Evaluation on the Use of Alternative Materials in Geosynthetic Clay Liners

P.M.F. Viana, E.M. Palmeira, H.N.L. Viana

Abstract. Geosynthetic clay liners (GCL) have been increasingly used in barrier systems of waste disposal areas and in hydraulic works. However, sometimes they are discarded as possible barrier solutions in these works because of their greater costs in comparison with other solutions (geomembranes or compacted clay liners). This paper presents a laboratory study to investigate the technical feasibility of mixing alternative materials to bentonite for the production of alternative low cost GCLs. The alternative materials used were sand, clay and tire grains. Direct shear, consolidation, and expansibility tests were carried out on bentonite mixtures with varying percentages in mass of the alternative material. Ramp tests and expansibility tests were also performed on alternative GCLs manufactured with these types of mixtures. The results obtained showed that the presence of the alternative materials in the bentonite increased the shear strength and the permittivity of the mixture and reduced its expansibility. The tests on the bentonite-tire grains mixtures suggest that alternative GCLs manufactured with this type of mixture may be used in less critical barrier systems (particularly under high stress levels) and as bedding/protective layers underneath geomembranes, also providing a better use for wasted tires in environmental terms.
Keywords: GCL, alternative materials, laboratory tests, ramp tests.

1. Introduction

Geosynthetic Clay Liners (GCLs) are relatively thin geosynthetic products used as barriers in hydraulic and waste disposal works. They consist of a layer of bentonite enveloped by geosynthetic layers (usually geotextiles). Variations are possible, like products consisting of a layer of bentonite on a geomembrane (Koerner, 2005).

The use of GCLs as barriers in environmental protection projects has increased markedly in the last decade, mainly due to its low hydraulic conductivity (typically ≤ 10^{-11} m/s), easy and quick installation, self-healing capacity in case of damage during installation and good overall performance. Several works can be found in the literature reporting successful applications of GCL in environmental protection works (Reuter & Markwardt 2002, Didier & Nassar 2002, Rowe & Orsini 2003 and Shan & Chen 2003, Touze-Foltz *et al.*, 2006).

Hydraulic conductivity is a major factor to be considered when using GCLs in hydraulic and environmental projects. The low permeability of the bentonite guarantees a satisfactory performance as a barrier if damages during transport of the product to the job site and installation are avoided or minimised. In this sense, the self-healing capacity of GCLs is a great advantage in comparison to other barrier systems. Shan & Daniel (1991) and Sivakumar Babu *et al.* (2001) have shown that cracks in a GCL, as a consequence of a dry period, were closed in a subsequent wetting period, without compromising its barrier function. Expansion of the GCL due to hydration may increase its thickness significantly, depending on the stress level on the GCL, reducing even further its permittivity. Permittivity (ψ) values of GCLs are typically lower than 10^{-9} s^{-1}.

Besides low hydraulic conductivity and self-healing capacity, the internal shear strength of GCLs products is of utmost importance in the design of lining systems on slopes, because of the low shear strength of bentonite, particularly when hydrated. The internal shear strength of a GCL depends on the bentonite shear strength and on the strength of the fibres used to fix its cover and carrier layers, as well as on the manufacturing process used (stitching or needle-punching). Chiu & Fox (2004), Fox & Stark (2004) and Viana & Palmeira (2009) discussed the importance of the internal shear strength of GCLs and how it can be severely reduced due to hydration. However, the internal shear strength of GCL products can be markedly increased depending on how they are manufactured and on the mechanical strength of the fibres used to fix the geotextile cover layers (Bouazza, 2002, Bouazza & Vangpaisal, 2007, Müller *et al.*, 2008).

Some materials can be mixed to the bentonite as a way to reduce the GCL cost, improve some of its relevant properties and, in the case of waste materials, to provide a better and more environmentally friendly destination of such materials (Viana & Palmeira 2008, Viana & Palmeira 2009, Ikizler *et al.* 2009). For instance, the mixture of fine sand to the bentonite can increase its internal shear strength and resistance against perforations and cuts, without compromising its low hydraulic conductivity. However, the manufacturing process and costs may be influenced by the presence of sand mixed to the bentonite. Besides, the

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expansibility, and by so the permittivity, of the alternative GCL may be affected because of the addition of a non expansive material and this should be properly evaluated.

This paper examines the influence of adding non conventional materials to bentonite to form alternative and low cost GCLs and the repercussion of the addition of these materials on the hydraulic and strength properties of the GCLs. Two commercially available conventional GCLs were used as references for comparisons. Small and large scale laboratory tests were performed in this study and the experimental methodology and results obtained are presented and discussed in the following sections.

2. Experimentals

2.1. Materials used in the experiments

2.1.1. Bentonite

A sodic bentonite (code BTN), produced by Bentonit Nordeste Ltd., Brazil, was used in the tests and its main properties are summarized in Table 1. X rays diffractometry tests showed that the bentonite was predominantly composed by sodium montmorillonite with some illite, calcite and quartz.

2.1.2. Materials used in the bentonite mixtures

Three materials were mixed to the bentonite (BTN) to form the alternative GCL products. These materials were a fine sand (code SND), a clay (kaolinite, code CLY) and tire grains (code TG) from wasted automobile tires. Table 2 presents the main properties of these materials. Figure 1 shows views of the materials mixed to the bentonite.

Table 1 - Physical properties of the bentonite used in laboratory testing.

Grain unit weight (kN/m^3)	26.60
Liquid limit (%)	381.0
Plastic limit (%)	133.0
Plasticity index (%)	248.0
Initial water content (%)	14.0%
Minimum dry unit weight (kN/m^3)	7.3

*Chemical composition: 60.2% de SiO_2, 18.5% Al_2O_3, 7.2% Fe_2O_3, 2,5% de Na_2O, 2.4% de CaO, 2.0% MgO e 0.53% K_2O.

2.1.3. GCLs tested

Two commercially available GCLs (codes GCLA and GCLB) manufactured with sodic bentonite and three

Table 2 - Physical properties of the materials used in the tests.

Property	Sand	Clay	Tire grains
D_{10} (mm)^1	0.08	0.02	0.12
D_{60} (mm)	0.25	0.07	0.48
D_{85} (mm)	1.00	0.08	0.60
Particle unit weight (kN/m^3)	26.8	28.2	11.5
CU^2	3.10	3.50	4.0
Friction angle (degrees)	34^{3,4}	34.1^6	23^{3,7}
Cohesion (kPa)	-	6.14^{5,6}	-
Maximum void ratio	0.93	-	-
Minimum void ratio	0.63	-	-
Liquid limit (%)	-	36	-
Plastic limit (%)	-	26	—
Optimum moisture content (%)^8	-	23	—
Maximum dry unit weight (kN/m^3)^8	16.3	14.9	4.9
Percentage of carbon (%)	-	-	> 80

Notes: (1) D_n - diameter for which n%, in mass, of the remaining soil particles are smaller than that diameter; (2) Coefficient of uniformity (= D_{60}/D_{10}); (3) Friction angle obtained in direct shear tests for a stress level ranging from 15 kPa to 200 kPa (4) For a sand unit weight of 16.3 kN/m^3; (5) From drained direct shear tests for a stress level ranging from 15 kPa to 200 kPa; (6) Under optimum moisture conditions (clay dry unit weight of 14.9 kN/m^3); (7) For a tire grains unit weight of 4.9 kN/m^3; (8) Normal Proctor compaction energy.

