Geotechnical properties of a silt-bentonite mixture for liner construction

Propriétés géotechniques d'un mélange limon-bentonite pour barrières étanches des dépôts de déchets

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ABSTRACT
Cover and bottom liners at waste disposal sites are usually composed of a compacted clay layer (CCL) or a geosynthetic clay liner (GCL) overlain by a geomembrane. Employing local materials in the compacted layer should be attempted, since transportation costs and environmental impacts associated to borrow pit exploitation may be significantly reduced. Saprolitic silty soils of acidic rocks, which occur extensively in tropical regions, may present adequate geotechnical properties when compacted and confined, but their compacted permeability is generally at least tenfold higher than the limit value of 10^{-9} m/s usually required for liners. Furthermore, characterization of this construction material is particularly difficult due to the occurrence of thick layers with great spatial heterogeneity relative to mechanical and hydraulic properties. This paper shows the results of an investigation on the technical feasibility of using a silty saprolitic soil of the metropolitan region of São Paulo for liner construction by means of bentonite addition and compaction at modified energy. Initially, optimum bentonite content was determined considering the mixture permeability. Compressibility, shear strength and expansibility were also determined for the natural soil and the soil-bentonite mixture. A test liner was built in a waste disposal site to consider practical construction aspects. Bentonite addition reduces soil permeability and ensures conformity to specification limits, without significantly modifying other geotechnical properties. The swelling potential of the natural soil and the mixture is a negative aspect that has to be properly addressed.

RÉSUMÉ
Cet article montre les résultats d'une recherche sur la praticabilité technique d'employer un sol limoneux de la région métropolitaine de São Paulo pour la construction de barrières étanches au moyen d'addition de bentonite et le tassement à l'énergie modifiée. Au commencement, le contenu optimum de bentonite a été déterminé en considérant la perméabilité du mélange. La compressibilité, la résistance au cisaillement et l'expansion ont été déterminés pour le sol naturel et le mélange sol-bentonite. Une barriere d'essai a été construit dans un dépôt de déchets pour considérer des aspects pratiques constructives. L'addition de bentonite réduit la perméabilité du sol et assure la conformité aux limites de spécifications, sans modifier de manière significative les autres propriétés géotechniques. Le potentiel de gonflement du sol normal et du mélange sont des aspects négatifs qui doivent être correctement adressés.

Keywords : liners, tropical soils, bentonite, compaction, permeability, swelling pressure

1 INTRODUCTION

Compacted clay liners (CCLs) have traditionally been employed in barrier systems for waste disposal sites. Due to the low availability of clays in some regions, however, the utilization of alternative local materials may be important not only from economical but also environmental viewpoints, circumscribing the implantation environmental impact to the disposal site.

Saprolitic silty soils derived from acidic rocks occur widely in tropical regions; for instance, they cover 20% of the State of Sao Paulo, Brazil, including the metropolitan area of Sao Paulo and other densely populated and industrialized areas. These soils are very heterogeneous in situ but may present adequate homogeneity, high shear strength and low deformability when compacted and confined. Such materials have been investigated and used in road and dam construction in Brazil (Mori 1979, Trichês e Valle 1985, Cruz 1996). Compacted permeability may be around or higher than 10^{-8} m/s; for CCL construction, it must be reduced to 10^{-9} m/s, reference value for most environmental regulations. Pollutant retention capacity has also been evaluated (Gurjão et al 2008, Stuermer et al 2008).

This paper shows results of an on-going experimental research on the technical feasibility of using a saprolitic silt of phyllite as construction material for bottom liners of waste disposal sites. A previous investigation based on laboratory and field tests concluded that a content of 5% of bentonite and a higher compaction effort i.e. modified effort were necessary to achieve a hydraulic conductivity lower than $1x10^{-9}$ m/s (Ferrari 2005). Changes in shear strength, compressibility (Boscov et al 2007) and expansibility due to bentonite addition have been investigated. Test liners furnished information about practical construction aspects such as homogenization of the mixture, soil disaggregation, and compaction control (Ferrari 2005).

