Hydraulic Conductivity and Shear Strength Behavior of Compacted Lateritic Soil-Bentonite Mixtures Used for Sanitary Landfill Liners

Juliana Azoia Lukiantchuki, Edmundo Rogério Esquivel

Abstract. The use of soil-bentonite mixtures for sanitary landfill liners with the purpose of retaining pollutants is becoming very common. This work shows the results of hydraulic conductivity and shear strength tests performed with soil-bentonite mixtures with bentonite contents of 3%, 5% and 7%. Additionally, shear strength test results carried out with a mixture with bentonite content of 9%, are shown. The selected natural soil for this research is a lateritic residual clayey sand originated from Adamantina Formation sandstones of the Bauru Group. Samples of this soil were collected in the Pindorama County, which is located in the northeast of the State of Sao Paulo, Brazil. The hydraulic conductivity tests were performed with rigid and flexible wall permeameters. Test results show that mixtures with bentonite content higher than 6% are suitable, in terms of hydraulic conductivity, for the construction of sanitary landfill liners. The shear strength parameters of natural soil and mixtures were assessed by performing undrained triaxial compression tests and unconfined compression tests. It was found that there is a tendency showing that the cohesion increases when the bentonite content is increased. The addition of bentonite to natural soil causes the friction angle to decrease. However, it cannot be concluded from test results, that the higher the bentonite content, the lower the friction angle. In terms of shear strength, the unconfined compression test results have shown that mixtures with bentonite content of 5% are suitable for the construction of sanitary landfill liners when relative compaction is equal or higher than 95%.

Keywords: sanitary landfill, liners, bentonite, hydraulic conductivity, shear strength.

1. Introduction

In the last decades, the population growth and industrial expansion have caused serious problems, such as contaminant waste production and unsafe waste disposal. Waste decomposition produces gases and liquids, which may cause soil and groundwater contamination. At present, more importance has been given to this subject due to the concerns with the environmental protection. For this reason, many researchers (Rowe, 2001; Daniel, 1984, 1989 and 1993; Daniel & Koerner, 1995; Gleason *et al.*, 1997, Daniel & Wu., 1993; Rowe *et al.*, 2004; McBean *et al.*, 1995; Tripathi & Viswanadham, 2005; Sivapullaiah *et al.*, 2000; Anderson & Hee, 1995; Farnezi & Leite, 2007; Kumar & Yong, 2002, Magistris *et al.*, 1998) have discussed the issue concerning the adequate final waste disposal.

Among other factors, the efficiency of solid waste landfills depends on the liner performance. Liners are low hydraulic conductivity layers used in solid waste landfills to minimize infiltration of leachate into the groundwater (Dixon *et al.*, 1999). Such layers should show some basic characteristics such as low hydraulic conductivity, suitable shear strength, and durability. Materials used as liners may be either synthetic (geomembranes or geosynthetic clay liners) or natural (compacted clays or soil-bentonite mixtures).

Since soil liners serve as primary barrier to liquid movement, they should be composed of soils with a high percentage of clay-sized particles. In the case of places where the local soils show high hydraulic conductivity, suitable liners are constructed either with imported soils from other places or with local soils, improved by adding very fine materials, such as bentonite (McBean *et al.*, 1995).

Bentonites are clay minerals of the smectite group. Water is easily absorbed between the layers of smectite, causing swelling of the clay and consequently lowering its hydraulic conductivity. Because of its intense swelling and CEC (cation exchange capacity) properties, bentonite is widely used in the construction of liners. The sodium bentonite is frequently used for the construction of liners because its expansion is higher than that of the calcium bentonite. Consequently, the hydraulic conductivity of the sodium bentonite is lower than that of the calcium bentonite (Gleason *et al.*, 1997; Khera, 1995; Daniel & Koerner, 1995; Hoeks *et al.*, 1987, Mollins *et al.*, 1996).

According to Rowe (2001), the successful construction of soil-bentonite liners with low hydraulic conductivity depends on: (a) obtaining and maintaining a

Juliana Azoia Lukiantchuki, M.Sc, Doctoral Student, Departamento de Geotecnia, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, SP, Brazil. e-mail: jazoia@yahoo.com.br.
Edmundo Rogério Esquivel, D.Sc, Professor, Departamento de Geotecnia, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, SP, Brazil. e-mail: esquivel@sc.usp.br.
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homogeneous mixture of the base soil with bentonite, avoiding segregation prior to and during placement; (b) compaction and water content control during placement; (c) reduced lift thickness to ensure uniform mixing of soil and bentonite.

The process of mixing soil and bentonite in the field may be done using motor grader blades and/or grids. According to Gouveia Filho (2006), the efficiency of the homogenization, when using this process, is very reasonable. Before mixing, the existing soil must be broken up and cleaned, with gravel and roots being removed. After mixing, the soil-bentonite mixture should be compacted according to the project recommendations, in terms of dry unit weight and optimum water content (Gouveia Filho, 2006).

When designing a soil-bentonite liner, it is important to find the optimum proportion of bentonite and water content on a site-specific basis. This can be achieved by preparing different soil mixtures with different bentonite contents and different water contents. Then laboratory hydraulic conductivity tests are performed on compacted specimens. Rowe (2001) reported that in barriers built with soil-bentonite mixtures, the bentonite content typically ranges between 4% and 10%, which leads to hydraulic conductivities ranging between 10^{-9} m.s^{-1} and 10^{-11} m.s^{-1}. Previous studies (Daniel, 1993) reported that in mixtures even with low bentonite content, the hydraulic conductivity could be reduced up to four orders of magnitude, as shown in Fig. 1.

When selecting materials for liner construction, if only the hydraulic conductivity characteristics are considered without taking into account the material shear strength, the liner performance can be negatively affected. Liner integrity, among other factors, is fundamental for waste landfill success (Boscov, 2008). Generally, liners undergo different states of stress, which may lead to failure. Thus, it is important to evaluate the shear strength of the materials used in the liner construction, in order to perform the required stability analyses.