(a) (b) (c)

Figure 1 - Materials mixed with the bentonite to produce the alternative GCLs: (a) Tire grains (TG); (b) Sand (SND) and (c) Clay (CLY) - 50x enlargement.

alternative GCLs with cores consisting of mixtures of bentonite with sand, clay or tire grains were tested. The alternative GCLs had cores consisting of 50% (in mass) of the alternative material (sand – code GCL-SND, clay – code GCL-CLY or tire grains – code GCL-TG). This percentage of alternative material was adopted based on results of tests performed with varying percentages of alternative materials that will be presented and discussed later in this paper. Table 3 summarises the main properties of the GCLs tested.

The alternative GCLs using cores with different mixtures of bentonite, sand, clay and tire grains were manufactured in the laboratory. Woven and a nonwoven geotextiles, whose main properties are listed in Table 4, were used as carrier and cover layers of these GCLs, as in conventional products. The geotextiles were stitch-bonded to form the GCL with 25 mm spacing between stitch-bonding rows, as shown in Fig. 2. Initially, a study on the influence of the stitching process was carried out, with products being manufactured with spacing between stitches equal to 2 mm, 4 mm and 8 mm. Based on this study, the 8 mm spacing was adopted for the manufacture of the GCL specimens that were subjected to expansibility and inclined plane tests.

2.2. Equipment used in the experimental programme

2.2.1. Expansion test cells

Free expansion tests on bentonite-alternative materials and on alternative GCLs were carried out for the evaluation of the influence of the type of bentonite mixture used on the product's expansibility potential. Figure 3 shows the equipment used in these tests. Each GCL specimen, 100 mm in diameter, was accommodated in the testing cell with natural moisture content. The specimen was then inundated for 96 h without any confinement and its vertical expansion was measured with dial gauges until readings stabilisation.

2.2.2. Consolidation and hydraulic conductivity tests

Consolidation and hydraulic conductivity tests under confinement on bentonite mixtures and on the alternative materials described above were performed using a standard soil consolidation testing cell. The GCL specimens were 75 mm in diameter, 20 mm thick and during the tests were subjected to normal stresses up to 200 kPa. Initially, the specimens were hydrated under a vertical stress of 5 kPa for 48 h. This period of time was adopted based on results from preliminary tests that showed that to be sufficient for mixture expansion stabilisation. After specimen expansion had been completed, the loading stages were applied, as in conventional one-dimensional soil consolidation tests. At the end of each loading stage the hydraulic conductivity of the mixture was assessed by performing a variable water head test using ports connected to the cell ends.

Table 4 - Properties of the geotextiles of the GCLs.

Property	Woven	Nonwoven
Polymer type	Polypropylene	Polypropylene
Mass per unit area (g/m^2)	110	350
Tensile strength (kN/m^2)(1)	10/10(2)	17/14(2)
Filtration opening size (μm)(3)	NA(5)	1.2 x 10^{-5}
Permittivity (s^{-1})(4)	NA	1.31

Notes: (1) Wide-strip tensile tests according to ASTM D4595; (2) Number on the left is the tensile strength along the warp direction while number on the right is the tensile strength along the weft direction; (3) According to NF EN ISO 12956; (4) According to ASTM D4491; (5) Not available.

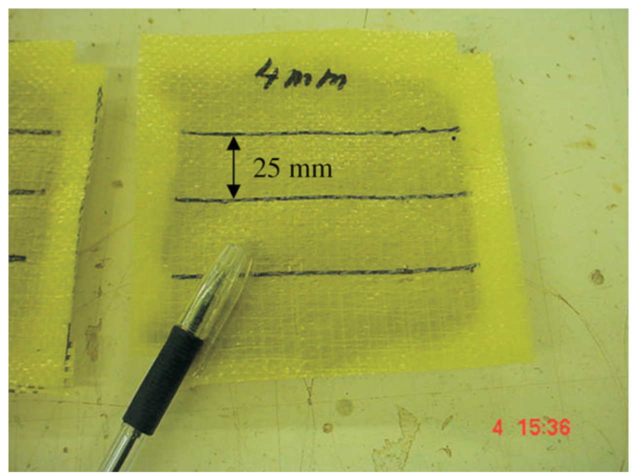


Figure 2 - Alternative GCL product.

Table 3 - Properties of the GCLs used in the tests.

Property	GCLA	GCLB	GCL-SND	GCL-CLY	GCL-TG
Bentonite type	sodic	sodic	sodic	sodic	sodic
Core dry minimum density (kN/m^3)	7.3	7.3	10.6	9.2	6.1
Thickness (mm)	6-7	6-7	6-7	6-7	6-7
Mass per unit area (g/m^2)	5000	4500	6858	5948	3965
Moisture content (%)	13.6	13.4	12.7	12.7	8.6
Manufacturing process	Stitch bonded	Needle punched	Stitch bonded	Stitch bonded	Stitch bonded

Note: The percentage (in mass) of sand, clay and tire grains in GCL-SND, GCL-CLY and GCL-TG, respectively, was equal to 50%.

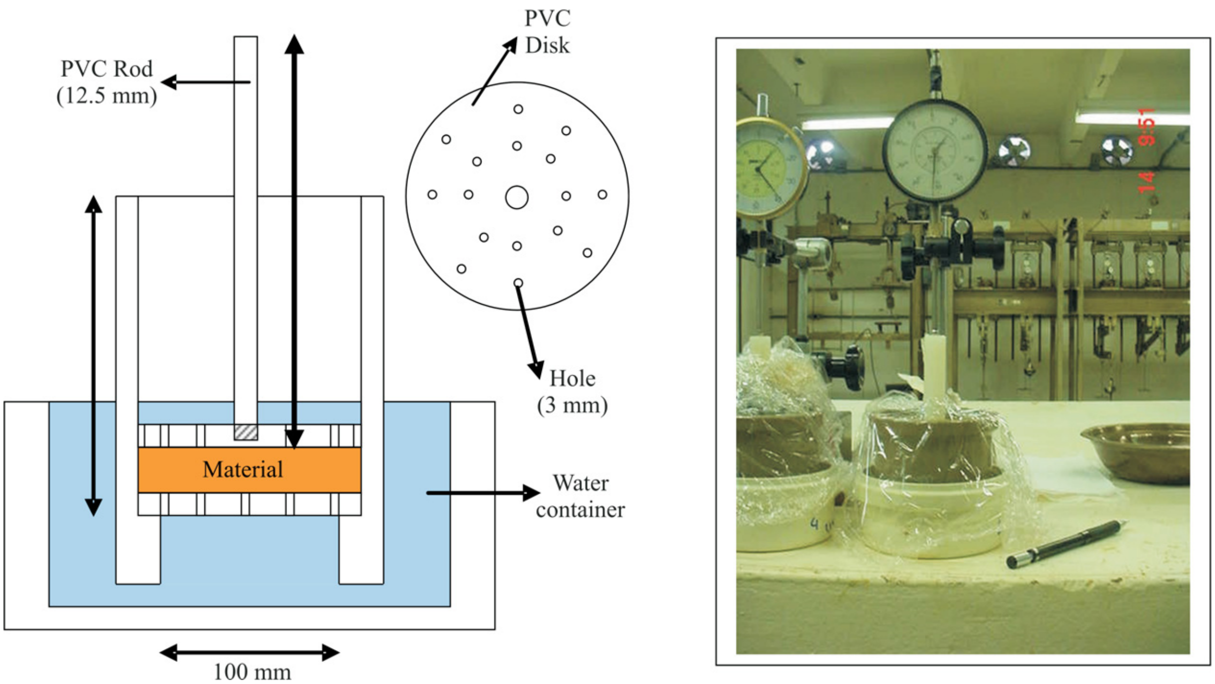


Figure 3 - Free expansion test apparatus.

