

Characterization, Hydraulic Conductivity and Compatibility of Mixtures of Tropical Soil and Bentonite for Barrier Usage Purpose

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Abstract. Compacted tropical soils have great potential to be used in barriers, once some technical issues are correctly addressed, including low hydraulic conductivity and compatibility to the disposed fluids. This paper involves a laboratorial study of the hydraulic conductivity of mixtures of a tropical soil sample and bentonite and also their compatibility to different chemical solutions. The experimental program consisted of (1) sample characterization, (2) hydraulic conductivity determination using a triaxial cell, and (3) compatibility assessment with different chemical solutions (HNO_3 , NaOH , NaCl , and ethanol) using the modified Atterberg Limits. The characterization results revealed important changes in the index properties of the tropical soil sample as the result of the bentonite addition, especially in the plasticity, cation exchange capacity and free swelling. The hydraulic conductivity, in turn, experimented significant decreasing as the proportions of bentonite and confining pressure increased. The compatibility results showed a significant reduction in the plasticity of the samples when subjected to the chemical solutions, especially for the salt solution. In general terms, the addition of bentonite reduced the compatibility of the samples.

Keywords: tropical soils, bentonite, hydraulic conductivity, compatibility, compacted clay barriers.

1. Introduction

Compacted clay barriers are widely used for waste containment throughout the world, including domestic, industrial, health-care and radioactive refuse. Base liners, also called compacted clay liners (CCL), are intended to isolate the waste from the nearby environment, especially groundwater. Additionally, cover systems of compacted clay are designed to reduce the rain infiltration, decreasing the leachate generation inside the refuse (Rowe, 2001; Farnezi & Leite, 2007; Chalermyanont *et al.*, 2009).

A CCL mainly works by reducing the hydraulic conductivity (k) and by retarding the migration of contaminant through sorption mechanisms (Daniel & Benson, 1990; Benson *et al.*, 1994; Allen, 2001; Egloffstein, 2001; Kominé, 2004). So, suitable materials for CCL construction must fulfill technical requirements mainly represented by low k values, 10^{-9} m/s as an example, and high sorption capacity. Other issues play also an important role, such as low compressibility and long term performance. In addition, the maintenance of the barrier properties when in contact with the waste liquids, called compatibility, should be considered (Eklund, 1985; Bouazza, 2002).

Due to their wide distribution over the globe, tropical soils have a great potential to be used in these compacted barriers, once some technical and economical requirements are satisfied. The origin of tropical soils is related to hot and humid climates, and vast extensions of these soils cover some old plateaus of South America, Africa and other tropi-

cal parts of the world. Their occurrence is characterized by thick and relative homogeneous weathering profiles as the result of advanced weathering. Their typical composition is quite peculiar, comprising quartz, Fe-Al oxides/hydroxides and kaolinite clay, which makes them not as active as most of the soils of cold and temperate climates.

Additionally, some authors such as Pandiam *et al.* (1993), Cozzolino & Villibor (1993) and Fernandes (2005) consider that some conventional geotechnical soil classification systems do not give satisfactory results for tropical soils. They attribute this discrepancy to some specific properties of the tropical soils such as: 1) soil aggregation, which may exert influence on the grain size analysis and Atterberg Limits; 2) surface chemistry: alkaline conditions may originate positive charges on the solid surface, which increases the interfacial tension and capillarity; 3) silt plasticity, originated by large crystals of kaolinite and mica and 4) pore configuration: some soils from tropical climates exhibit large voids as the result of flocculation and grain fragmentation, which may alter grain size distribution and soil saturation conditions.

In spite of their extensive occurrence, sometimes tropical soils do not attend the low k conditions required for barrier construction, because of its aggregate nature. Cozzolino & Villibor (1993) mention the aggregate (soil peds) and porous nature of tropical soils, resulting in high hydraulic conductivities. Besides, due to their low activity, the potential of retarding contaminants is restricted.

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Bentonite clays are well known by their large swelling, high cation exchange capacity (*CEC*) and sorption capacity, high plasticity and low hydraulic conductivity (Laird, 2006; Jan *et al.*, 2007). Thus, bentonite can be a potential additive to reduce the permeability and increase the sorption capacity of tropical soils. The results presented by Anderson & Hee (1995), Osinubi & Nwaiwu (2002), Farnezi & Leite (2007), Nayak *et al.* (2007) and Sunil *et al.* (2009) confirm this potentiality.

Some papers have assessed the addition of bentonite to natural sands for reducing the hydraulic conductivity, such as Chapuis (1990), Keeney *et al.* (1992), Sivapullaiah *et al.* (1998), Stewart *et al.* (2003), Ebina (2004) and Kamine (2004). Other papers describe laboratory studies to investigate the possible changes in the properties of soils from cold and temperate climate when exposed to different chemical solutions (Bowders & Daniel, 1987; Madsen & Mitchell, 1989; Budhu *et al.*, 1990; Shackelford, 1994; Shackelford *et al.*, 2000; Jo *et al.*, 2001; Roque & Didier, 2006; Yamaguchi *et al.*, 2007; Castellanos *et al.*, 2008; Katsumi *et al.*, 2008; Smiles, 2008; Cuisinier *et al.*, 2009; Kinsela *et al.*, 2010). Therefore, it is latent the need of a more specific research on the hydraulic properties of tropical soils and their long term performance (compatibility) to different liquids.

This paper investigates a tropical soil sample and its mixtures with bentonite in the proportions of (dry weight basis) 3, 6, 9 and 12% of this additive. The experimental program was mainly intend to elucidate the following issues: (1) the actual effect of the bentonite addition to the geotechnical and physico-chemical properties of the tropical soil sample, which was achieved by an extensive characterization; (2) the possible reduction in the *k* value, assessed through permeability tests using a flexible wall permeameter (triaxial cell) and (3) the compatibility of the soil samples when exposed to different chemical solutions (HNO_3 , NaOH , NaCl e ethanol) by means of the evaluation of modified Atterberg limits and modified free-swelling test.

2. Sample Preparation

The bentonite sample used in the tests is commercially called BRASGEL, and according to the manufacturer it came from the state of Parafba, northeastern Brazil. In turn, the tropical soil sample was collected on a soil outcrop by the road that connects the cities of Mariana and Ponte Nova, in the state of Minas Gerais, southeastern Brazil. In the field, the reddish weathering profile was quite thick and homogeneous. Soil peds and blocky structure dominate the outcrop.

The proportions of bentonite used to compose the mixtures were defined according to previous work, such as Anderson & Hee (1995); Gardner & Arias (2000); Ryan & Day (2002); Farnezi & Leite, (2007); Jan *et al.* (2007). In

this way, the following denominations and proportions are given (dry weight basis):

- SN: 100% natural soil;
- SN03: 97% natural soil + 3% bentonite;
- SN06: 94% natural soil + 6% bentonite;
- SN09: 91% natural soil + 9% bentonite;
- SN12: 88% natural soil + 12% bentonite;
- BB: 100% bentonite.

The sample preparation for the characterization and compatibility tests was guided by the Brazilian standard NBR-6457 (ABNT, 1986). The samples were firstly dried at room temperature, and then homogenized, sieved and reduced. The samples used in the hydraulic conductivity tests were compacted under Proctor Energy as indicated by NBR-7182 (ABNT, 1986), with the moisture content around 2% above the optimum. After compaction they were cut and trimmed to a diameter of 5 cm and 10 cm height.

3. Sample Characterization

3.1. Procedures

Physico-chemical properties (pH, electrical conductivity of aqueous extract, cation exchange capacity and specific surface) and geotechnical properties (grain size distribution, liquid limit, plastic limit, specific gravity of solids, optimum moisture content and maximum dry unit weight) were determined for the natural soil, bentonite and mixtures, following the references listed in the Table 1.