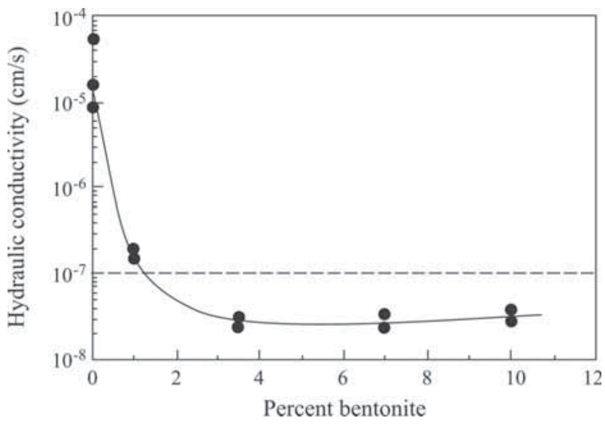

Figure 1 - Hydraulic conductivity *vs.* bentonite content (Daniel, 1993).

The addition of bentonite to a natural soil may modify its shear strength parameters. Chalermyanont & Arrykul (2005) reported that in barriers compacted with soil-bentonite, the cohesion and the friction angle increased and decreased, respectively, with the increase of the bentonite content.

The present paper describes the results of hydraulic conductivity and shear strength tests performed with natural soil and soil-bentonite mixtures. The natural soil used is a typical lateritic clayey sand found in the Southeast of Brazil. Hydraulic conductivity tests were performed with natural soil and three different soil-bentonite mixtures, with bentonite contents of 3%, 5% and 7%. The natural soil was tested in a rigid-wall permeameter and the soil-bentonite mixtures in flexible-wall permeameters. The shear strength parameters of the compacted soil and compacted mixtures were obtained through consolidated undrained triaxial compression tests (CU) and unconfined compression tests. In this case, shear strength tests were also carried out with a mixture with bentonite content of 9%.

2. Materials and Methods

2.1. Materials

Disturbed samples were collected in an industrial landfill located in Pindorama, São Paulo State, Brazil. The typical soil of this area is a lateritic residual clayey sand originated from Adamantina Formation sandstones of the Bauru Group. The natural soil was classified as lateritic soil according to the methylene blue adsorption test results (Lukiantchuki, 2007). Table 1 shows cation exchange capacity (CEC), specific surface (SS), clay activity (CA) and mineralogical composition of natural soil.

Figure 2 shows the grain size distribution of the natural soil and the bentonite used for mixtures (ABNT, 1984). Clay, silt and sand contents were about 22%, 14% and 64%, respectively. The uniformity coefficient (C_U) and the coefficient of gradation (C_C) are equal to 85 and 5, respectively.

The clay content of the bentonite was about 74%. According to the Unified Soil Classification the natural soil was classified as clayey sand (*SC*).

In the present work, besides the natural soil, three different soil-bentonite mixtures were studied, with bentonite contents of 3%, 5% and 7%. The natural soil and the mixtures were respectively designated by *S00*, *S03*, *S05* and *S07*, according to the bentonite contents. Further information about mixture preparation can be obtained in Lu-

Table 1 - Natural soil properties.

CEC (cmol kg^{-1})	4.39
SS (m^{2}g^{-1})	34.25
CA	6.45 (normal)
Mineralogical composition	kaolinite (dominant)

Table 2 - Natural soil and mixtures properties.

		S00	*S03*	*S05*	*S07*	Bentonite
Gs		2.61	2.67	2.67	2.68	2.83
Atterberg limits (ABNT,1984)	w_L (%)	26	36	39	42	455
	w_P (%)	17	16	17	17	54
	I_P (%)	9	20	22	25	401
Unified soil classification		*SC*	*SC*	*SC*	*SC*	-

G_s = specific gravity. w_L = liquid limit. w_P = plastic limit. I_P = plasticity index.

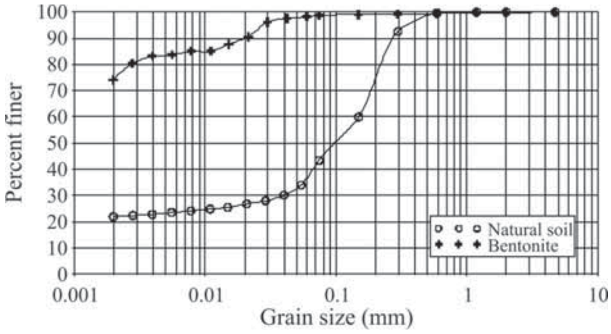

Figure 2 - Grain size distribution of natural soil and bentonite (ABNT, 1984).

kiantchuki (2007). Figure 3 shows the grain size distribution of the mixtures. Since the mixture bentonite content is relatively low, the grain size distribution curves are very alike. Some properties of natural soil, bentonite and soil-bentonite mixtures are shown in Table 2. According to X-ray diffraction test results, the bentonite used in this research is mineralogically composed of sodium smectite and low quartz. The bentonite chemical composition is show in Table 3.

2.2. Compaction test

Compaction tests were carried out to assess optimum water contents and maximum dry unit weights for natural soil and sand-bentonite mixtures. Proctor compaction tests were performed using standard effort (ABNT, 1986).

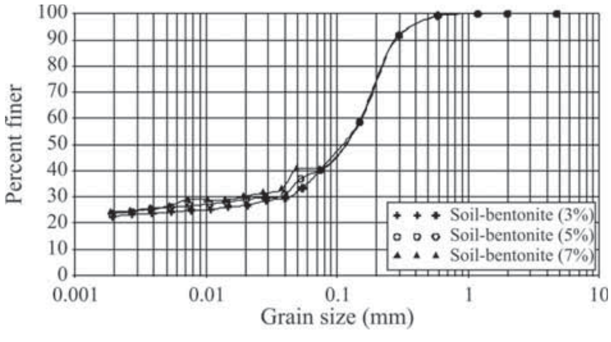

Figure 3 - Grain size distribution of soil-bentonite mixtures (ABNT, 1984).