2.2.3. Direct shear tests

Conventional direct shear tests were performed on the bentonite mixtures used in the experimental programme. The dimensions of the specimens tested in the conventional direct shear apparatus were 100 mm x 100 mm. Dry (under natural moisture content) bentonite mixtures were tested under minimum dry unit weight condition (loosest state) using a test speed of 0.3 mm/min. Tests on hydrated mixtures were also carried out after a period of 48 h of specimens submersion in water. A test speed of 0.03 mm/min was used for the hydrated specimens (ASTM D 6243). Vertical stresses up to 200 kPa were applied to the specimens during the tests and the procedure used was that used in conventional soil direct shear tests. Post-test investigations included assessing the shear zone at the specimen mid-height. Figure 4 shows the region of the shear zone in one of the specimens after the end of the test.

2.2.3. Ramp tests

The ramp (inclined plane) test equipment used (Fig. 5) is capable of testing GLC specimens with dimensions up to 0.6 m x 2.2 m. In this equipment the specimen can be fixed to the ramp along its entire length or to have one end anchored to the ramp (Palmeira *et al.* 2002, Palmeira & Viana 2003, Palmeira 2009, Viana & Palmeira 2010). The latter case was the one adopted in the present work. In the series of tests described in this work the dimensions of the specimens tested were 0.6 m (width) x 1.0 m (length). Tests with normal stresses up to 10 kPa were carried out. The interface between the GCL specimen and the smooth metal ramp surface was lubricated with double layers of plastic films and grease to minimise friction along this interface. Concrete blocks accommodated in a rigid box were used to provide vertical stresses on the GCL specimen. Displacement transducers allowed for the measurement of the displacements of this box during the tests and a load cell fixed to the anchored GCL end measured the tensile forces mobilised in the specimen. In these tests the upper geotextile layer was cut and only the bottom one (carrier layer) was anchored to the ramp extremity. This procedure was adopted to favour internal failure of the GCL. Tests on dry and on hydrated GCL specimens were carried out. For the latter case a water filled container was installed on the ramp for the hydration of the specimen prior to testing.

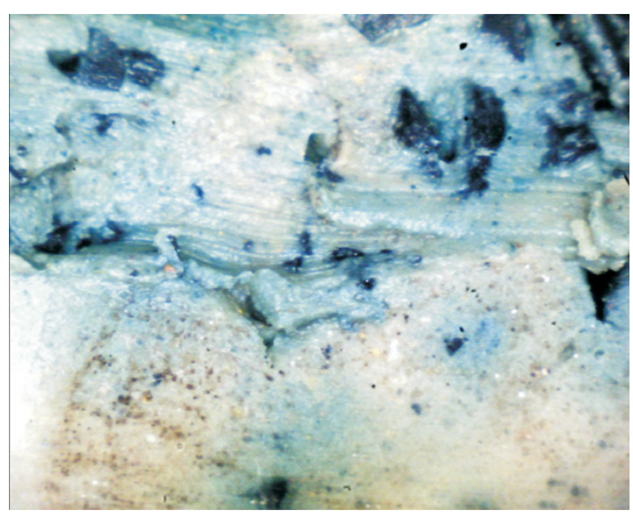


Figure 4 - Shear zone region in a test on GCL-TG 50% (50% in mass of tire grains) at the end of a direct shear test.

Figure 5 - Large scale ramp test equipment.

3. Results Obtained

3.1. Tests on bentonite mixtures

Direct shear, expansion and consolidation tests were performed in the mixtures of bentonite with sand, clay or tire grains for percentages (in mass) of these materials in the mixtures equal to 25%, 50% and 75%. Tests on each individual material were also carried out and their results were used as references for comparisons.

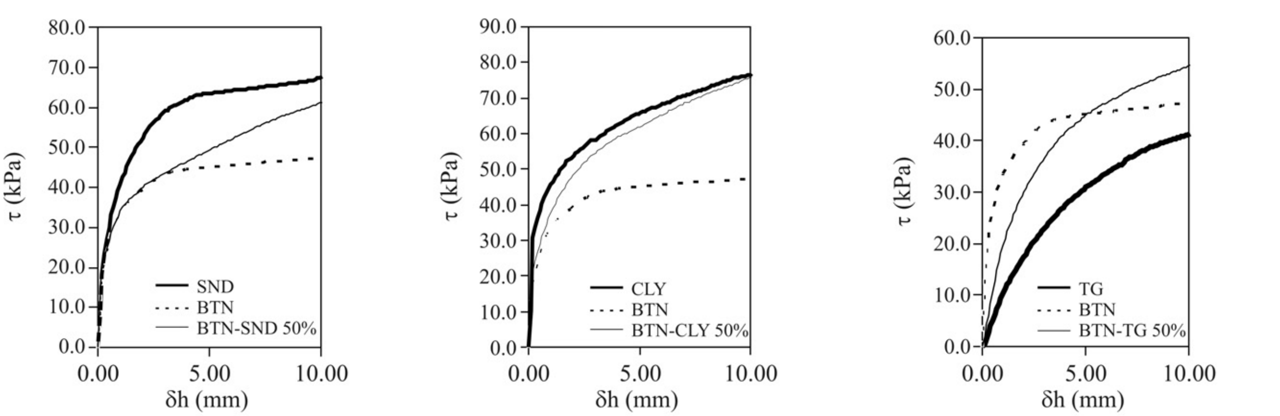
3.1.1. Direct shear tests

Figures 6(a) to (c) shows typical shear stress – shear displacement curves obtained in conventional direct shear tests (100 mm x 100 mm specimens) carried out on "dry" (natural moisture content) bentonite mixtures, containing 50% of the alternative material in mass, under a normal stress of 100 kPa, as well as results of tests on each individual component of the mixture. Table 5 shows the initial conditions of the specimens in terms of moisture contents and void ratios. The mixture specimens were prepared under the loosest stated possible by gently placing the mixture in the testing cell (no compaction). The results in Fig. 6 show the beneficial aspects brought by the presence of the alternative material to the increase of the shear strength of the mixture. The presence of these materials reduced the mixture void ratio, increasing the shear strength of the mixture. This increase is more clearly visualised at later stages of the tests on the BTN-SND and BTN-CLY mixtures (Figs. 6a and 6b). Regarding the BTN-TG mixture, gains of shear strength with respect to test on the bentonite alone only occurred after large shear displacements (above 5 mm, Fig. 6c). This was in part due to the compressibility and to the greater values of initial void ratios of the mixture with tire grains.

Figure 7 summarises the results of friction angles of the dry bentonite mixtures obtained in the direct shear tests. In this figure, R_ϕ is the ratio between the tangent of the mixture friction angle and the tangent of the friction angle of the bentonite alone. It can be noted that R_ϕ tends to increase with the increase of the percentage of the alternative material in the mixture, with greater gains in friction angle for the BTN-SND and BTN-CLY mixtures. The presence of a coarser material mixed with bentonite will provide greater strength along the shear plane. This can be observed in Fig. 8, which shows views (50x enlargement) of shear zones at the end of tests on hydrated BTN-TG mixtures for percentages of tire grains of 25%, 50% and 75%. It is interesting to note the reduction on the value of R_ϕ for the test on the tire grains alone ($R_\phi = 0.7$) in Fig. 7. This was due to the large value of void ratio ($e = 4.6$) of the tire grains specimen, as shown in Table 5.

Very low values of cohesion intercept were obtained in direct shear tests on dry bentonite mixtures. These intercepts were negligible for BTN-SND and BTN-TG mixtures. For BTN-CLY mixtures it varied between 0 and 6.1 kPa, depending on the percentage of clay in the mixture.