According to Camargo *et al.* (1986), the sample pH can be determined in a suspension of 1:2.5 soil/solution ratio, and the electrical conductivity (*EC*) is measured in the water extract of a suspension of 1:1 soil/solution ratio. The *CEC* and specific surface (*SS*) of the fraction passed through the 2 mm sieve were estimated using the method of blue methylene adsorption on a filter paper (Pejon, 1992).

Table 1 - References used for sample characterization.

Properties	References
Grain size distribution	ABNT-NBR7181 (1984)
Liquid limit (ω_L)	ABNT-NBR6459 (1984)
Plastic limit (ω_p)	ABNT-NBR7180 (1984)
Specific gravity of solids (G_s)	ABNT-NBR6508 (1984)
Optimum moisture content (w_{ot}) and maximum dry unit weight (ρ_{dmax})	ABNT-NBR7182 (1986)
pH determination in H_2O ($\text{pH}_{\text{H}_2\text{O}}$) and KCl solution (pH_{KCl})	Camargo <i>et al.</i> (1986)
Electrical conductivity of aqueous extract (<i>EC</i>)	Camargo <i>et al.</i> (1986)
Cation exchange capacity (<i>CEC</i>) and specific surface (<i>SS</i>)	Pejon (1992)

X-ray diffraction was used to determine the mineralogy of the samples that passed through the 0.075 mm sieve under the conditions of: copper tube; rotation angles of 2 to 70° and velocity of rotation from 1 to 2° per second. For that, oriented thin sections were confectioned and submitted to ethylene glycol solvation and heating to 550 °C for 4 h.

The lateritic character of the tropical soil sample (SN) was investigated using a Modified MCT Classification (Vertamatti, 1988). For that, the Brazilian standards DNER-M256-94 and DER-M196-89 were applied.

3.2. Results

As can be seen in Fig. 1, the SN sample was classified as *transitional clayey* in the modified MCT classification system (Vertamatti, 1988), which refers to a transitional field between lateritic and non-lateritic. On the other hand, the outcrop conditions in which the sample was collected, characterized by a dark reddish color and deep/homogeneous weathering profile, clearly indicates that laterization is occurring.

The grain size distribution of all the samples is presented in Table 2. It is interesting to notice that the addition of bentonite had no influence on the clay fraction of the SN sample, despite its high content of clay (see BB sample in

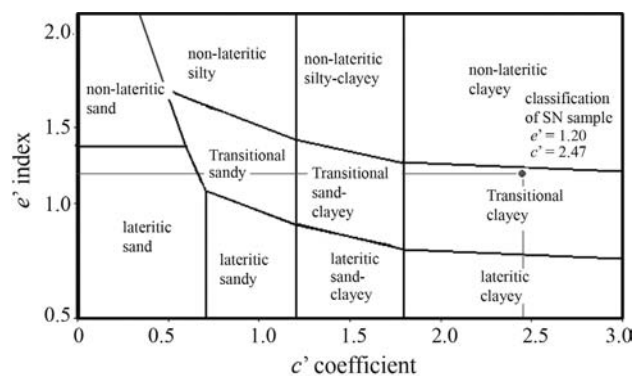


Figure 1 - Modified MCT classification of the SN sample (abacus as Vertamatti, 1988).

Table 2 - Grain size distribution of the samples.

Grain-size analysis ¹	Sample					
	SN	SN03	SN06	SN09	SN12	BB
Clay (%)	42	42	42	42	42	91
Silt (%)	6	3	6	6	6	9
Fine sand (%)	6	13	10	8	10	0
Medium sand (%)	36	30	32	32	32	0
Coarse sand (%)	8	10	8	10	8	0
Gravel (%)	2	2	2	2	2	0

¹Grain-size scale of the Massachusetts Institute of Technology.

Table 2). It is supposed that addition of bentonite has promoted the aggregation or flocculation of the silt and sand grains size of the natural soil (SN sample), which “increases” the “size” of the grains even under the influence of the deflocculating agent (sodium hexametaphosphate, 45.7 g/L). This aggregation could be noticed by a visual inspection in the laboratory.

Some other properties are presented in the Table 3. As was expected, the BB sample showed high values of plasticity, activity, pH, EC, CEC and SS. In turn, the SN sample presented acidic pH and a ΔpH around zero (slightly positive), which is quite common for tropical soils.

The influence of the bentonite addition on the Atterberg Limits, CEC and SS is demonstrated on Figs. 2 and 3, respectively. Figure 2 shows that the increase in the Plastic Index with the bentonite content was quasi-linear ($R^2 = 0.983$), mainly influenced by the increase in the Liquid Limit. CEC and SS, in turn, experimented a significant increase with the bentonite addition (Fig. 3).

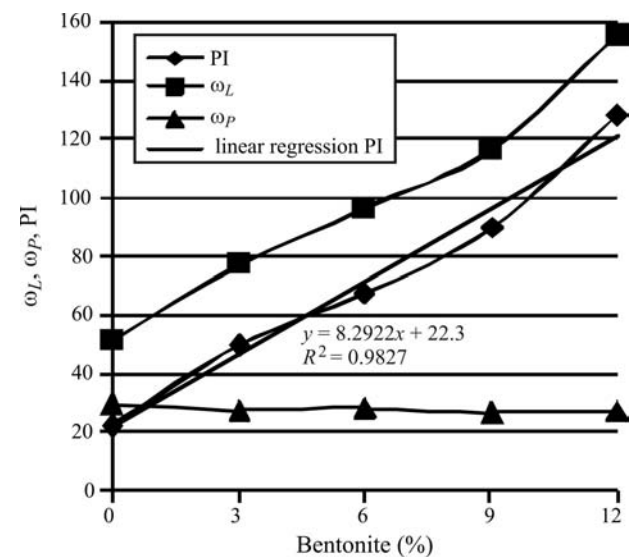


Figure 2 - Atterberg limits (ω_L , ω_P , PI) with bentonite addition.

Figure 4 shows the compaction curves for all the samples. It is clear the influence of the bentonite addition on the compaction behavior, increasing the w_{ot} and decreasing ρ_{dmax} .

The x-ray diffraction analysis of the SN sample has showed a mineralogy predominantly composed of kaolinite, gibbsite, hematite and goethite, which is typical for tropical soils. Additionally, the BB sample was mainly composed of smectite, with small amounts of kaolinite, quartz and mica, as shows Figs. 5 and 6.

The high content of aluminum ($Al_2O_3 = 15.4\%$) and iron ($Fe_2O_3 = 26.7\%$) of the SN sample indicates that extensive leaching (laterization) took place in the soil formation. On the other hand, the percentage of silica (39.2%) is transitory between lateritic and non-lateritic soils.

4. Hydraulic Conductivity

4.1. Procedures

The hydraulic conductivity (k) of the samples was determined using a flexible wall permeameter (triaxial cell). The test methods were based on the suggestions of Head (1986), involving backpressure saturation and pre-consolidation of the samples of 5 cm in diameter and 10 cm high. Sample saturation was obtained by backpressure to a limit of 300 kPa and saturation was considered fulfilled when the B parameter reached a minimum of 0.94. After these procedures are completed, samples were percolated under constant head of 50 kPa.

Hydraulic conductivity testing was not performed in the bentonite due to the difficulties faced in compacting, shaping and saturating this sample.

The schematic of the apparatus used in the tests is depicted on Fig. 7. Pressure application systems were installed at the base (p_1) and over the top (p_2) of the soil specimens, along with the confining pressure system (σ_3). A transducer for pore pressure (u) monitoring and an electronic gage for flow measures were coupled to the triaxial cell. Anderson and Hee (1995), Shackelford *et al.* (2000), and Ahn & Jo (2009) have obtained satisfactory results with similar equipment.