For sample preparation, first, water was added to the dry soil-bentonite mixtures. Next, the specimens were sealed in plastic bags and left to hydrated for at least 24 h prior to compaction.

2.3. Hydraulic conductivity tests

The hydraulic conductivity tests were performed with natural soil and soil-bentonite mixtures with bentonite contents of 3%, 5% and 7%. These tests were carried out with three different specimens at each bentonite content. Specimens were molded at optimum water content and 95% of maximum dry unit weight. For the natural soil, the tests were performed with four different specimens in a rigid-wall permeameter (ABNT, 2000). The sample diameter and height were 50 mm and 100 mm, respectively.

The tests with soil-bentonite mixtures were performed using the flexible-wall permeameter (FWP) technique. In this case, the sample diameter and height were 100 mm and 100 mm, respectively. The FWP tests were conducted with a constant volume hydraulic system (closed system). The permeameter was connected to three different pressure sources, providing sample confinement, backpressure saturation and hydraulic gradient. Figure 4 shows the closed hydraulic system developed by Dourado (2003).

In this test, the specimen was placed between filter paper sheets and porous discs, and sealed with a rubber membrane, as shown in Fig. 5. The porous discs were previously saturated with water.

Table 3 - Bentonite chemical composition.

Chemical component	Percent
Silicon dioxide (SiO_2)	60.2
Aluminum oxide (Al_2O_3)	18.5
Ferric oxide (Fe_2O_3)	7.2
Magnesium oxide (MgO)	2.0
Calcium oxide (CaO)	2.4
Sodium oxide (Na_2O)	2.5
Titanium dioxide (TiO_2)	0.9
Potassium oxide (K_2O)	0.53

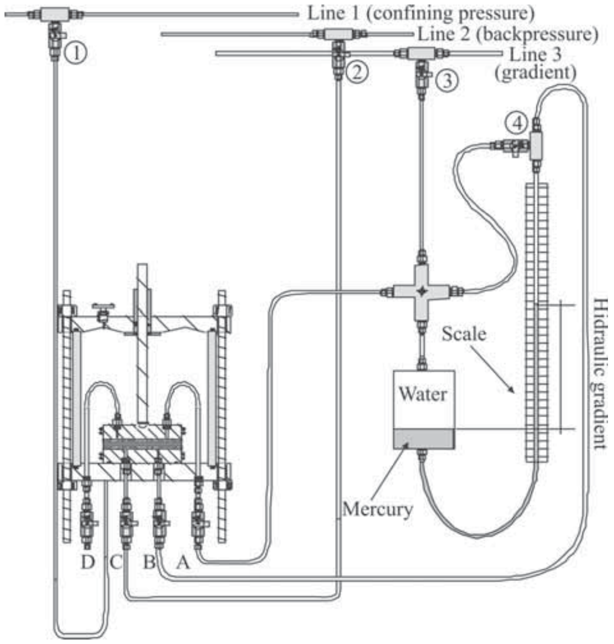

Figure 4 - Closed hydraulic control system (Dourado, 2003).

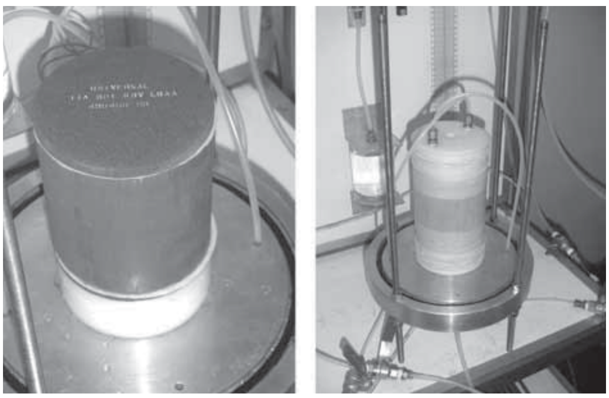

Figure 5 - Details of specimen assembly in the flexible-wall permeameter.

The FWP test comprised two stages: saturation and percolation. The specimen was initially saturated by applying the backpressure and the confining pressure, simultaneously. According to Head (1986), the saturation degree can be evaluated through the pore-pressure parameter *B*, which is defined as:

$$B = \frac{\Delta u}{\Delta \sigma_3} \quad (1)$$

where Δu is the pore pressure variation and $\Delta\sigma_3$ is the confining pressure variation. The tests were conducted by increasing the pressure in steps of 50 kPa, maintaining a difference of 10 kPa between the confining pressure and the backpressure. The specimens were considered fully saturated when $B \geq 0.90$, which was confirmed through index properties tests, performed after the FWP tests.

After full saturation, a flow through the sample was imposed by increasing pressure in line 3, creating a hydraulic gradient between the specimen top and bottom (Fig. 4). The initial hydraulic gradient adopted was 10, as recommended by ASTM (2001). The pressure increase caused the mercury in the capillary tube to heave, indicating the hydraulic gradient level. The hydraulic conductivity k (m.s^{-1}) was calculated by Eq. (2), measuring the variation with time of the mercury column height:

$$k = \frac{a \times A}{(a + A)\left(\frac{\gamma_{Hg}}{\gamma_w} - 1\right)} \times \frac{L}{S \times \Delta t} \times \ln\left(\frac{Y_i}{Y_{i+1}}\right) \quad (2)$$

where a = the capillary tube cross section area (m^2); A = mercury container cross section area (m^2); γ_{Hg} = mercury unit weight (kN.m^{-2}); γ_w = water unit weight (kN.m^{-2}); L = specimen height (m); S = specimen cross section area (m^2); Y_i and Y_{i+1} = mercury column height at instants t_i and t_{i+1}, respectively (m); Δt = elapsed time between the readings of Y_i and Y_{i+1} (s).