2 MATERIALS AND METHODS

2.1 *Soil*

The studied soil is a saprolitic silt derived from phyllite collected in the outskirts of the metropolitan region of São Paulo. The thickness of the saprolitic layer varies with the topography, reaching 35 m at hills tops. In some localized areas there is an overlying layer of lateritic clay, otherwise the saprolitic layer is superficial. The subsoil profile presents gradual weathering along depth, from weathered rock (saprolite) in the bottom to saprolitic silty soil near the surface; the silty soil also changes upwardly from sandy to clayey (Ferrari 2005).

Soil samples collected from a 10-m high cut slope were constituted of approximately 6% sand, 87% silt and 7% clay. Liquid limit and plasticity index are, respectively, 37 to 41% and 7 to 11%. The soil classifies as ML, a silt of low compressibility. According to MCT, a Brazilian system of classification of tropical soils (Nogami and Villibor 1995), the soil is a saprolitic silt.

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2.2 *Bentonite*

Activated sodium bentonite Permagel, a blend of natural bentonites developed for geo-environmental applications by Bentonit União Nordeste S.A., was used in this investigation. Permagel is composed of 80% clay and 20% silt fractions. Liquid limit and plasticity index are, respectively, 540% and 480%. Water content in air-dried condition in the laboratory is 17.2%, and permeability coefficient was measured as $1x10^{-14}$ m/s (Boscov et al. 2007).

2.3 *Mixtures*

Mixtures in the laboratory and in the field were prepared with air-dried materials. Bentonite content is referred to oven-dry mass of bentonite to oven-dry mass of soil. After homogenization of the two materials water was added and the mixture was again homogenized and sieved in the ASTM No. 4 sieve (4.78 mm).

2.4 *Compaction tests*

Compactions tests were carried out with the natural soil and mixtures with 5% and 10% bentonite, at standard and modified effort, according to ASTM D698 and D1557. In some tests, the soil was not air-dried and clods were not ground in a mortar previously to compaction in order to be more representative of field conditions, since undisturbed samples collected from the test pads showed that field compaction did not destroy altered rock fragments as thoroughly as laboratory compaction.

2.5 *Permeability tests*

Permeability tests were carried out with the natural soil and mixtures with 5% and 10% bentonite. Soil specimens were compacted at optimum and wet of optimum under standard and modified effort and carefully trimmed to cylinders with diameter of 0.07 m and height of 0.05 m. Constant head permeability tests were performed in a flexible-wall permeameter (Tri-Flex2 permeameter, Wykeham-Farrance) after consolidation of the soil specimen under a confining pressure of 50 kPa ; seepage of tap water was carried out under a hydraulic gradient of 60, by means of application of a 30-kPa pressure at the bottom of the specimen. The maximum hydraulic gradient recommended by ASTM D5084 (1990) for soils with permeability coefficient equal or lower than 10^{-9} m/s is 30. However, an on-going research with the investigated soil showed that the hydraulic gradient does not significantly influence the measured permeability coefficient, which actually tends to increase slightly as a consequence of an increase in the hydraulic gradient. Similar behavior was observed for a saprolitic silt of granite (Stuermer 2006). Tests ended when the percolated water volume was equal to at least 2 times the void volume of the soil sample.

A specimen of natural soil compacted at optimum water content under modified energy was submitted to seepage of leachate collected from a waste disposal site. Initially a permeability test with water was carried out; after the percolation of a water volume equal to two pore volumes of the specimen, the test assemblage was changed and a downward gradient of 30 was applied by means of a Mariotte flask; then the water in the flask was substituted by leachate.

2.6 *Consolidation tests*

Consolidation tests were carried out with the natural soil and a mixture with 5% bentonite. Soil specimens were compacted at wet of optimum under modified effort and carefully trimmed to cylinders with diameter of 0.07 m and height of 0.02 m. Tests were performed accordingly to ASTM D2435.

2.7 *Shear strength tests*

Direct shear tests were carried out with the natural soil and a mixture with 5% bentonite. Soil specimens were compacted at wet of optimum under modified effort and carefully trimmed to prisms with a square cross section of 0.06 m side and height of 0.025 m. The tests were carried out under confining pressures of 50, 100 and 200 kPa.