The consolidation effective stresses of 20, 40 to 80 kPa have been applied as an attempt to simulate field pressures on CCL induced by municipal solid waste (MSW). The void ratio (e) during consolidation was estimated through the Eq. 1.

$$e = e_0 - (1 + e_0) \frac{\Delta V}{V_0} \tag{1}$$

where ΔV is the volume variation of the sample, V_0 is its initial volume and e_0 is its initial void ratio.

Flow was imposed to the soil specimen by the application of a p_1 of 300 kPa, while p_2 was kept constant at 250 kPa. These conditions have produced a hydraulic head of 50 kPa and a hydraulic gradient (i) in the order of 50. It is

Table 3 - SN and BB sample properties.

Property	Sample	
	SN	BB
Liquid Limit - ω_L (%)	51.9	682.5
Plastic Limit - ω_p (%)	29.6	90.6
Plasticity Index - PI (%)	22.3	591.9
Activity	0.53	6.50
Specific gravity of solids - G_s (Mg/m ³)	2.840	2.452
pH in H ₂ O - pH_{H_2O}	5.15	9.92
pH in KCl solution - pH_{KCl}	5.21	8.77
$\Delta pH = pH_{KCl} - pH_{H_2O}$	0.06	-1.15
Electrical conductivity - EC (mS/cm)	0.05	1.30
Cation Exchange Capacity - CEC (cmol/kg)	6.9	99.4
Specific Surface - SS (m ⁻¹)	1.53×10^4	1.90×10^5

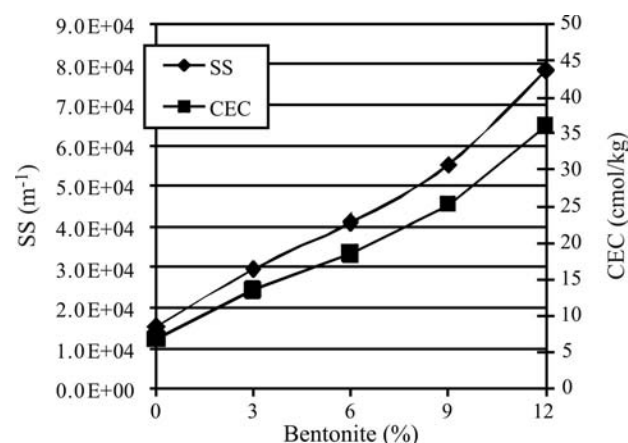


Figure 3 - Specific surface (SS) and Cation Exchange Capacity (CEC) of the SN sample with bentonite addition.

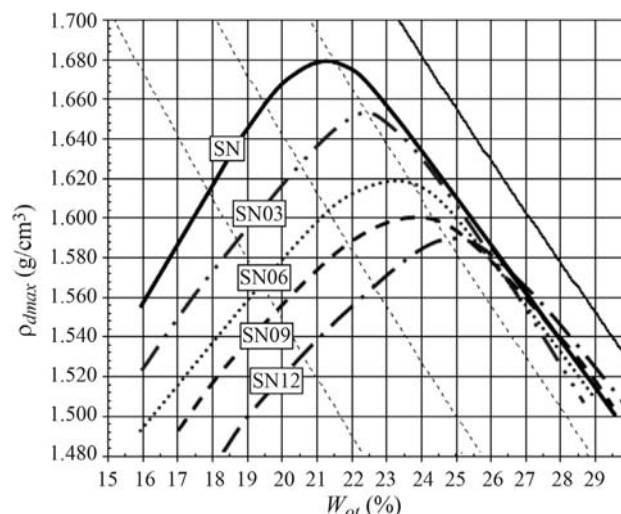


Figure 4 - Compaction curves of all the samples.

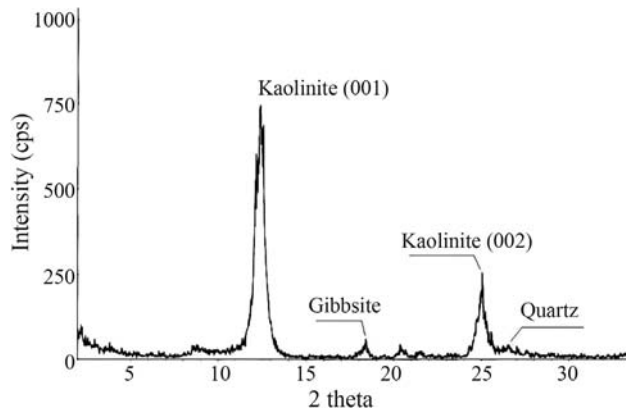


Figure 5 - X-ray diffraction analysis of the SN sample.

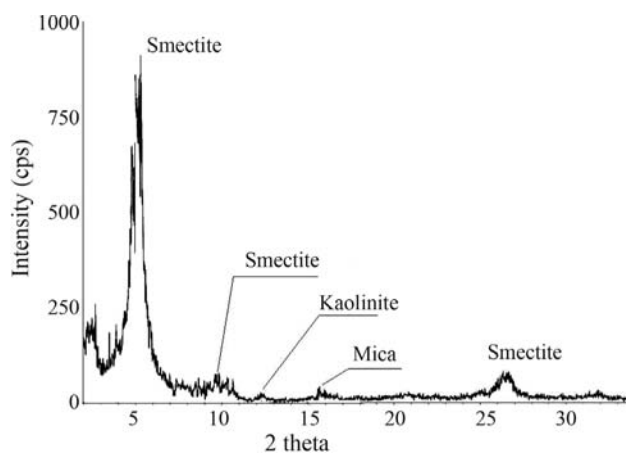


Figure 6 - X-ray diffraction analysis of the BB sample.

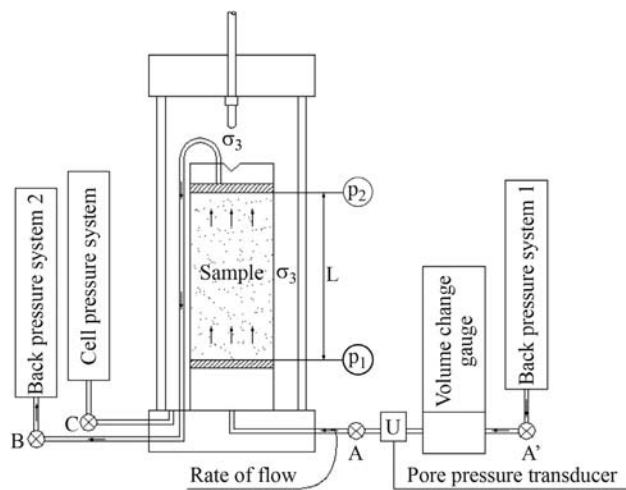


Figure 7 - Schematic of the apparatus used in the hydraulic conductivity tests.

recognized that this gradient is very high when compared to ordinary field conditions (gradients of 3 or less), however it was necessary for operational reasons, since very low hydraulic conductivities are expected for compacted clay samples.

Equation 2 (Darcy Law) was used for k [m/s] calculation when the flow conditions were stable. This stability was considered when the discharge, Q [m³], was linear over the time, t [s].

$$k = \frac{Q}{Ait} = K \frac{\gamma}{\mu} \quad (2)$$

where A is the soil cross sectional area, K [L²] the soil intrinsic permeability, γ [ML⁻³] the fluid unit weight and μ [ML⁻¹T⁻²] the fluid dynamic viscosity.