2.4. Shear strength tests

Shear strength parameters (cohesion and friction angle) of the natural soil and sand-bentonite mixtures were assessed by carrying out a series of consolidated undrained (CU) triaxial tests (ASTM, 1995). Specimens were molded at optimum water content and 85% of maximum dry unit weight. Shear strength tests were performed with natural soil and soil-bentonite mixtures with bentonite contents of 3%, 5%, 7% and 9% at three different confining pressures (50 kPa, 100 kPa and 200 kPa). The extra soil-bentonite mixture with bentonite content of 9% was designated *S09*. Specimen shearing rate of 0.2 mm/min was adopted based on the full consolidation time (Head, 1986).

The undrained shear strength of the natural soil and sand-bentonite mixtures were assessed by means of unconfined compression tests. For each relative compaction value (85%, 90% and 95%), one specimen was molded, which was tested under unconfined compression.

3. Results and Discussion

3.1. Compaction test results

Natural soil and soil-bentonite mixtures compaction test results are shown in Table 4 and Fig. 6. It can be noticed that the higher the bentonite content, the lower the maximum dry unit weight. Also, there is a tendency showing that the higher the bentonite content, the higher the optimum water content, although for mixtures *S03* and *S05* the optimum water contents are alike. These soil-bentonite behaviors are very similar to those found by Chalermyanont & Arrykul (2005).

Table 4 - Compaction characteristics.

	S00	*S03*	*S05*	*S07*
$\gamma_{dmáx}$ (kN.m^{-3})	18.90	18.50	18.30	17.8
w_{op} (%)	13.0	14.5	14.5	15.5

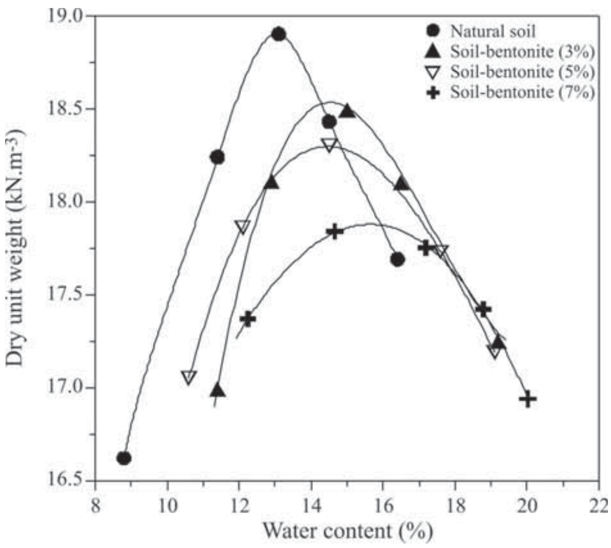

Figure 6 - Compaction curves for natural soil and soil-bentonite mixtures.

Figure 7 shows the influence of the bentonite content on some mixture properties. It can be noticed that the variation of the liquid limit (W_L) with bentonite content is approximately linear, whereas the plastic limit (W_P) remains almost constant. Consequently, the addition of bentonite significantly increased the plasticity (I_P) of the natural soil. These Atterberg limit behaviors were also observed by Magistris *et al.* (1998).

Many researchers reported noticeable changes in the compaction parameters as a result of bentonite addition to natural soil (Magistris *et al.*, 1998; Chalermyanont & Arrykul, 2005; Kumar & Yong, 2002; Farnezi & Leite, 2007). However, the observed behaviors of the compaction parameters show different trends. According to Magistris *et al.* (1998) the interpretation of these apparently erratic behaviors can be justified by comparing the particle size distribution parameters of the granular soils adopted as basic material (matrix). These authors also reported that the higher the bentonite content, the higher the optimum water content. However, the rate of increase appears to be less evident for the mixtures with well graded matrices and higher hygroscopic water contents, likely due to the hydration of bentonite particles.

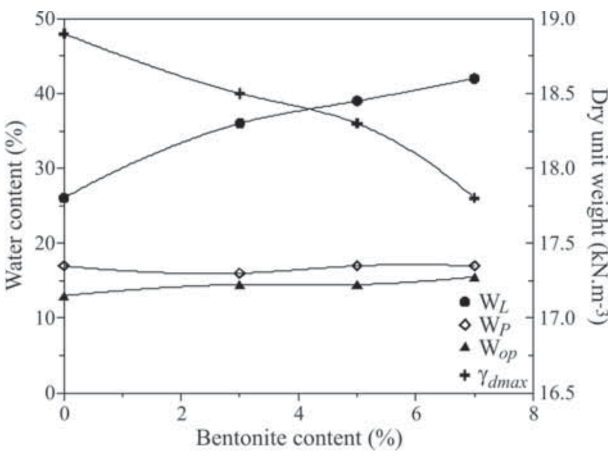

Figure 7 - Variation of some properties with the bentonite content.

3.2. Hydraulic conductivity test results

Figures 8 and 9 show the hydraulic conductivity test results for natural soil and soil-bentonite mixtures, respectively. Table 5 shows the average values of hydraulic conductivity.

It was observed that the higher the bentonite content, the lower the hydraulic conductivity. For mixtures with bentonite content of 7%, the hydraulic conductivity was reduced about four orders of magnitude when compared to the natural soil. This behavior has been also observed by other researchers (Daniel, 1993; Tripathi & Viswanadham, 2005; Chalermyanont & Arrykul, 2005).

Figure 10 shows the variation of hydraulic conductivity average with bentonite content. The reduction in hydraulic conductivity occurs due to high mineralogical activity of bentonite. Absorbing water, the bentonite particles swell, fill the pores of the coarse matrix and obstruct the free water flow (Magistris *et al.*, 1998).