Figure 9 presents values of mixture friction angle and R_ϕ obtained in conventional direct shear tests on hydrated (after 4 days under submersion) specimens. In general,



(a)Bentonite-sand mixture (BTN-SND 50%) b) Bentonite-clay mixture (BTN-CLY 50%) c) Bentonite-tire grains mixture (BTN-TG 50%)

Figure 6 - Typical shear stress-shear displacement curves obtained in tests on bentonite mixtures containing 50% (in mass) of bentonite.

Table 5 - Moisture content and void ratio of the mixtures tested.

Material	% of BTN (%)	$w_i^{(1)}$ (%)	w_{4d} (%)	e_o	e_{4d}
BTN	100	12	139	3.3	7.5
CLY	0	1	57	1.2	1.2
SND	0	0	22	0.9	0.9
TG	0	1	40	4.6	4.6
BTN-CLY 25%$^{(2)}$	75	10	123	3.1	7.3
BTN-CLY 50%	50	8	123	2.8	6.5
BTN-CLY 75%	25	8	103	2.6	5.6
BTN-SND 25%	75	11	117	2.8	6.3
BTN-SND 50%	50	10	112	2.5	5.6
BTN-SND 75%	25	7	107	1.9	3.5
BTN-TG 25%	75	10	123	3.2	7.3
BTN-TG 50%	50	9	111	3.0	7.3
BTN-TG 75%	25	6	79	2.9	5.1

Notes: (1) w_i = natural moisture content, w_{4d} = moisture content after 4 days of inundation, e_o = initial void ratio, e_{4d} = void ratio after 4 days of inundation; (2) Number on the right indicates the percentage of alternative material, in mass, mixed to the bentonite.

hydration caused a drastic reduction on mixture friction angles. The low friction angle obtained in the test with the bentonite alone is consistent with values reported in the literature (Fox *et al.* 1998, Thiel *et al.* 2001, Fox & Stark 2004, Viana & Palmeira 2009). A more significant increase on R_ϕ was observed for the mixture BTN-TG with a percentage of tire grains greater than 50%. In spite of the reduction of the friction angle caused by hydration, the addition of alternative material led to greater shear strength of the mixture in comparison to that of the bentonite alone.

The variation of the cohesion intercept with the percentage of alternative material in the mixture obtained in the direct shear tests on hydrated specimens is depicted in Fig. 10. It can be noted that the cohesion intercept decreases from the value (~12 kPa) obtained for the bentonite alone with the increase of mass of alternative material. For values up to 75% of alternative material in the mixture, the cohe-

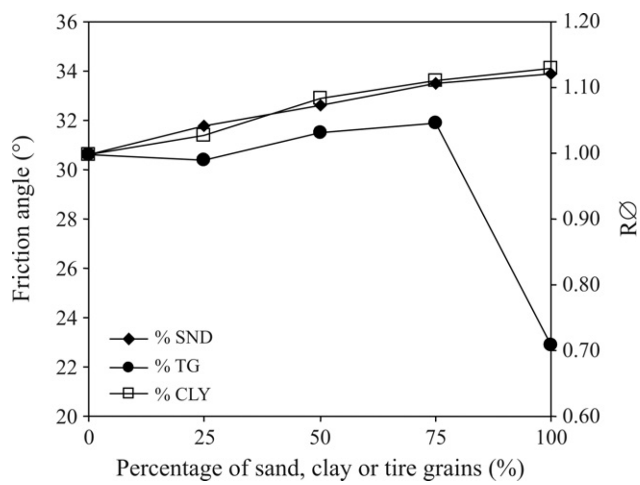
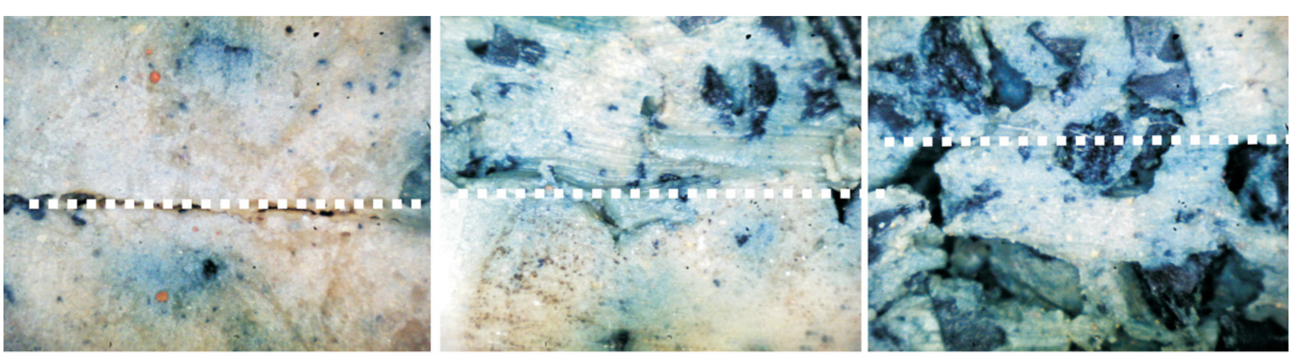


Figure 7 - Bentonite mixture friction angles for different percentages of alternative materials.



(a) (b) (c)

Figure 8 - Shear zones in specimens of BTN-TG mixtures (50x enlargement) at the end of tests with different values of tire grains content, (a) 25%, (b) 50% and (c) 75% of TG.

sion intercept varied between 7 kPa and 10 kPa (between 17% and 40% less than the value for the bentonite alone), depending on the material considered and its percentage in the mixture.

3.1.2. Consolidation, hydraulic conductivity and permittivity tests

The results obtained in consolidation tests on the bentonite mixtures are shown in Figs. 11(a) to (c) in terms of specimen vertical strain (equal to $\Delta e/(1 + e_o)$, where Δe is the void ratio variation and e_o is the initial void ratio) *vs.* vertical effective stress. For clarity sake the unloading stages of the tests are not presented in those figures. Greater expansions (negative values of $\Delta e/(1 + e_o)$) due to specimen inundation under the low initial vertical stress of 5 kPa were observed for the BTN-CLY mixtures (Fig. 11b). In spite of different initial values of vertical strain due to different expansion levels, the patterns of variation of e *vs.* σ of the mixtures are similar. The results obtained for the BTN-CLY specimens were little affected by the percentage of clay in the mixture, in contrast to what was observed for the other mixtures.

Table 6 presents results of hydraulic conductivity tests on bentonite mixture specimens for normal stresses

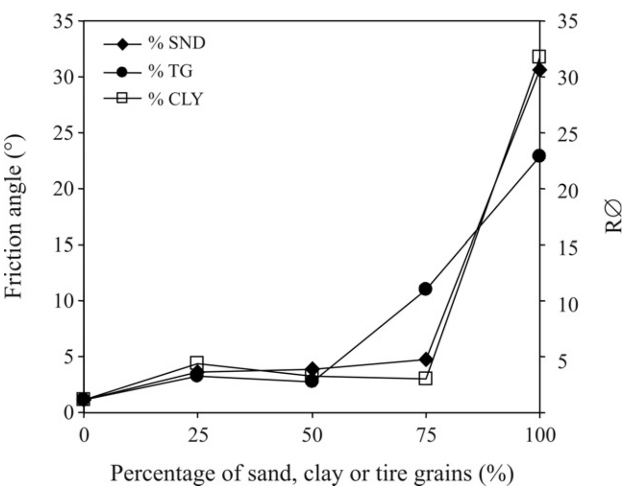


Figure 9 - Friction angles of bentonite mixtures after hydration.