Some aspects of the tests are pointed out: (1) because of operational reasons - difficulties in the compaction, molding, saturation and consolidation, the hydraulic conductivity of the BB sample was not measured. Anyway, all the characteristics of this sample illustrated on Figs. 2 and 3 (high clay content, high plasticity, high activity etc) have lead to the conclusion that it really is a quasi impermeable material; (2) porous stones placed at the base and top of the soil specimen prevented fine percolation; (3) the rule $\sigma_3 > p_1 > p_2$ has been obeyed to avoid the sample liquefaction induced by pore pressure increase; (4) the reported k results (see item 4.2) is an arithmetic average of 3 measures.

4.2. Results

All the hydraulic conductivity results are presented in Table 4. In this table k_i refers to the k value of each soil specimen under different confining pressure, k_a refers to the arithmetic average of the three measures, and the *Dif.k* parameter represents a percentage difference of the k_i value relative to the average k_a according to the Eq. 3.

$$Dif.k (\%) = \frac{k_i - k_a}{k_a} \times 100 \quad (3)$$

It can be noticed that the *Dif.k* parameter increases towards the highest contents of bentonite. This may be a consequence of the reduction of k , once the difficulty to measure very small flow volumes increases.

The dispersion of the *Dif.k* parameter can be evaluated by the standard deviation and the average deviation presented in Table 5. At first sight, these values seem to be quite high, with standard deviation of more than 14%. Considering the natural inaccuracy involved in the determination of k in laboratory, this dispersion can be viewed as ordinary. Once more the influence of the bentonite is apparent, since the greatest dispersions occur for the samples with more bentonite.

The reduction of the k values with the bentonite addition under increasing confining pressure is better demonstrated by the Fig. 8 and Table 6. This reduction was more expressive for the lower bentonite contents and for the higher values of σ_3 . This trend is corroborated by the k_a/k_{SN} index presented on Table 6.

As mentioned in the literature, the value of $k = 10^{-7}$ cm/s attend most of the regulations over the world as the

Table 4 - Hydraulic conductivity results and the parameter *Dif. k*.

Sample	Parameter	$\sigma_3 = 20$ kPa			$\sigma_3 = 40$ kPa			$\sigma_3 = 80$ kPa		
		Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
SN	k_i (cm/s)	1.61E-06	1.79E-06	1.82E-06	1.07E-06	1.14E-06	1.24E-06	8.24E-07	8.02E-07	7.96E-07
	k_a (cm/s)		1.74E-06			1.15E-06			8.07E-07	
	<i>Dif.k</i> (%)	-7.59%	3.17%	4.42%	-6.73%	-0.71%	7.44%	2.09%	-0.66%	-1.42%
SN03	k_i (cm/s)	2.1E-07	1.8E-07	1.7E-07	1.3E-07	1.3E-07	1.2E-07	7.6E-08	7.4E-08	6.2E-08
	k_a (cm/s)		1.8E-07			1.2E-07			7.0E-08	
	<i>Dif.k</i> (%)	12.48%	-2.21%	-10.27%	0.95%	4.27%	-5.22%	7.16%	4.81%	-11.97%
SN06	k_i (cm/s)	3.9E-08	4.5E-08	3.3E-08	2.1E-08	2.5E-08	1.9E-08	1.1E-08	1.3E-08	9.4E-09
	k_a (cm/s)		3.9E-08			2.1E-08			1.1E-08	
	<i>Dif.k</i> (%)	-0.81%	14.73%	-13.92%	-2.78%	15.86%	-13.08%	0.13%	14.24%	-14.37%
SN09	k_i (cm/s)	1.4E-08	1.6E-08	2.0E-08	9.5E-09	7.3E-09	9.0E-09	2.8E-09	3.5E-09	2.9E-09
	k_a (cm/s)		1.7E-08			8.6E-09			3.0E-09	
	<i>Dif.k</i> (%)	-16.41%	-2.95%	19.36%	10.75%	-15.34%	4.59%	-8.15%	14.16%	-6.01%
SN12	k_i (cm/s)	9.7E-09	1.1E-08	1.3E-08	4.7E-09	3.3E-09	4.9E-09	1.1E-09	1.4E-09	1.2E-09
	k_a (cm/s)		1.1E-08			4.3E-09			1.2E-09	
	<i>Dif.k</i> (%)	-13.16%	-5.81%	18.97%	9.02%	-23.79%	14.78%	-9.39%	10.84%	-1.45%

Table 5 - Standard deviation and average deviation of the parameter *Dif. k*

Index	Sample				
	SN	SN03	SN06	SN09	SN12
Standard deviation	4.94%	8.14%	12.51%	12.88%	14.32%
Average deviation	3.80%	6.59%	9.99%	10.86%	11.91%

Table 6 - k_i/k_{SN} values.

k_i/k_{SN}	Sample				
	SN	SN03	SN06	SN09	SN12
$\sigma_3 = 20$ kPa	1.000	0.107	0.022	0.010	0.007
$\sigma_3 = 40$ kPa	1.000	0.108	0.019	0.008	0.004
$\sigma_3 = 80$ kPa	1.000	0.087	0.014	0.004	0.002

minimum k for CCL construction (Anderson & Hee, 1995; Mulligan *et al.*, 2001; Allen, 2001). Figure 9 demonstrates that this value was achieved for 3% of bentonite (SN03 sample) under a confining pressure of 40 kPa. Higher bentonite content and σ_3 reduced the k values even more.

The influence of the soil void ratio (e) and specific surface (SS) on the hydraulic conductivity was evaluated through Figs. 10 and 11. This relation is expressed in the well known Kozeny-Carman Eq. 4, which assumes that C is a dimensionless factor that takes into account the shape and tortuosity of the soil channels (Carrier, 2003). This equa-

tion incorporates also the fluid parameters γ and μ (see Eq. 2).

$$k = \left(\frac{\gamma}{\mu} \right) \left(\frac{1}{C} \right) \left(\frac{e^3}{(1+e)(SS^2)} \right) \quad (4)$$

The plot of void ratio and $e^3/(1+e)SS^2$ vs. k , as respectively depicted on Figs. 10 and 11, shows that the best fit equations are non-linear (2nd order polynomials). These results corroborate many authors, such as Carman (1937, 1939) and others, who recognize this non-linearity for fine grained materials, as in the present case. On the other hand, Chapuis & Albertin (2003) provide a comprehensive study for the application of the Kozeny-Carman equation, and conclude that this equation may give reasonable estimations for all kind of soils, including silts and clays.

Figure 11 is important not only because it shows the behavior of the hydraulic conductivity for the studied soil, but also because it suggests that the first term in the Kozeny-Carman equation ($\gamma/\mu C$) is not a constant composed by properties of percolating fluid (γ/μ) and soil (C) constants,

but rather a non-linear term, which depends upon the fluid/soil interaction.

In addition, it is worth to point out that the plot of $k^{1/2}$ vs. $1/PI^2$ (Fig. 12) is quite linear, as demonstrated by the high values of the determination coefficients (R^2).

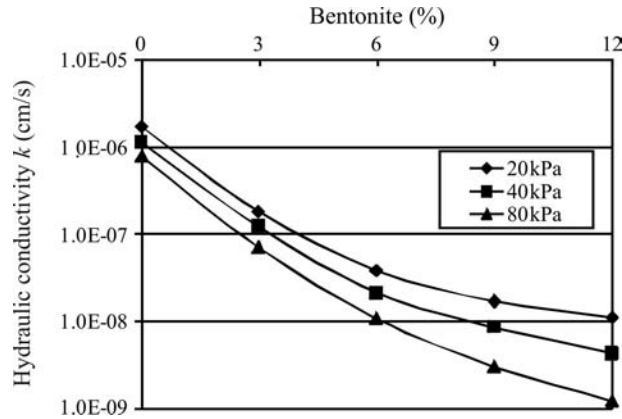


Figure 8 - Hydraulic conductivity (k) vs. bentonite content.