The usual municipal waste standards for compacted soil liners state that the hydraulic conductivity should be less than 10^{-9} m/s. Therefore, according to laboratory tests,

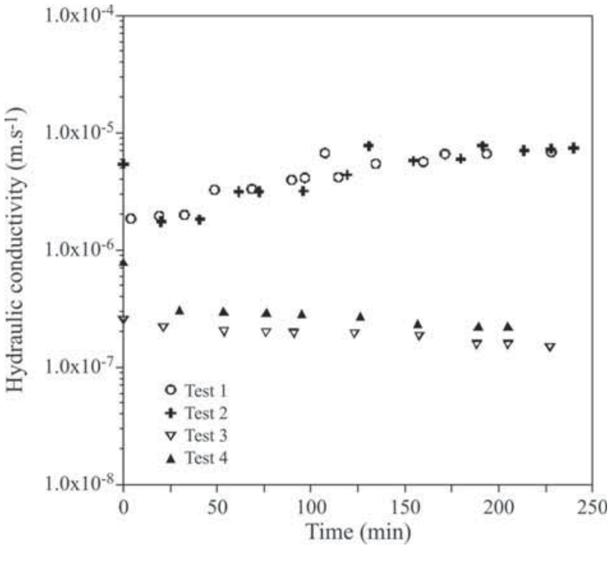

Figure 8 - Hydraulic conductivity test results for natural soil.

the compacted soil-bentonite mixtures with bentonite content higher than 6% fulfill the requirements for liners. However, it must be taken into account that hydraulic conductivity in the field will be generally higher than that measured in laboratory tests (Daniel, 1984). In a research conducted by Ferrari (2005), the hydraulic conductivity obtained in the field was very similar to that one obtained in laboratory. According to the same author, this can be accomplished when some precautions are taken, including proper bentonite hydration, homogeneous mixtures of base soil with bentonite and reduced lift thickness to ensure uniform mixing of soil and bentonite.

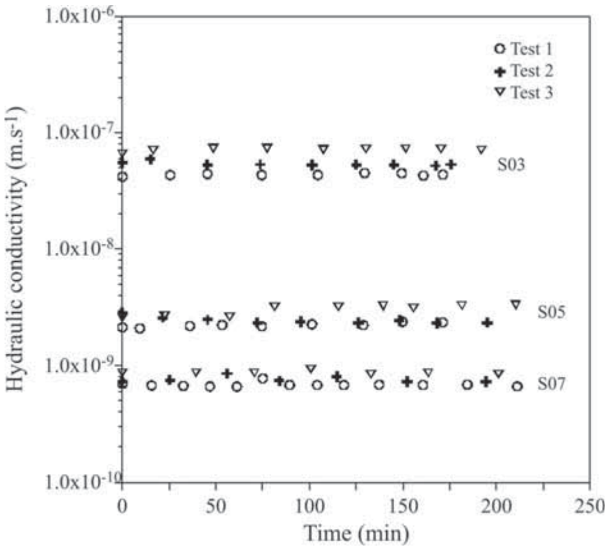

Figure 9 - Hydraulic conductivity test results for soil-bentonite mixtures.

Table 5 - Average values of hydraulic conductivity results.

Test	k (m.s^{-1})			
	S00	*S03*	*S05*	*S07*
1	1.2×10^{-6}	4.4×10^{-8}	2.2×10^{-9}	6.8×10^{-10}
2	3.3×10^{-6}	5.3×10^{-8}	2.4×10^{-9}	7.5×10^{-10}
3	3.0×10^{-6}	7.2×10^{-8}	3.1×10^{-9}	8.8×10^{-10}
Average	2.5×10^{-6}	5.6×10^{-8}	2.6×10^{-9}	7.7×10^{-10}

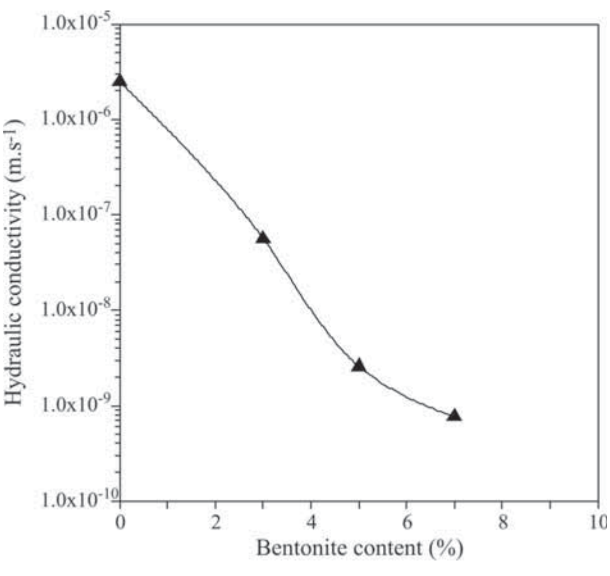

Figure 10 - Average hydraulic conductivity *vs.* bentonite content.

3.3. Shear strength test results

Figure 11 shows the maximum deviator stress for different confining pressures and different bentonite contents. It is observed that the shear strength of the soil decreases with bentonite addition. However, among the mixtures the shear strength tends to increase when bentonite content is increased. This behavior was also observed by Magistris *et al.* (1998). The shear strength parameters are shown in Table 6 and total and effective stress failure envelopes are shown in Figs. 12 and 13, respectively.