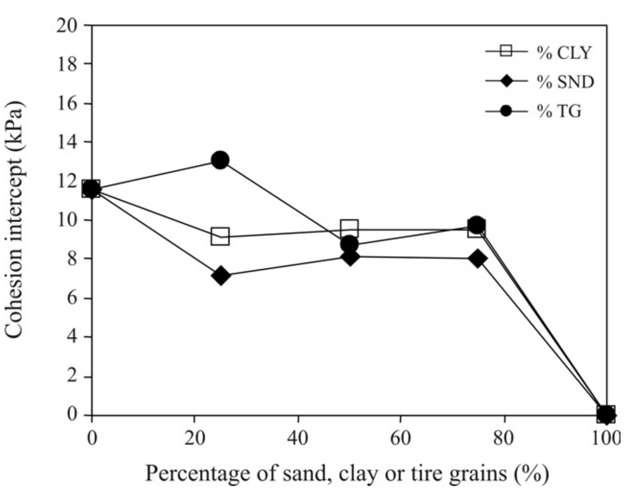


Figure 10 - Cohesion intercept obtained in direct shear tests on hydrated specimens.

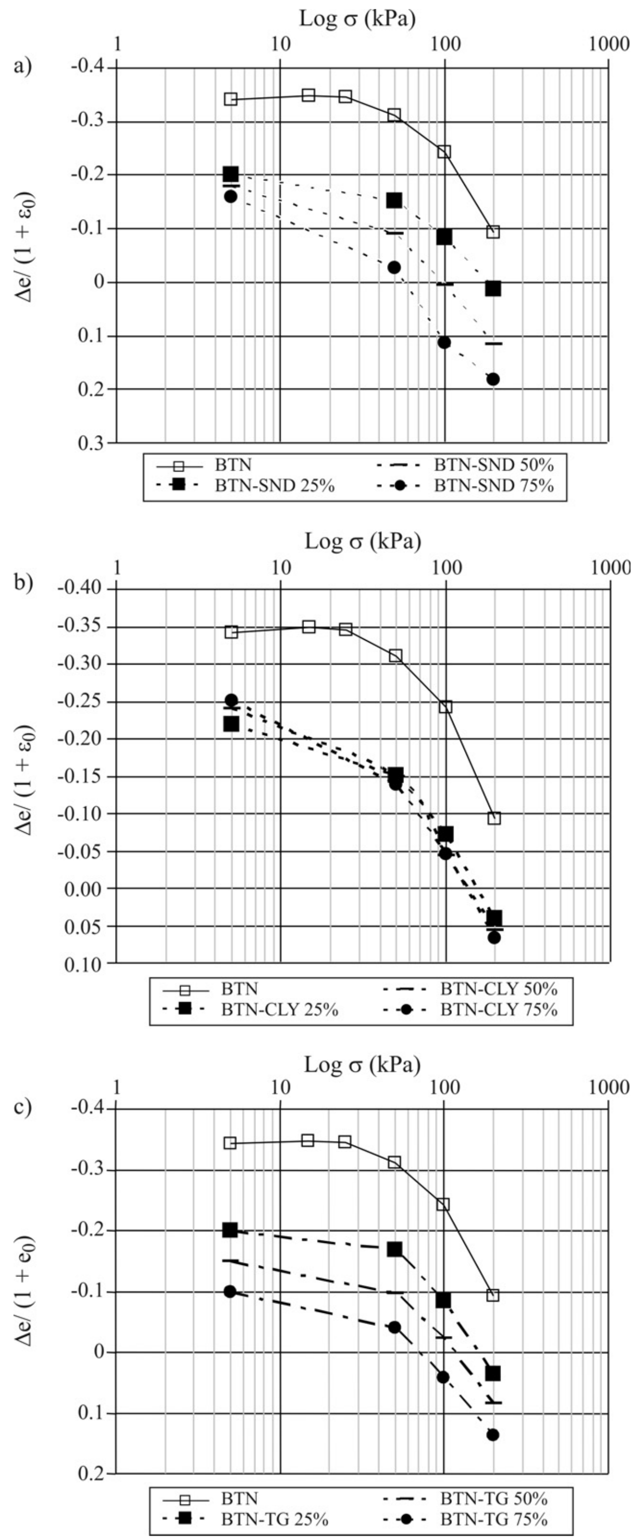


Figure 11 - Results of consolidation tests.

Table 6 - Hydraulic conductivity (k_N, cm/s) *vs.* normal stress (σ_N, kPa).

σ_N (kPa)	BTN (k_N x 10^{-9})	BTN-SND (k_N x 10^{-8})			BTN-CLY (k_N x 10^{-8})			BTN-TG (k_N x 10^{-8})		
		25%	50%	75%	25%	50%	75%	25%	50%	75%
50	3.3	2.3	2.3	2.4	5.2	4.6	5.2	3.4	4.0	4.9
100	3.0	1.4	2.3	1.1	2.0	1.0	2.1	2.0	1.6	4.2
200	2.0	1.4	2.3	1.1	2.0	1.0	2.1	1.6	1.6	2.1

varying from 50 kPa to 200 kPa. It can be noted that the hydraulic conductivity (k_N) of the bentonite alone was less sensitive to the normal stress than those of the mixtures. The values of k_N for the mixtures were 3.3 to 15.8 times greater than that of the bentonite alone, depending on the mixture and normal stress considered.

The hydraulic conductivity alone is not sufficient to assure a good performance of a material as a barrier, as its thickness plays also a fundamental role in the process. In this context, the permittivity (ratio between a medium hydraulic conductivity and its thickness, ψ) of the material provides a better measurement of the difficulty that a fluid will face to cross it. Figures 12 and 13 show the variations of permittivity and of permittivity ratio (R_ψ, ratio between mixture permittivity and bentonite permittivity) with normal stress, respectively, obtained from consolidation tests. A rather large scatter of test results can be observed and this is a consequence of the natural scatter of results of hydraulic conductivity in permeability tests, associated with the variability of the initial thickness of the mixtures under very loose states, depending on the type and content of the alternative material used. Figure 12 shows that the permittivity of the bentonite alone is less sensitive to the normal stress (ψ varying between 1.1 x 10^{-10} s^{-1} and 2.6 x 10^{-10} s^{-1}). For the bentonite mixtures, ψ varied between 7.4 x 10^{-9} s^{-1}, for the BTN-SND 75% mixture under 5 kPa normal stress (Fig. 12a) and to 6 x 10^{-10} s^{-1}, for BTN-CLY 50% mixture under 200 kPa normal stress (Fig. 12b). The ratio (R_ψ) between permittivity values of the mixture and of the bentonite alone varied between 5 and 29 (Figs. 13a to c), depending on the mixture and stress level considered. For a normal stress of 200 kPa the mixture permittivity was 5 to 12 times greater than that of the bentonite alone, depending on the alternative material considered, with lower values of ψ for mixtures of bentonite with clay. Despite the greater permittivity values of the mixtures, the results obtained show that the use of bentonite mixtures may be interesting in less critical barrier problems, particularly under stress levels greater than 100 kPa.