2.8 *Expansion tests*

Expansion tests were carried out in triplicates with the natural soil and a mixture with 5% bentonite. Soil specimens were compacted at wet of optimum under modified effort and carefully trimmed to cylinders with diameter of 0.07 m and height of 0.02 m. Soil specimens were restrained laterally by the oedometer ring and loaded axially in a consolidometer with access to free water. The specimens were maintained at constant height by the application of increments of vertical pressure after being inundated to measure the swell pressure. A free expansion test was subsequently performed to estimate potential heave.

2.9 *Field test liners*

Two test pads were constructed inside the area of Caieiras Sanitary Landfill in the metropolitan region of Sao Paulo, where the samples of the investigated soil had been collected. Test Pad 1 was built with the natural soil and Test Pad 2 with a mixture of natural soil with 5% bentonite. The dimensions of each test pad were 10m width, 20m length and 0.60m height.

Compaction specifications were relative compaction of 95%, water content equal to 0 to 4% wet of optimum at modified effort, and 60 passes of tamping compaction roller (CA-25 Dynapac) for each 0.30m-thick lift at the maximum speed of 3 Km/h.

From each test pad three undisturbed samples of soil were collected for permeability tests with hydraulic gradient of 30.

3 RESULTS

3.1 *Compaction tests*

Results of compaction tests are shown in Table 1 and Figure 1.

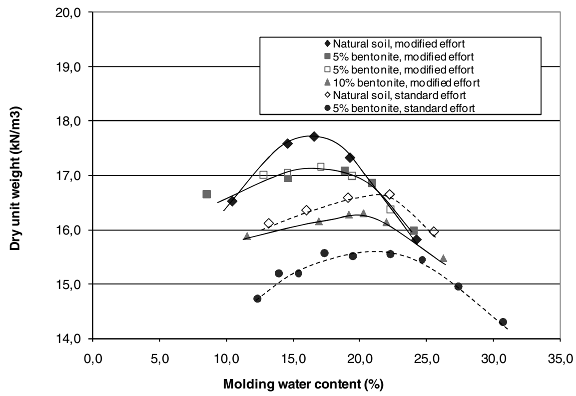

Figure 1. Compaction curves of natural soil and mixtures.

Table 1. Results of compaction tests.

Effort	Bentonite content	w_{ot} (%)	γ_{dmax} (kN/m^3)
Standard	0	20.0	16.33
Standard	5	21.0	15.65
Modified	0	16.6	17.70
Modified	5	18.0	17.10
Modified	10	20.0	16.27

w_{ot} = optimum water content, γ_{dmax} = maximum dry unit weight

As expected, bentonite addition increases the optimum water content and decreases the maximum dry unit weight. The effect of bentonite addition on the optimum water content is more relevant at modified than at standard effort: there was an increase of 1.4% and 3.4% for respectively 5% and 10% bentonite content at modified effort, compared to 1% for 5% bentonite at standard effort. The effect of bentonite addition on the maximum dry unit weight was similar for both energies.

3.2 *Permeability tests*

Results of permeability tests are presented in Table 2 and Figures 2 to 4. Figure 2 shows the variation of the permeability coefficient as function of bentonite content. Figure 3 exemplifies the results of a permeability test, whereas Figure 4 shows the influence of the percolating fluid in the measured permeability coefficient.

Table 2. Permeability tests: molding characteristics of specimens.

Effort	B (%)	Δw (%)	RC (%)	K (m/s)
Standard	0	3.3	97	$3.5x10^{-8}$
Standard	0	0.1	96	$5.6x10^{-8}$
Standard	0	-1.1	96	$1.0x10^{-7}$
Standard	5	1.3	96	$1.0x10^{-8}$
Modified	0	0.0	99	$5.2x10^{-8}$
Modified	0	1.5	98	$2.2x10^{-8}$
Modified	0	4.2	95	$3.5x10^{-8}$
Modified	2.5	4.5	97	$2.5x10^{-9}$
Modified	5	0.1	100	$6.2x10^{-10}$
Modified	7.5	1.9	94	$5.7x10^{-10}$
Modified	10	5.2	97	$1.7x10^{-10}$

B = bentonite content, $\Delta w = w_m - w_{ot}$; w_m = molding water content; w_{ot} = optimum water content; RC = relative compaction (= γ_d/γ_{dmax}); γ_d = molding dry unit weight; γ_{dmax} = maximum dry unit weight, K = permeability coefficient

Observation: values of w_{ot} and γ_{dmax} for 2.5% and 7.5% bentonite were interpolated from Table 1.