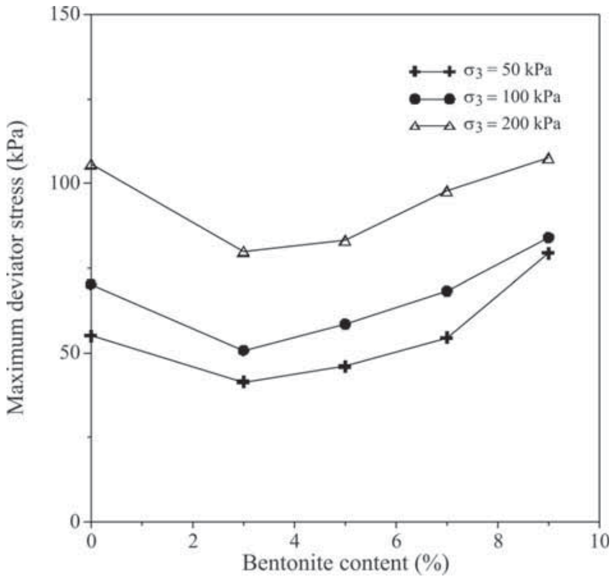

Figure 11 - Maximum deviator stress *vs.* bentonite content.

Table 6 - Shear strength parameters of compacted soil-bentonite mixtures.

Bentonite content (%)	Total parameters		Effective parameters	
	ϕ (°)	*c* (kPa)	ϕ' (°)	*c'* (kPa)
0	10.0	10.1	20.9	5.9
3	6.7	11.9	13.4	14.4
5	6.3	15.1	11.3	15.7
7	7.2	17.6	15.5	14.4
9	6.4	25.8	15.7	22.1

ϕ = total friction angle. *c* = total cohesion. ϕ' = effective friction angle. *c'* = effective cohesion.

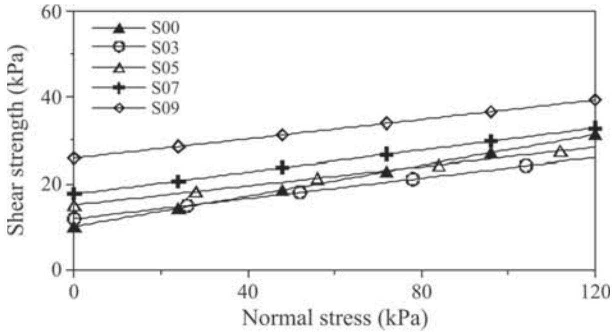

Figure 12 - Total stress failure envelopes.

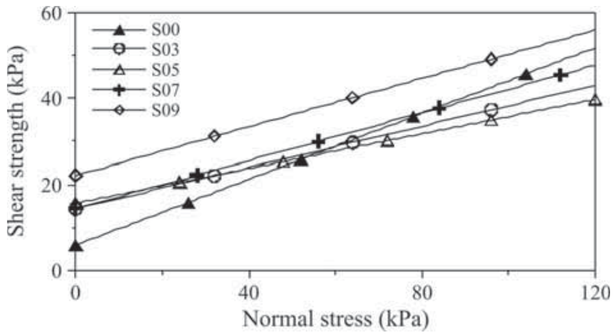

Figure 13 - Effective stress failure envelope.

As shown in Table 6, the total and effective friction angle of compacted soil-bentonite mixtures decreases from 10.0° to 6.3° and from 20.9° to 11.3°, respectively, when bentonite content is increased from 0 to 5%. The natural soil shows the highest friction angle, for both total and effective stresses. The addition of bentonite to natural soil causes the friction angle to decrease. However, it cannot be concluded from test results, that the higher the bentonite content, the lower the friction angle. One explanation for this behavior is that the bentonite swelling causes the mixtures to become loose. Nevertheless, for bentonite content of 7%, the total and effective friction angles increased to 7.2° and 15.5°, respectively. For bentonite content of 9%, the total and effective friction angles found are 6.4° and 15.7°, respectively, showing a modification of the mixture behavior.

In contrast, the cohesion increases when the bentonite content is increased, as shown in Table 6. The total and effective cohesion of the soil-bentonite mixtures increased from 10.1 kPa to 25.8 kPa and 5.9 kPa to 22.1 kPa, respectively, when the bentonite content was increased from 0 to 9%. From shear strength test results it can be observed that there is a tendency of the cohesion to increase when the bentonite content is increased. This behavior was also observed by Chalermyanont & Arrykul (2005).

Magistris *et al.* (1998) also reported that the shear strength parameters are affected by the addition of bentonite. According to these authors, this is in agreement with the microstructural changes reflected by the increase in plasticity.

3.4. Unconfined compression tests results

Figures 14 to 18 show the stress-strain curves, obtained from unconfined compression tests, for samples *S00*, *S03*, *S05*, *S07* and *S09*. The corresponding unconfined compression results are shown in Table 7. Figure 19 shows the variation of the unconfined compression strength with the bentonite content, for three different relative compaction values.

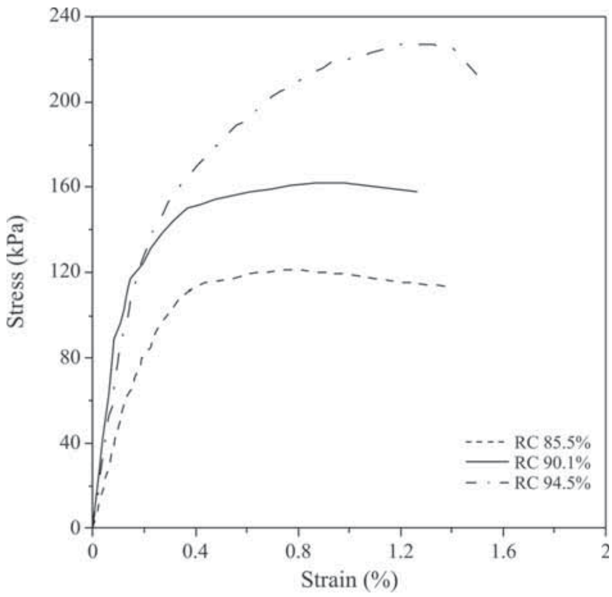

Figure 14 - Stress-strain curve (*S00*).