As permittivity is a function of the layer thickness, for larger thicknesses than the ones tested in the present study significantly lower values of permittivity could be obtained for the mixtures. Thus, thicker layers of bentonite-alternative material mixtures could function as a barrier as well as traditional (even thicker) compacted clay layers. In this

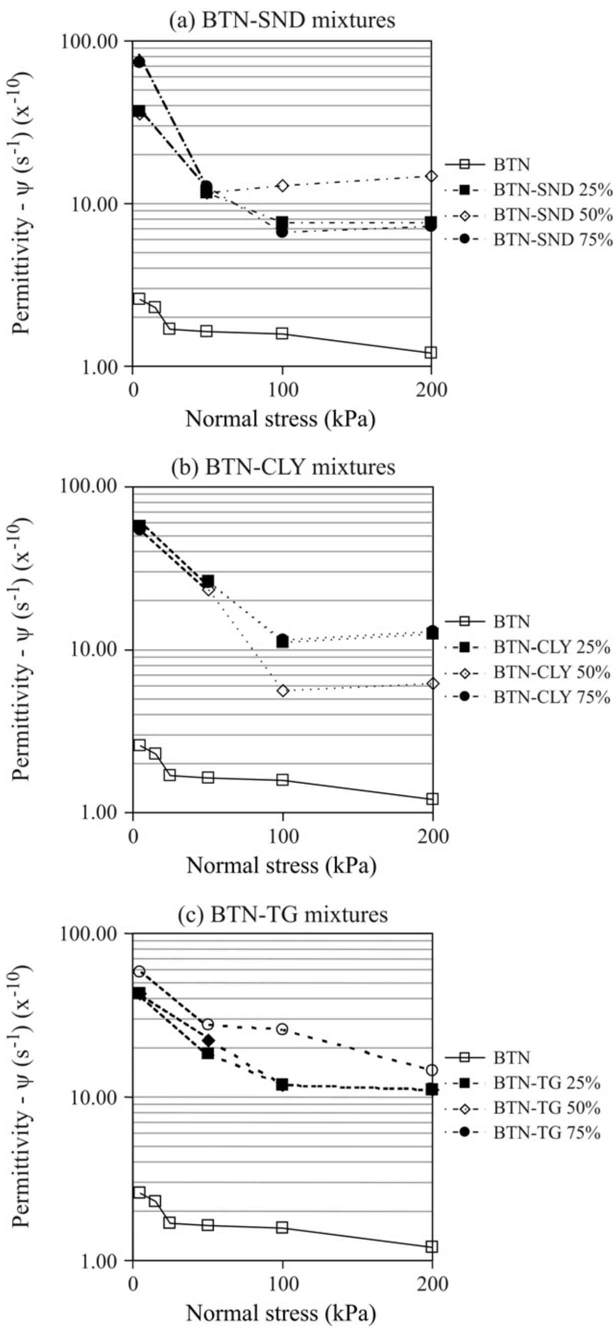


Figure 12 - Permittivity of mixtures *vs.* normal stress.

sense, thicker bentonite-tire grains mixtures would consume a greater number of tires, which would be beneficial to the environment regarding a better use for this type of waste. However, obviously the cost of this alternative solution would have to be compared to those of other traditional solutions (compacted clay liner, GCL) to check its economical feasibility as a barrier.

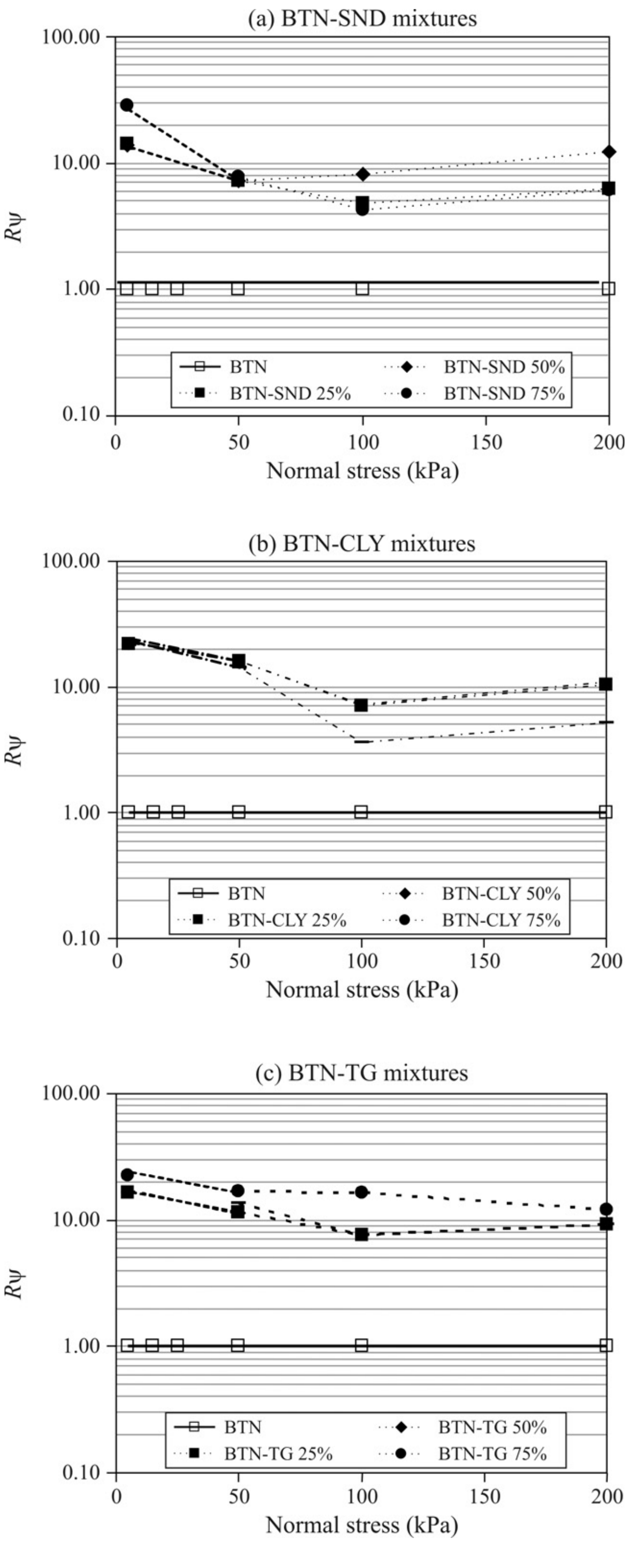


Figure 13 - Permittivity ratio *vs.* normal stress.

3.1.3. Expansibility tests

Figures 14(a) to (c) present the final relative expansion of the mixtures after 4 days under submersion in distilled water *vs.* confining normal stress (≤ 5 kPa). In these figures relative expansion is defined as the ratio between the specimen thickness increase and its initial thickness (prior to inundation). As expected, the expansibility of the mixture decreases with the increase of the amount of alter-