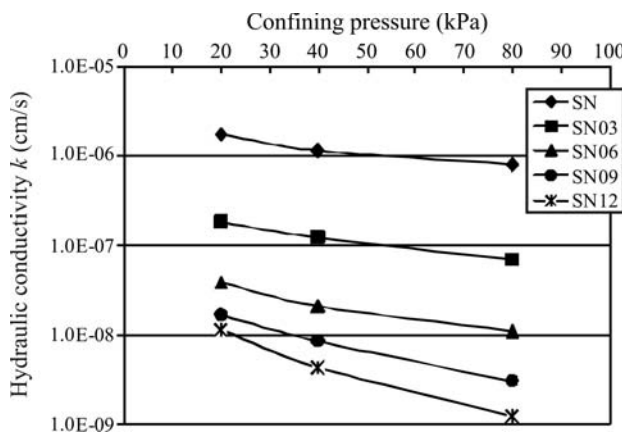


Figure 9 - Hydraulic conductivity (k) of the samples under different confining pressures.

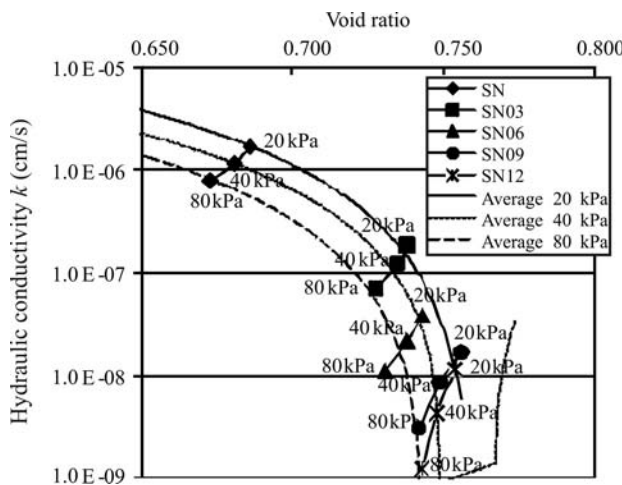


Figure 10 - Hydraulic conductivity (k) vs. void ratio (e) under different confining pressures.

The result presented in Fig. 12 suggests a fourth order inverse proportionality between the hydraulic conductivity and the plasticity index ($k \propto 1/PI^4$), which justifies the study of the compatibility of the samples under the effect of different solutions, as presented in Chapter 5. As an example, a decrease of 50% in PI would produce an increase of 16 times in k .

5. Compatibility Tests

5.1. Procedures

Compatibility can be defined as the ability of a soil to maintain its original properties after being inundated with different chemical solutions. The long term performance of a CCL strictly depends upon the compatibility (Shackelford, 1994).

Some papers such as Jo *et al.* (2001), Stewart *et al.* (2003), Laird (2006), Katsumi *et al.* (2008), Castellanos *et al.* (2008) and Chalermyanont *et al.* (2009) describe compatibility studies by using laboratory tests to evaluate the influence of different chemical solutions over soil sample. Most of them refer to the *diffusion double layer theory* to explain the soil behavior, as well explicated by Mitchell (1993).

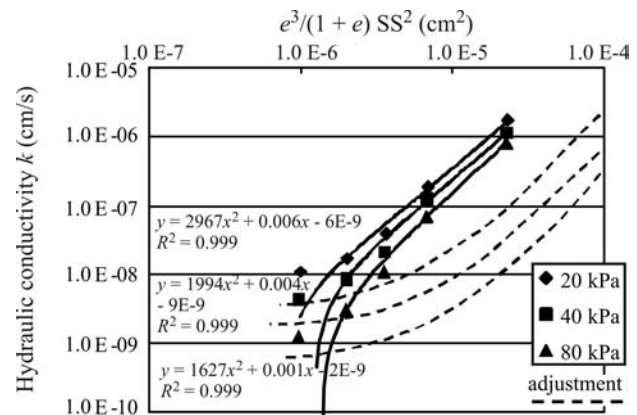


Figure 11 - Hydraulic conductivity (k) vs. $e^3/(1+e)SS^2$.

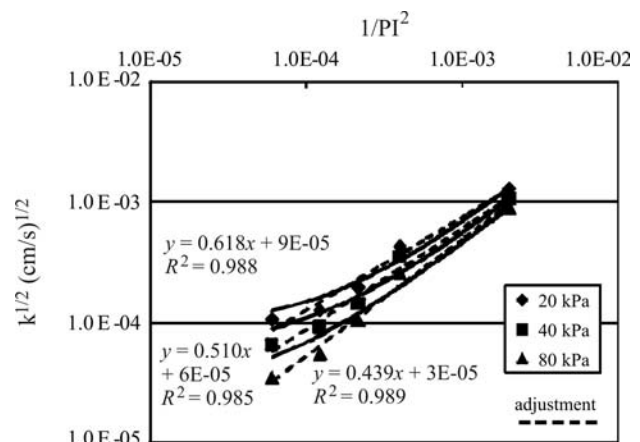


Figure 12 - Root of hydraulic conductivity ($k^{1/2}$) vs. $(1/PI^2)$.

In this paper, the compatibility of the samples was assessed in two ways: (1) determination of modified Atterberg Limits for all samples (Shackelford, 1994; Bouazza *et al.*, 2007) and (2) determination of the modified free-swelling index (*FS*) for pure bentonite (BB sample). Free-swelling tests were not performed in mixtures by the fact that these samples do not expand enough to a satisfactory inquiry. The term “modified” refers to the fact that other solutions besides water have been used in the tests. These solutions were: nitric acid (HNO₃ - pH 3); sodium hydroxide (NaOH - pH 11); sodium chloride (NaCl - 5 g/L) and ethanol P.A. These solutions may represent some of the most aggressive conditions that a CCL can face in the field.

The modified Atterberg Limits ω_L and ω_p were determined according to the standards ABNT-NBR6459/84 and 7180/84. The Incompatibility Index (*IC*), as defined in Eq. 5 (Farnezi & Leite, 2007), was used to evaluate the incompatibility (inverse of compatibility) of the samples. According to this equation, the higher the *IC* value, the higher the incompatibility of the soil sample upon the soil solution being tested.

$$IC (\%) = \frac{PI_w - PI_f}{PI_w} \times 100 \quad (5)$$

Being PI_w the plastic index with water and PI_f the plastic index with the analyzed fluid.

In turn, the modified free-swelling test (*FS*) consisted of adding gradually (over 30 min) 1 g (dry weight) of bentonite on a graduate test tube filled with 100 mL of distilled water or chemical solution. The *FS* index [mL/g] is determined by direct inquiry in the test tube after 24 h (no agitation) and 48 h (after agitation). This procedure is known worldwide as Foster swelling (Foster 1953, Laird, 2006, Ferreira *et al.*, 2008, Delbem *et al.*, 2010).

5.2. Results

Figures 13, 14 and 15 show the Atterberg limits of the SN sample with the increasing bentonite content for the different solutions. An increase in the ω_L was noticed for all the solutions as the bentonite content increases (see Fig. 13), while ω_p was more stable, exception made for the proportion of 12% of bentonite (Fig. 14). Figure 13 also demonstrates that, relative to water, all the solutions reduced ω_L in the following order: NaCl > HNO₃ > NaOH > ethanol. As expected, the plastic index curves (Fig. 15) are very similar to those of ω_L (Fig. 13). Table 7 presents the results of modified Atterberg limits for the bentonite sample (BB).

