions observed in the Atterberg limits, grain size analysis, oedometer and triaxial tests was more accentuated for the 1 m depth due to the higher level of clay it contained than for the 5 m depth (around tenfold). The physicochemical interaction changed the fabric and microstructure of lateritic soil. The aggregation was destroyed and the plasticity index reduced as the concentration of the solution increased.
3) Specimens formed intact at 1 m-depth (lateritic soil) and 5 m (saprolitic soil), despite the same weathering environment, presented different behavior in the oedometer compression tests due to their (chemical and mineralogical) composition and microstructure peculiarities, associated with the degree of alteration of each soil. The behavior of the 1-meter intact soil reflects the existence of the cementing of iron and aluminum sesquioxides, while the behavior of saprolitic soil reflects the influence of the arrangement of the constituent minerals. The cementing (lateritic soil) and the mineral arrangements (saprolitic soil) were gradually broken, while for the highest vertical stress, the behavior of the intact soil was closer to the behavior of the remolded soil.
4) The physico-chemical interaction between the solution and the lateritic soil increased the compressibility of the soil. There was a reduction in the vertical yield stress and the compression index with the increase in the concentration of Na, maintaining pH = 10.5. The recompression index for the lateritic soil obtained in the initial part of the load increased with concentration.
5) The intact saprolitic soil did not swell when being inundated with water (oedometric tests) although it expanded significantly when inundated with solutions containing sodium. These expansions were probably caused by structural changes and the rupture of connections that inhibit the expansion of the intact state when inundated with water. Electronic microscope sweep tests using soil treated with the solution allowed the visualization of these structural changes. The mechanical behavior of the saprolitic soil was verified to be associated with the initial expansion (unlike the lateritic soil). There is a direct relationship between the void ratio after swelling and the vertical yield stress. The interaction was found not to significantly influence C_c or C_r, even though C_s rose according to the increase in the concentration of Na, maintaining the pH constant and equal to 10.5. The compression curves for the saprolitic soil tend to converge in the 'normally condensed' band, which does not occur with the lateritic soils.

The study confirmed that the mechanical and physicochemical interaction when the pH is kept constant and elevated also depends on the concentration. This can be important in monitoring the dispersion of solutions such as NaOH. It was shown that not only pH is important but also the concentration of specific chemical elements.

Acknowledgments

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List of Symbols

c: cohesion
ϕ: friction angle
e: void ratio
G_s: specific gravity of soil grains
I_P: plasticity Index
S: degree of saturation
w: gravimetric water content
w_L: liquid limit
w_P: plastic limit
C_c: compression index
C_s: swelling index
C_r: recompression index
σ'_v: vertical effective stress
σ_c: confining pressure
σ_d: deviator stress (σ_1 - σ_3)
σ_{vy}: vertical yield stress
γ: unit weight