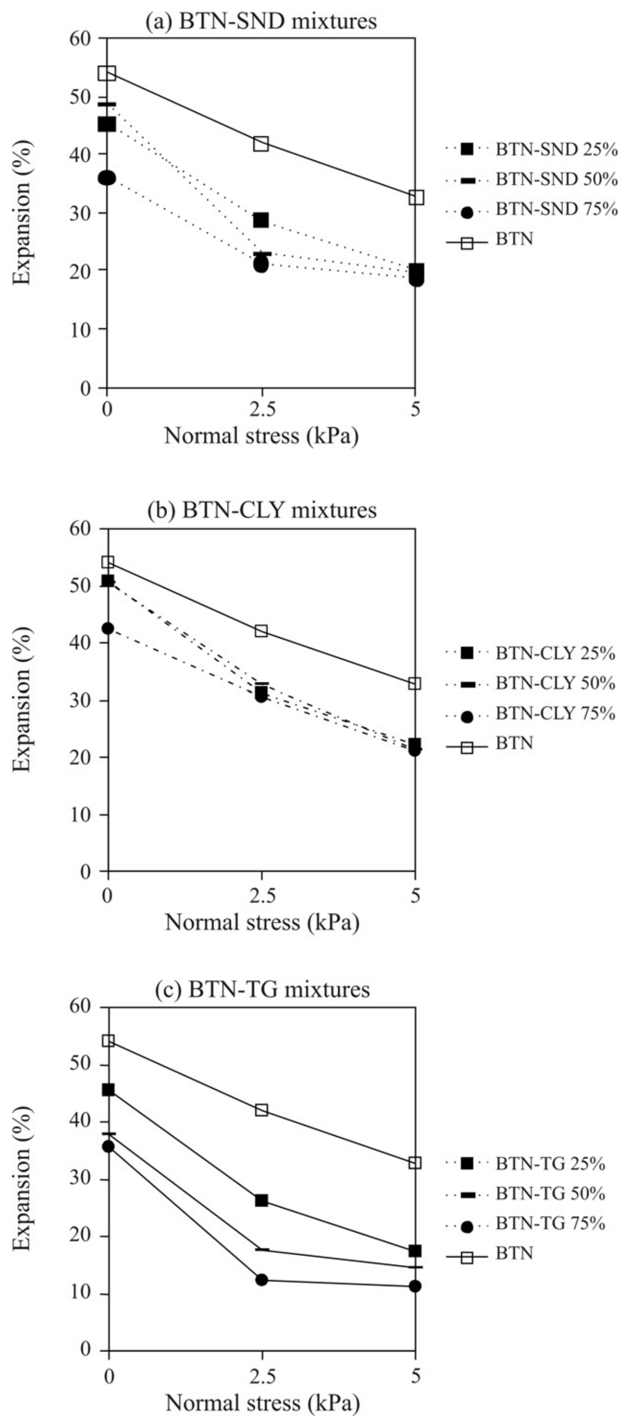


Figure 14 - Mixture expansion *vs.* normal stress.

native material in the mixture and with the increase of confining stress. The BTN-TG mixtures were the ones that presented the smallest expansions, which may be associated with the smaller water retention capacity and large initial void ratios of these mixtures.

Figure 15 shows the value of the ratio (R_e) between the final expansion of the mixture and the final expansion of the bentonite alone for each mixture tested. As expected, R_e decreased with the confining stress and, for a given alternative material, with the percentage of that material in the mixture. A more significant reduction on the value of R_e with the percentage of alternative material in the mixture was observed for the BTN-TG mixtures. This is in part a consequence of the smaller dry specific unit weight of this mixture.

3.2. Performance of GCLs with alternative core materials

3.2.1. Tests on alternative GCLs

Based on the results of the tests carried out on the bentonite mixtures presented in the previous section, a 50% percentage in mass of alternative material was chosen for the production of the alternative GCLs. This percentage is a compromise between the use of a great percentage of the alternative material in the mixture and less losses of relevant geotechnical and hydraulic parameters for barrier systems. Three alternative GCLs (GCL-SND 50%, GCL-CLY 50% and GCL-TG 50%) and the conventional GCL A and B were subjected to free expansion tests and to ramp tests (0.6 m x 1.0 m size specimens).

3.2.1.1. Free expansion tests

Figure 16 presents the results obtained in the free expansion tests performed. This figure shows that the GCLs with cores resulting from the mixtures of bentonite and alternative materials (50% in mass) presented less expansion than that of the conventional commercial products GCL A and GCL B. This was a consequence of the non expansive

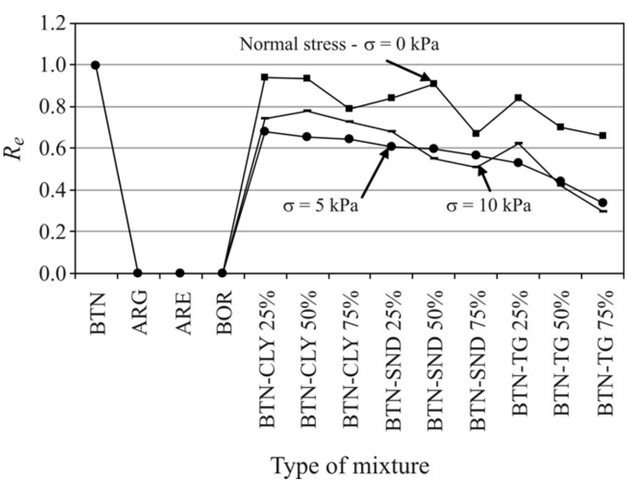


Figure 15 - Value of the ratio R_e for different types of mixtures.

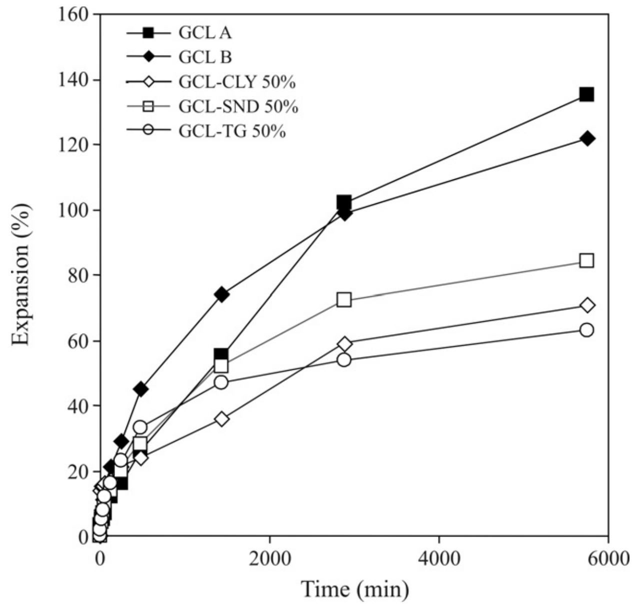


Figure 16 - GCL free expansion *vs.* time.

nature of the alternative materials employed. GCL BTN-TG 50% was the one showing less expansion, of the order of half the expansion observed for the conventional products.

3.2.1.2. Ramp tests

Figure 17 shows the relationship between shear stress and normal stress on the GCL under dry conditions and after hydration for 24 h ("H") obtained at the end of the ramp tests. It is important to point out that only for GCL B tested after hydration this relationship represents a failure envelope, because of internal shear failure having been reached in this case. For the other products tested internal failure was not obtained in the ramp tests because of the contribution from the stitches' strength. In these cases, the maximum inclination imposed to the ramp was of the order of 50°. As a result, for a given normal stress, similar mobilized shear stresses were obtained for GCL A (dry or hydrated), GCL B (dry) and the alternative GCLs. This shows that for the conditions of the test the presence of the alternative materials did not influence the GCL internal strength, in part because in these cases the internal shear strength was controlled by the strength of the stitches. For the same reason, hydration had little effect on the behaviour of the alternative GCLs in comparison with the reference commercial GCLs used in this experimental programme.

The stitch filaments can have a marked effect on the internal shear strength and on the shear stiffness of the GCL. For the ramp tests carried out, internal failure occurred only for hydrated GCL B. In this case, it was observed that the expansion of the bentonite of GCL B caused failure of some stitches, which yielded to lower internal shear strength. This reduction on the internal shear strength of the GCL may compromise the stability of the lining system in a slope, if this aspect is not properly considered in the design. Figures 18(a) and (b) show enlarged views of stitches in GCLs A and B, respectively. Figure 18(b) shows a stitch filament that failed during hydration of GCL B. This failure mechanism can be minimized or avoided if hydration takes place under high stress levels, because under such conditions the expansion of the bentonite will be inhibited to some extent. Therefore, the critical conditions will take place under low stress levels and in this case the ramp test on hydrated GCLs can provide important information on the internal strength of the GCL under normal stresses closer to those expected in the field.