Figure 16 curves depict increasing rates of *IC* with the growing proportions of bentonite, which may be interpreted as a negative effect of the bentonite on the compatibility of the samples. This negative effect is less noticeable for the NaCl and ethanol curves. In fact, the SN sample is very sensitive to NaCl solution even without any bentonite

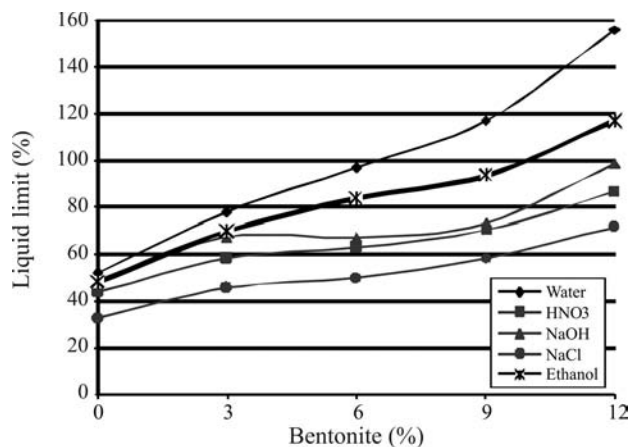


Figure 13 - Liquid limit (ω_L) vs. bentonite content for different chemical solutions.

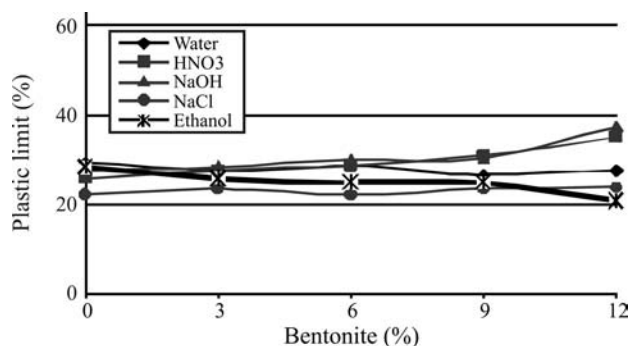


Figure 14 - Plastic limit (ω_p) vs. bentonite content for different chemical solutions.

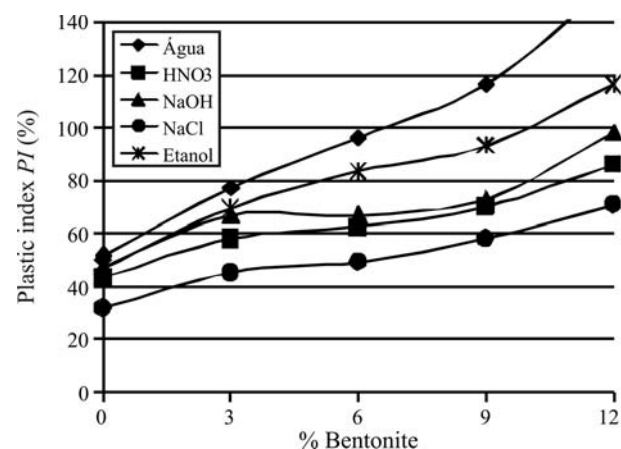


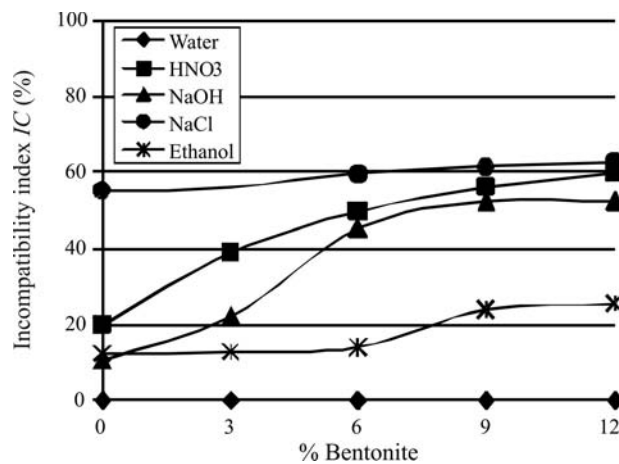
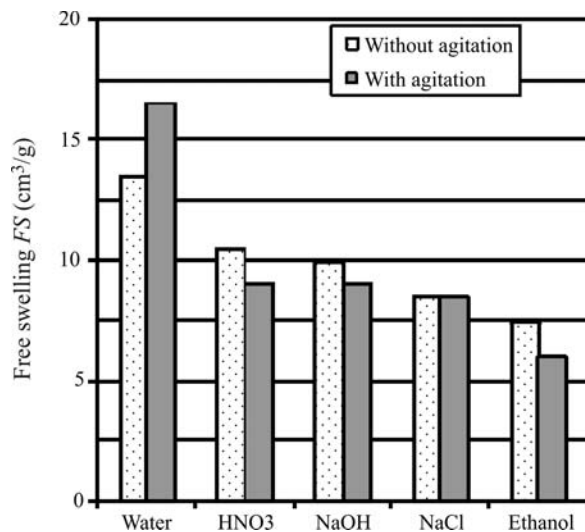
Figure 15 - Plastic index (*PI*) vs. bentonite content for different chemical solutions.

content. Additionally, the NaOH and HNO₃ curves have similar behavior, approaching the NaCl curve at the highest bentonite contents (9-12%).

The bentonite free swelling (*FS*) results for different solutions are depicted on Fig. 17, including the 24-hour (without agitation) and 48-hour tests (with agitation). All

Table 7 - Modified Atterberg Limits for bentonite sample.

Solutions	ω_L (%)	ω_P (%)	PI (%)
Water	682.5	90.6	591.9
HNO ₃	495.2	140.5	354.7
NaOH	470.6	83.0	387.6
NaCl	310.9	82.8	228.1
Ethanol	372.9	82.6	290.3


Figure 16 - Incompatibility index (IC) vs. bentonite content for different chemical solutions.

Figure 17 - Results for free swell tests (FS) of BB sample.

the solutions reduced FS relative to water in the following order: $H_2O > HNO_3 > NaOH > NaCl > Ethanol$. The ethanol and NaCl influence on FS is easily associated to the contraction of the double diffuse layer (DDL) of the clay minerals. The ethanol effect, in turn, is due to its low dielectric constant (24.3) relative to water (80) (see Acar & Olivieri, 1989). For NaCl, the DDL contraction under high salt concentrations is well known (Mitchell, 1993).

Exception made to water and NaCl, the 48-hour tests reduced FS relative to the 24-hour tests, which may be related to the thixotropic nature of bentonite clay.

6. Conclusions

The main conclusions of the flow studies are summarized as follows:

- The addition of bentonite as well as the increase in the confining pressure has led to a significant reduction in hydraulic conductivity. For instance, 12% of bentonite (SN12 sample) reduced k approximately a thousand times in relation to 0% of bentonite (SN sample) at a confining pressure of 80 kPa. This reduction is potentially increased at higher confining pressures;
- The criteria of $k = 10^{-7}$ cm/s as the minimum k for safe barriers was achieved at bentonite contents of 4.5% ($\sigma_3 = 20$ kPa), 3.5% ($\sigma_3 = 40$ kPa) and 2.5% ($\sigma_3 = 80$ kPa);
- The reduction in k even for higher porosity/void ratios suggests that the adsorbed water did not contribute to the overall flow;

In terms of compatibility, the following conclusions are highlighted:

- Relative to water, all the solutions reduced the plasticity, reflected by the ω_L and PI values, in the following order: NaCl > HNO₃ > NaOH > ethanol;
- Except for the NaCl solution, the compatibility of the samples reduces as the bentonite content increases, as demonstrated by the increase in the Incompatibility Index (IC);
- The free swell tests of the bentonite indicate the following order of impact: ethanol > NaCl > NaOH > HNO₃.