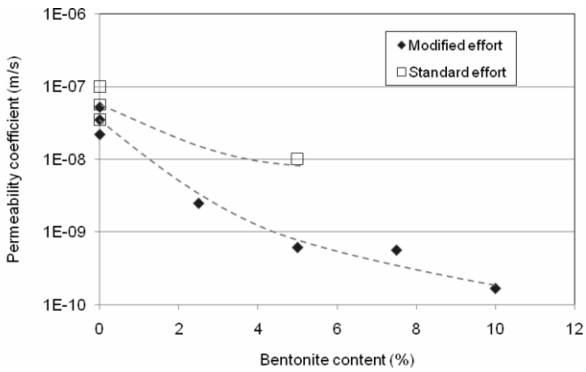

Figure 2. Permeability coefficient as a function of bentonite content.

A bentonite content of 5% decreases the permeability coefficient to 10^{-8} m/s at standard effort and to a value lower than 10^{-9} m/s at modified effort, indicating that it is necessary to use both procedures to use the saprolitic silt for liner construction. Higher bentonite contents were tested at modified effort to better define the variation of the permeability coefficient in function of bentonite content, but are not likely to be employed in the field because of cost effectiveness.

The decrease in the permeability due to the percolation of leachate is probably related to the effects of the fluid composition on the soil structure i.e. the distribution of electric charges on the surface of the clay minerals, since the density and viscosity of leachate as determined in laboratory are very similar to those of water.

3.3 *Consolidation tests*

Results of consolidation tests are presented in Table 3 and Figure 5. Addition of bentonite increases the deformability of the soil, so that it compresses and expands more under the same vertical stress variation. This effect, however, is not remarkable: the compression and the expansion coefficients increased, respectively, 35% and 19%.

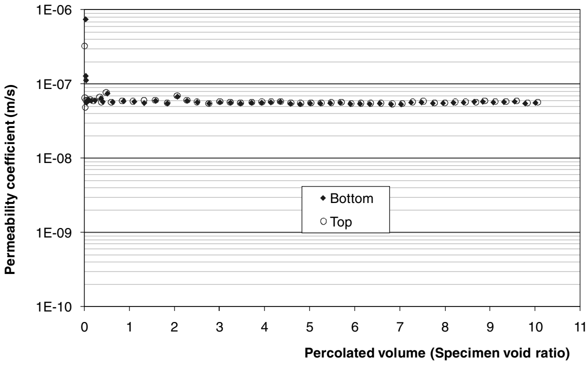

Figure 3. Permeability test with Tri-Flex 2 permeameter: Natural soil compacted at optimum water content under standard effort.

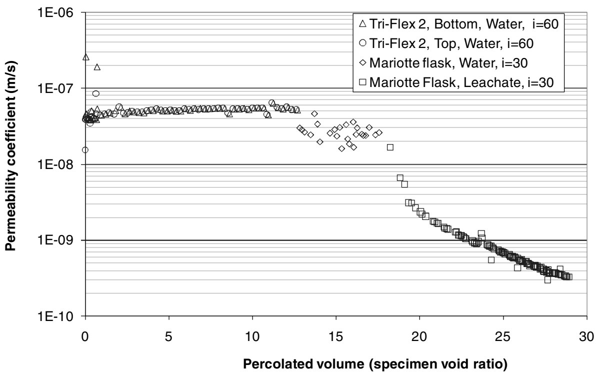

Figure 4. Permeability test: Natural soil compacted at optimum water content under modified effort.