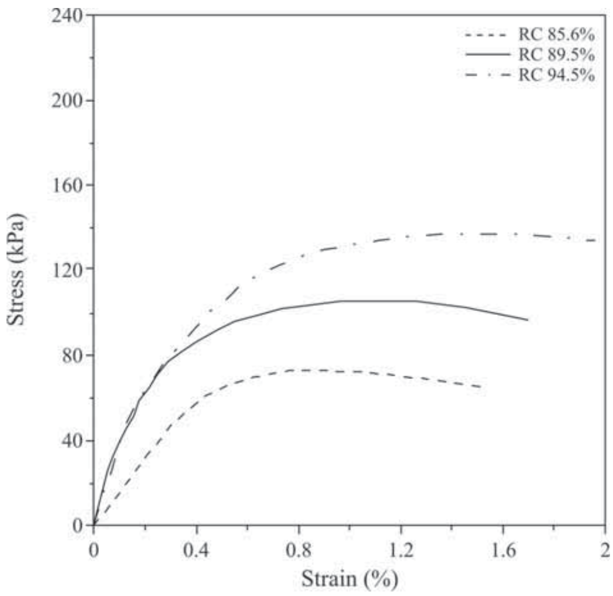

Figure 15 - Stress-strain curve (*S03*).

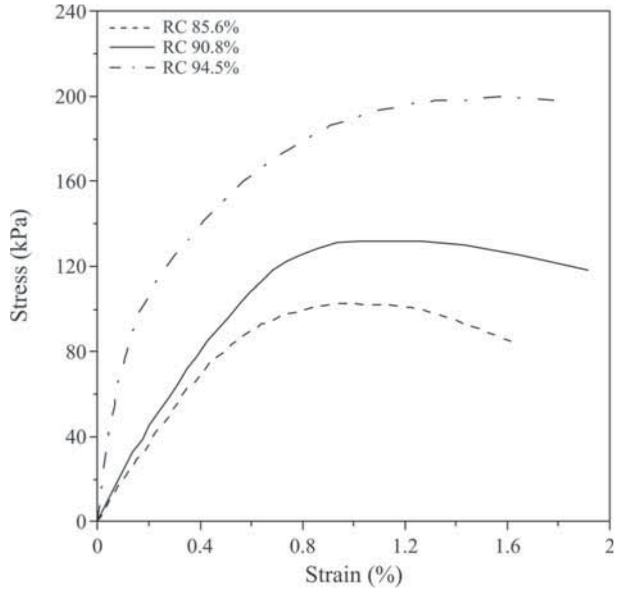

Figure 16 - Stress-strain curve (*S05*).

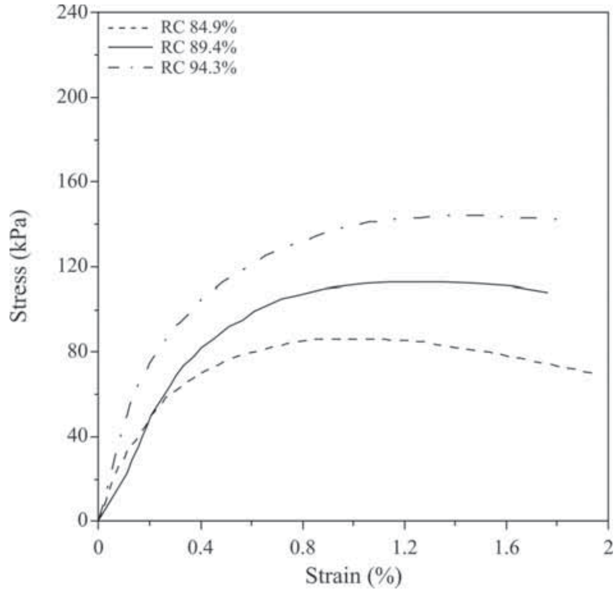

Figure 18 - Stress-strain curve (*S09*).

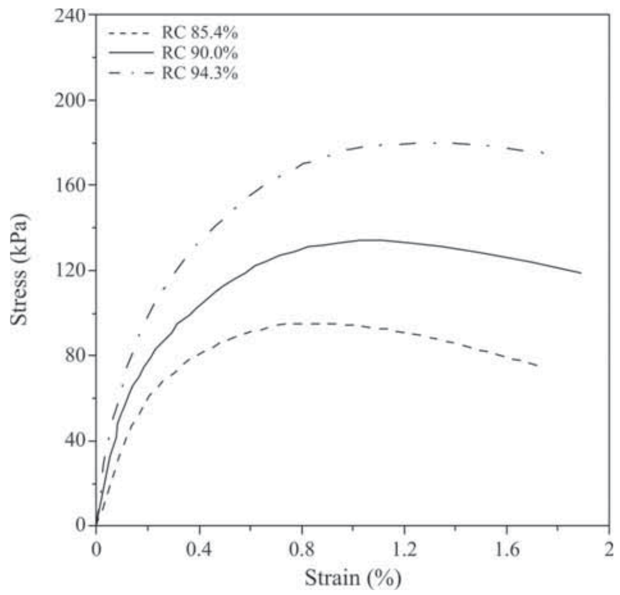

Figure 17 - Stress-strain curve (*S07*).