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References

- ABNT (1984a) Soil - Grain-size Distribution Analyses - NBR 7181. Rio de Janeiro, 13 pp (In Portuguese).
- ABNT (1984b) Soil - Determination of the Liquid Limit - NBR 6459. Rio de Janeiro, 6 pp (In Portuguese).
- ABNT (1984c) Soil - Determination of Plastic Limit - NBR 7180. Rio de Janeiro, 6 pp (In Portuguese).
- ABNT (1984d) Soil Grains Passing the Sieve 4,8 mm - Determination of Solids Density - NBR 6508. Rio de Janeiro, 8 pp (In Portuguese).

- ABNT (1986a) Soil Samples - Preparation for Characterization and Compaction tests - NBR 6457. Rio de Janeiro, 9 pp (In Portuguese).
- ABNT (1986b) Soil - Compaction Test - NBR 7182. Rio de Janeiro, 10 pp (In Portuguese).
- Acar, Y.B. & Olivieri, I. (1989) Pore fluid effects on the fabric and hydraulic conductivity of laboratory-compacted clay. *Transportation Research Record*, v. 1219, p. 144-159.
- Ahn, H.S. & Jo, H.Y. (2009) Influence of exchangeable cations on hydraulic conductivity of compacted bentonite. *Applied Clay Science*, v. 44, p. 144-150.
- Allen, A. (2001) Containment landfills: Myth of sustainability. *Engineering Geology*, 60:1-4, p. 3-19.
- Anderson, S.A. & Hee, B.H. (1995) Hydraulic conductivity of compacted lateritic soil with bentonite admixture. *Environmental & Engineering Geoscience*, v. 1:3, p. 299-312.
- Benson, C.H.; Zhai, H. & Wang, X. (1994) Estimating hydraulic conductivity of compacted clay liners. *Journal of Geotechnical Engineering*, v. 120:2, p. 366-385.
- Bouazza, A. (2002) Geosynthetic clay liners. *Geotextiles and Geomembranes*, v. 20:1, p. 3-17.
- Bouazza, A.; Jefferis, S. & Vangpaisal, T. (2007) Investigation of the effects and degree of calcium exchange on the Atterberg limits and swelling of geosynthetic clay liners when subjected to wet-dry cycles. *Geotextiles and Geomembranes*, v. 25:3, p. 170-185.
- Bowders, J.J. Jr. & Daniel, D.E. (1987) Hydraulic conductivity of compacted clay to dilute organic chemicals. *Journal of Geotechnical Engineering*, v. 113:12, p. 1432-1448.
- Budhu, M.; Giese, R.F.; Campbell, G. & Baumgrass, L. (1990) The permeability of soils with organic fluids. *Canadian Geotechnical Journal*, v. 28:1, p. 140-147.
- Camargo, O.A.; Moniz, A.C.; Jorge, J.A.; & Valadares, J.M.A.S. (1986) Methods for Chemical, Mineralogical and Physical Analyses of Soils of the Instituto Agrônomo de Campinas. IAC Technical Bulletin n. 106, Campinas, 95 pp (In Portuguese).
- Carman, P.C. (1937) Fluid flow through granular beds. *Transactions of the Institution of Chemical Engineers*, v. 15, p. 150-166.
- Carman P. C. (1939) Permeability of saturated sands, soils and clays. *Journal of Agricultural Science*, v. 29:2, p. 263-273.
- Carrier, W.D. (2003) Goodbye, Hazen; Hello, Kozeny-Carman. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 129:11, p. 1054-1056.
- Castellanos, E.; Villar, M.V.; Romero, E.; Lloret, A. & Gens A. (2008) Chemical impact on the hydro-mechanical behaviour of high-density FEBEX bentonite. *Physics and Chemistry of the Earth*, v. 33:1, p. 516-526.
- Chalermyanont, T.; Arrykul, S. & Charoenthaisong, N. (2009) Potential use of lateritic and marine clay soils as landfill liners to retain heavy metals. *Waste Management*, v. 29:1, p. 117-127.
- Chapuis, R.P. (1990) Sand-bentonite liners: predicting permeability from laboratory tests. *Canadian Geotechnical Journal*, v. 27:1, p. 47-57.
- Chapuis, R.P. & Aubertin, M. (2003) On the use of the Kozeny-Carman equation to predict the hydraulic conductivity of soils. *Canadian Geotechnical Journal*, v. 40:3, p. 616-628.
- Cozzolino, V.M. & Villibor, D.F. (1993) Classification Tropical Soils for Geotechnical MCT. *Soils and Rocks*, v. 16:2, p. 77-91 (In Portuguese).
- Cuisinier, O.; Deneele, D. & Masrouri, F. (2009) Shear strength behaviour of compacted clayey soils percolated with an alkaline solution. *Engineering Geology*, v. 108:3-4, p. 177-188.
- Daniel, D.E. & Benson, C.H. (1990) Water content-density criteria for compacted soil liners. *Journal of Geotechnical Engineering*, v. 116:12, p. 1811-1830.
- Delbem, M.F.; Valera, T.S.; Valenzuela-Diaz, F.R. & Demarquette, N.R. (2010) Modification of Brazilian smectite clay with different quaternary ammonium salts. *Química Nova*, v. 33:2, p. 309-315.
- DER-SP. (1989) Classificação de Solos Tropicais Segundo a Metodologia MCT - M 196-89. São Paulo, Brasil, 6 pp (In Portuguese).
- DNER. (1994) Solos compactados com equipamento miniatura - Determinação da perda de massa por imersão-M256-94. Rio de Janeiro (In Portuguese).
- Ebina, T.; Minja, R.J.A.; Nagase T.; Onodera, Y. & Chatterjee, A. (2004) Correlation of hydraulic conductivity of clay-sand compacted specimens with clay properties. *Applied Clay Science*, v. 26:1-4, p. 3-12.
- Egloffstein, T.A. (2001) Natural bentonites influence of the ion exchange and partial desiccation on permeability and self-healing capacity of bentonites used in GCLs. *Geotextiles and Geomembranes*, v. 19:7, p. 427-444.
- Eklund, A.G. (1985) A Laboratory comparison of the effects of water and waste leachate on the performance in soil liners. Johnson, A.I.; Frobels, R.K.; Cavalli, N.J. & Petersson, C.B. (eds) *Hydraulic Barriers in Soil and Rock*. American Society for Testing and Materials, Philadelphia, pp. 188-202.
- Farnezi, M.K. & Leite, A.L. (2007) Lateritic soil and bentonite mixtures assessment for liner usage purpose. *Soils and Rocks*, v. 30:2, p. 102-112.
- Fernandes, G. (2005) Behavior of Pavement Rail Thin with Land Use and / or Residues from Mining of Iron Associated with Geosynthetics. PhD Thesis, Universidade de Brasília, Brasília, 253 pp (In Portuguese).
- Ferreira, H.S.; Menezes, R.R.; Martins, A.B.; Neves, G.A. & Ferreira, H.C. (2008) Analysis of the influence of the purification treatment on the swelling behavior in non-aqueous media of organophilic clays. *Cerâmica*, v. 54:329, p. 77-85 (In Portuguese).