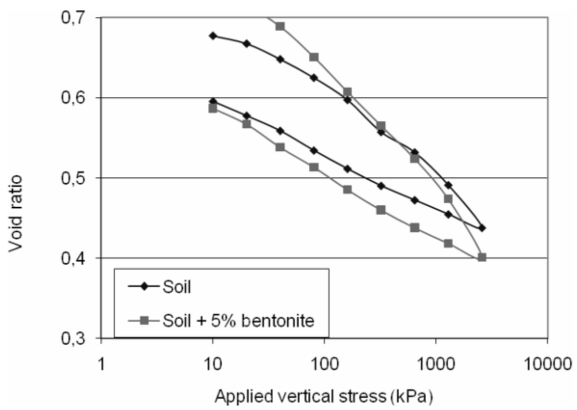

Figure 5. Results of consolidation tests.

Table 3. Deformability parameters determined by consolidation tests.

Material	Compression index C_c	Expansion index C_e
Soil	0.11	0.067
Soil + 5% bentonite	0.15	0.080

3.4 *Shear strength tests*

Results of shear strength tests are presented in Table 4 and Figure 6.

Table 4. Shear tests results and strength envelopes

Material	σ (kN/m²)	τ_{max} (kN/m²)	Strength envelope
Soil	50	40.6	s = 9.9 + σ tg32.2° (kPa)
	100	73.9	
	200	135.4	
Soil + 5%	50	42.5	s = 15.7 + σ tg29.2° (kPa)
bentonite	100	73.5	
	200	127.1	

σ = vertical stress; τ_{max} = maximum shear stress; s = shear strength

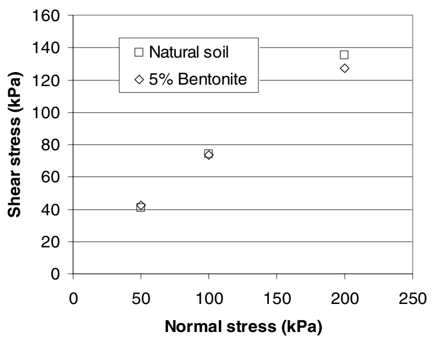

Figure 6. Results of direct shear tests

Addition of bentonite did not cause a significant change in the soil shear strength; the cohesion intercept increased and the friction angle decreased, both slightly, as expected due to the higher clay fraction of the soil-bentonite mixture.

3.5 *Expansion tests*

Results of the expansion tests are presented in Table 5. Average values of 20 kPa and 34 kPa can be related, respectively, to the soil and to the mixture with 5% bentonite. Potential heave of the soil, on the other hand, is significant and increased from 11% to 21% with the addition of bentonite.

The high expansibility of saprolitic silt soils composed of mica and kaolinite associated with low swelling pressures have been extensively reported (Nogami and Villibor 1995, Stuermer 2006, among others).

Table 5. Results of expansion tests.

Material	Δw (%)	RC (%)	Swelling pressure (kPa)	Potential heave (%)
Soil	3.8	95	21	7
	2.5	97	24	15
	2.8	97	16	-
Soil + 5%	3.7	93	26	20
bentonite	3.3	94	40	20
	2.7	96	35	23

3.6 *Test liners*

Average results of permeability tests with undisturbed specimens were 3.6×10^{-8} m/s for Test Pad 1 (soil) and 3.0×10^{-9} m/s for Test Pad 2 (soil with 5% bentonite). These results showed that the addition of bentonite to the silty soil reduced permeability to acceptable values and provided an alternative for CCL construction, considering that the clay borrow pit is almost 50 Km distant from the site.

Test liners also showed the need of thorough mixing in the field, of programming compaction to avoid rainy days (since exposed lifts may be severely damaged by expansion), and of using representative samples in laboratory tests, as field compaction is not so effective to disaggregate the soil, resulting in compacted materials with different permeability coefficients.

4. CONCLUSIONS

The silty saprolitic soil may be employed in the construction of compacted bottom liners for waste disposal sites with the addition of 5% bentonite and modified effort. Construction quality control, e.g. mixture homogeneity and bentonite hydration, is mandatory to ensure adequate performance. Permeability requirements are met without significant loss of shear strength; on the other hand, the mixture presents higher expansibility than the natural soil, a problem that must be properly addressed in the field. Swelling pressures are however low, what is a very relevant aspect in the expansion behavior.

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