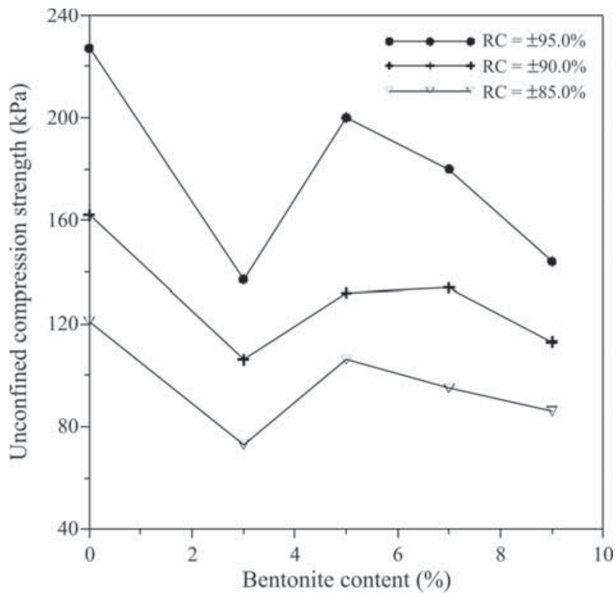

Figure 19 - Variation of the unconfined compression strength with the bentonite content.

It can be noticed that unconfined strength of the natural soil decreases with the addition of bentonite (Fig. 19). However, it can be observed that when the bentonite content is increased, the unconfined strength increases, reaching a maximum value, and then starts to decrease again. Figure 19 also shows that the higher the relative compaction, the higher the unconfined strength. According to Daniel e Wu (1993), the unconfined compression strength for the conduction of liners should be equal or higher than 200 kPa. Therefore, the 5% soil-bentonite mixture is suitable for liner constructions when relative compaction is equal or higher than 95%. The same authors reported that the higher molding water content, the lower the unconfined strength. This tendency can be observed in Fig. 19, although tests performed with mixture *S03* showed the lowest strengths.

4. Conclusions

The properties of compacted soil-bentonite mixtures were assessed by carrying out a series of hydraulic conductivity and shear strength tests. The following conclusions

Table 7 - Unconfined compression results.

	Specimen	RC (%)	UCS (kPa)
	01	85.5	121
S00	02	90.1	162
	03	94.5	227
	01	84.8	73
S03	02	89.5	106
	03	94.5	137
	01	85.6	106
S05	02	90.8	132
	03	94.9	200
	01	85.4	95
S07	02	90.0	134
	03	94.3	180
	01	84.9	86
S09	02	89.4	113
	03	94.3	144

RC = relative compaction. *UCS* = unconfined compression strength.

can be stated concerning the influence of bentonite content on the soil-bentonite mixture properties.

1. The grain size distribution do not show any significant changes by adding bentonite to the natural soil.

2. As it was expected, the liquid limit increases when the bentonite content is increased, while the plastic limit remains constant. Consequently, the bentonite addition significantly increases the plasticity of the natural soil.

3. The maximum dry unit weight decreases and the optimum water content increases when the bentonite content of the compacted soil-bentonite mixtures is increased. Compaction test results have shown that when the bentonite content varies from 0 to 7%, the maximum dry unit weight decreases from 18.90 to 17.86 kN.m^{-3} and the corresponding optimum water content increases from 13 to 15.5%. It is also noticed that the higher the bentonite content, the lower the maximum dry unit weight. Moreover, there is a tendency showing that the higher the bentonite content, the higher the optimum water content, although for mixtures *S03* and *S05* the optimum water contents are alike.

4. As it was expected, the hydraulic conductivity of the soil-bentonite mixtures decreases when the bentonite content is increased. The hydraulic conductivity decreases two to four orders of magnitude when compared to the compacted natural soil. The results have shown that the relationship between the bentonite content and the reduction of the hydraulic conductivity is non-linear.

5. The usual municipal waste standards for compacted soil liners state that the hydraulic conductivity should be less than 10^{-9} m.s^{-1}. Therefore, for the studied soil, compacted soil-bentonite mixtures with bentonite content equal or higher than 6% are suitable for constructing liners.

6. Adding bentonite to the natural soil modifies its shear strength parameters. From shear strength test results it can be noticed that there is a tendency showing that the cohesion increases when bentonite content is increased. The addition of bentonite to natural soil causes the friction angle to decrease. However, it cannot be concluded from test results, that the higher the bentonite content, the lower the friction angle.

7. As it was already expected, the unconfined strength of natural soil is higher than the unconfined strength of soil-bentonite mixtures. The mixture with bentonite content of 5% shows higher unconfined strength than the other mixtures.

The laboratory test results of this research leads to the conclusion that the addition of 6% or more of bentonite to the studied lateritic soil makes it suitable for sanitary landfill liners with the purpose of retaining pollutants. However, it must be taken into account that the hydraulic conductivity in the field will be generally higher than that measured in laboratory tests. Likewise, it should be taken into account that the leachate viscosity affects the hydraulic conductivity and the potential interaction of soil-bentonite mixture and leachate.

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Symbols

G_s: specific gravity
w_L: liquid limit
w_P: plastic limit
I_P: plasticity index
Δu: pore-pressure variation
$\Delta\sigma_3$: confining pressure variation
B: Pore-pressure parameter
a: capillary tube cross section area
A: mercury container cross section area
γ_{Hg}: mercury unit weight
γ_w: water unit weight
$D_{máx}$: maximum grain diameter
C_U: uniformity coefficient
C_C: coefficient of gradation
CEC: cation exchange capacity
SS: specific surface
CA: clay activity
L: specimen height
S: specimen cross section area
Y_i and Y_{i+1}: mercury column height at instants t_i and t_{i+1}

Δt: elapsed time between the readings of Y_i and Y_{i+1}.
k: hydraulic conductivity
$\gamma_{dmáx}$: maximum dry unit weight
w_{op}: optimum water content
S00: natural soil
S03: sample with 3% of bentonite (dry weight basis)
S05: sample with 5% of bentonite (dry weight basis)
S07: sample with 7% of bentonite (dry weight basis)
S09: sample with 9% of bentonite (dry weight basis)
ϕ: total friction angle
ϕ': effective friction angle
c: total cohesion
c': effective cohesion
RC: relative compaction
UCS: unconfined compression strength