- Foster, M.D. (1953) Geochemical studies of clay minerals: II - Relation between ionic substitution and swelling in montmorillonites. *American Mineralogist*, v. 38, p. 994-1006.
- Gardner, K. & Arias M. (2000) Clay swelling and formation permeability reductions induced by a nonionic surfactant. *Environmental Science & Technology*, v. 34:1, p. 160-166.
- Head, K. (1986) *Manual of Soil Laboratory Testing*, v. 3. Pentech Press, London, 712 pp.
- Jan, Y.L.; Tsai, S.C.; Wei, Y.Y.; Tung, N.C.; Wei, C.C. & Hsu, C.N. (2007) Coupled mechanics, hydraulics and sorption properties of mixtures to evaluate buffer/backfill materials. *Physics and Chemistry of the Earth*, v. 32:8-14, p. 789-794.
- Jo, H.Y.; Katsumi, T.; Benson, C.H. & Edil, T.B. (2001) Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single-species salt solutions. *Journal of Geotechnical and Geoenvironmental Engineering*, v. 127:7, p. 557-567.
- Katsumi, T.; Ishimori, H.; Onikata, M. & Fukagawa R. (2008) Long-term barrier performance of modified bentonite materials against sodium and calcium permeant solutions. *Geotextiles and Geomembranes*, v. 26:1, p. 14-30.
- Keeney, T.; van Veen, M.; Swallow, M. & Singalia, M. (1992) Hydraulic conductivity of compacted bentonite-sand mixtures. *Canadian Geotechnical Journal*, v. 29:3, p. 364-374.
- Kinsela, A.S.; Tjitradjaja, A.; Collins, R.N.; Waite, T.D.; Payne, T.E.; Macdonald, B.C.T. & White, I. (2010) Influence of calcium and silica on hydraulic properties of sodium montmorillonite assemblages under alkaline conditions. *Journal of Colloid and Interface Science*, v. 343:1, p. 366-373.
- Komine, H. (2004) Simplified evaluation on hydraulic conductivities of sand-bentonite mixture backfill. *Applied Clay Science*, v. 26:1-4, p. 13-19.
- Laird, D.A. (2006) Influence of layer charge on swelling of smectites. *Applied Clay Science*, v. 34:1-4, p. 74-87.
- Madsen, F.T. & Mitchell, J.K. (1989) Chemical effects on clay fabric and hydraulic conductivity. Baccini, P. (ed) *The Landfill. Lecture Notes in Earth Sciences*, v. 20. Springer-Verlag, Berlin, pp. 201-251.
- Mitchell, J.K. (1993) *Fundamentals of Soil Behavior*, 2 ed. John Wiley & Sons, New York, 437 pp.
- Nayak S.; Sunil B.M. & Shrihari S. (2007) Hydraulic and compaction characteristics of leachate-contaminated lateritic soil. *Engineering Geology*, v. 94:3-4, p. 137-144.
- Osinubi, K.J. & Nwaiwu, C.M.O. (2002) Compacted lateritic soils as hydraulic barriers in waste containment systems. *Proc. IV International Congress On Environmental Geotechnics*, Rio de Janeiro, pp. 225-230.
- Pandiam, N.S.; Nagaraj, T.S. & Sivakumar Babu, G.L. (1993) Tropical clays. Index properties and microstructural aspects. *Journal of Geotechnical Engineering*, v. 119:5, p. 826-839.
- Pejon, O.J. (1992) *Engineering Geological Mapping of the Piracicaba, SP (1:100000 scale): A Study of Methods, Characterization and Presentation of the Attributes*. PhD Thesis, Engineering School of São Carlos, University of São Paulo, pp. 59-71 (In Portuguese).
- Roque, A.J. & Didier G. (2006) Calculating hydraulic conductivity of fine-grained soils to leachates using linear expressions. *Engineering Geology*, v. 85:1-2, p. 147-157.
- Rowe, R.K. (2001) *Geotechnical and Geoenvironmental Engineering Handbook*. Kluwer Academic Publishing, Norwell, 1160 pp.
- Ryan, C.R. & Day, S.R. (2002) Soil-cement-bentonite slurry walls. *Geotechnical Special Publication*, ASCE, v. 116, p. 713-727.
- Shackelford, C.D. (1994) Waste-soil interactions that alter hydraulic conductivity. *Hydraulic Conductivity and Waste Contaminant Transport in Soil*. ASTM STP 1142, Philadelphia, pp. 111-166.
- Shackelford, C.D.; Benson, C.H.; Katsumi, T.; Edil, T.B. & Lin L. (2000) Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids. *Geotextiles and Geomembranes*, v. 18:2-4, p. 133-161.
- Sivapullaiah, P.V.; Sridharan, A. & Stalin, V.K. (1998) Evaluation of bentonite and sand mixtures as liners. *Proc. III International Congress on Environmental Geotechnics*, Lisboa, pp. 17-21.
- Smiles, D.E. (2008) Effects of solutes on clay-water interactions: Some comments. *Applied Clay Science*, v. 42:1-2, p. 158-162.
- Stewart, D.I.; Studds, P.G. & Cousens, T.W. (2003) The factors controlling the engineering properties of bentonite-enhanced sand. *Applied Clay Science*, v. 23:1-4, p. 97-110.
- Sunil, B.M.; Shrihari, S. & Nayak S. (2009) Shear strength characteristics and chemical characteristics of leachate-contaminated lateritic soil. *Engineering Geology*, v. 106:1-2, p. 20-25.
- Vertamatti, E. (1988) New geotechnical considerations on Amazon tropical soils of fine texture. *Proc. XXII Annual Meeting Of Paving*, Florianópolis, pp. 533-564 (In Portuguese).
- Yamaguchi, T.; Sakamoto, Y.; Akai, M.; Takazawa, M.; Lida, Y.; Tanaka, T. & Nakayama, S. (2007) Experimental and modeling study on long-term alteration of compacted bentonite with alkaline groundwater. *Physics and Chemistry of the Earth*, v. 32:1-7, p. 298-310.

Symbols

μ : fluid dynamic viscosity

γ : fluid unit weight

<i>A</i> : soil cross sectional area	<i>p</i> ₂ : pressure application systems at the over the top of the soil specimens
<i>BB</i> : bentonite sample	<i>PI</i> : plasticity Index
<i>C</i> : dimensionless factor of tortuosity of the soil	<i>PI</i> _f : plastic index with the analyzed fluid
<i>CEC</i> : cation exchange capacity	<i>PI</i> _w : plastic index with water
<i>Dif.k</i> : difference of the <i>k</i> _{<i>i</i>} value relative to the average <i>k</i> _{<i>a</i>}	<i>Q</i> : discharge
<i>e</i> : void ratio	SN03: natural soil sample with 3% of bentonite
<i>e</i> ₀ : initial void ratio of sample	SN06: natural soil sample with 6% of bentonite
<i>EC</i> : electrical conductivity of aqueous extract	SN09: natural soil sample with 9% of bentonite
<i>FS</i> : free-swelling index	SN12: natural soil sample with 12% of bentonite
<i>G</i> _s : specific gravity of solids	SN: natural soil sample
<i>i</i> : hydraulic gradient	SS: specific surface
<i>IC</i> : Incompatibility Index	SS: specific surface
<i>k</i> : hydraulic conductivity	<i>u</i> : pore pressure
<i>K</i> : soil intrinsic permeability	<i>V</i> ₀ : initial volume of sample
<i>k</i> _{<i>a</i>} : <i>k</i> value of arithmetic average of the three measures	<i>w</i> _{ot} : optimum moisture content
<i>k</i> _{<i>i</i>} : <i>k</i> value of each soil specimen	Δ <i>V</i> : volume variation of the sample
<i>k</i> _{SN} : <i>k</i> value of natural soil sample	ρ _{dmax} : maximum dry unit weight
<i>p</i> ₁ : pressure application systems at the base of the soil specimens	σ ₃ : pressure system
	ω _L : liquid limit
	ω _p : plastic limit