Figure 19 presents maximum values of mobilized tensile load on the lower (carrier) geotextile of the GCL *vs.* normal stress at the end of the ramp tests. In all cases, except for hydrated GCL B, the mobilized tensile force increased with normal stress with little difference among results of tests on different GCLs. The results obtained for the GCL with BTN-TG 50% mixture were close to those of GCLA. The rather constant value of mobilized tensile load with normal stress for the hydrated GCL B was due to internal failure having occurred prior to significant mobilization of force in the carrier geotextile of this product.

The variation of shear displacement (difference between displacements of the cover and carrier geotextiles of the GCL) with normal stress at the end of the ramp tests is depicted in Fig. 20 for each GCL tested. It can be noted that hydration slightly increased the relative displacement between cover and carrier geotextiles of GCL A. Under dry conditions the variation of these displacements with normal stress was similar for GCLs A and B for normal stresses greater than 2.5 kPa. However, hydration caused catastrophic internal failure of GCL B, with relative displacements in excess of 100 mm. With the exception of GCL B

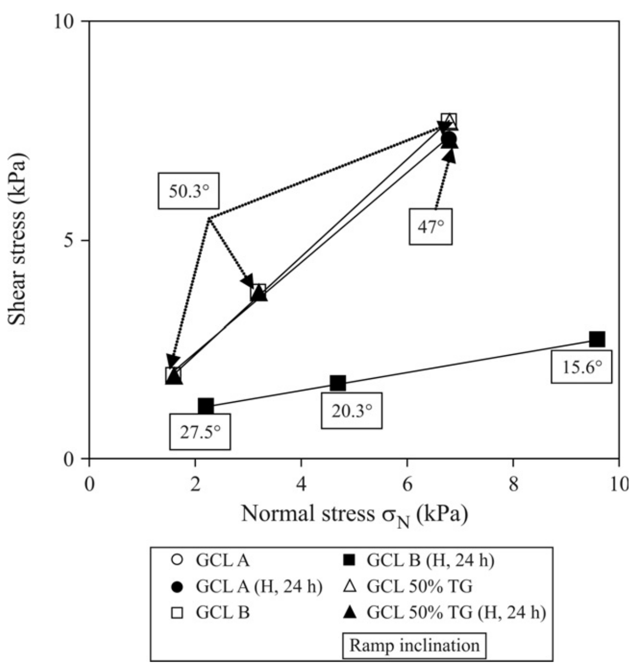


Figure 17 - Mobilised shear stress *vs.* normal stress on the GCL for dry and hydrated specimens.

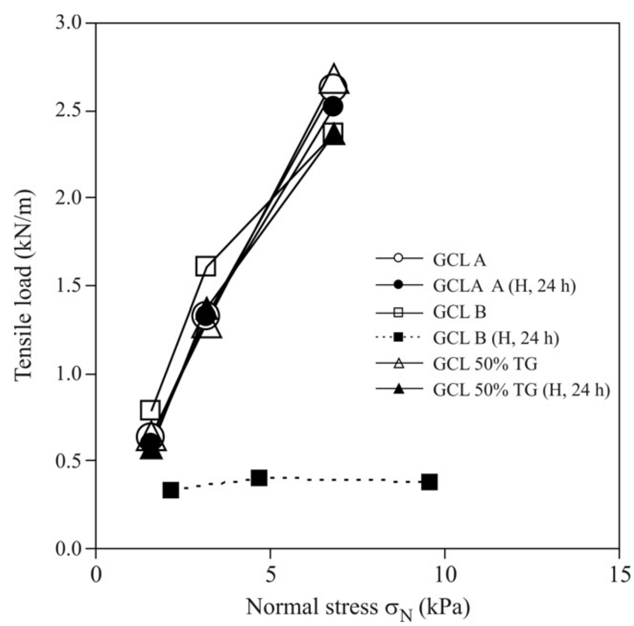


Figure 19 - Maximum mobilised tensile force *vs.* normal stress.

Figure 18 - Stitches of GSLs A and B after hydration: (a) GCL A stitch after hydration; (b) Failed stitch in GCL B after hydration.

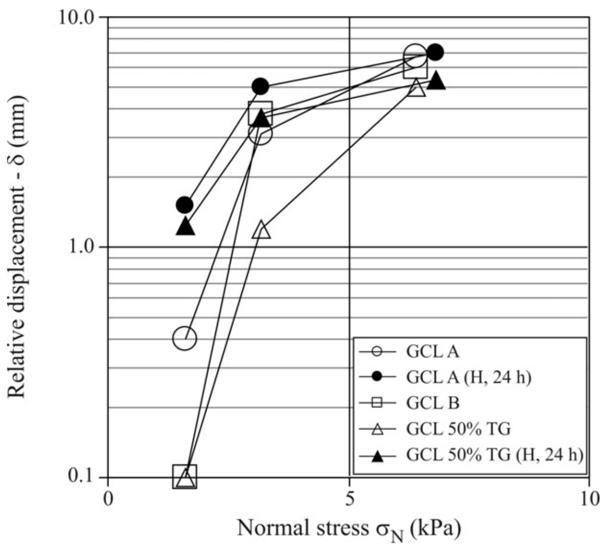


Figure 20 - Relative displacement *vs.* normal stress in ramp tests.

(H, 24 h), the maximum relative displacement for the range of normal stresses used was approximately 7 mm. Similar results of maximum relative displacements were obtained for the alternative GCLs independent on the material (tire grains, sand or clay) mixed to the bentonite, with maximum values below 5.5 mm for dry and hydrated conditions. Great distortions of the GCL will increase the deformation of the lining system as a whole, which may favour the formation of cracks in compacted soil layers overlying the GCL and increase the tensile load in the geomembrane (if present) on the GCL at the anchorage region.

4. Conclusions

This paper presented results of a laboratory study on the use of alternative materials mixed to bentonite in GCLs. The main conclusions obtained are summarised below.

The presence of the alternative materials (sand, clay or tire grains) increased the shear strength of the mixture. For the mixture with tire grains the shear strength increase was observed at the late stages of direct shear tests, mainly due to the compressible nature of the tire grains, which increased the deformability of the mixture. The friction angles of the mixtures were also greater than that of the bentonite alone under dry and hydrated conditions, although for the latter condition the values were still low. Under hydrated conditions, the cohesion intercept obtained for the mixtures were smaller than that of the bentonite alone, being between 17% and 40% smaller than the value obtained for the bentonite, depending on the mixture considered.

The compressibility of the mixtures was greater than that of the bentonite. This was due to the loose state of the specimens tested and compressibility of individual grains, like in the case of the tests with tire grains.

The addition of alternative materials to the bentonite reduced the expansibility and increased the permittivity of the mixture. Permittivity values of the mixtures were 5 to 29 times greater than that of the bentonite alone, depending on the mixture and stress level considered. In general, the greatest increases on permittivity were observed for the bentonite-tire grains mixtures. Even so, the permittivity of bentonite-tire grains mixtures for percentages (in mass) of tire grains up to 50%, and normal stresses above 100 kPa, were of the order of 10^{-9} s^{-1} (0.18 x 10^{-9} s^{-1} for the bentonite alone). The expansions of the hydrated alternative GCLs manufactured in the laboratory were also smaller than those of the two commercial conventional GCLs tested.

The internal shear strength, as measured in ramp tests, was controlled by the strength of the stitches of the GCLs. Only commercial GCL B failed in this type of test. The results obtained for the alternative GCL made with core consisting of a mixture of bentonite and tire grains (50% in mass) were similar to those presented by commercial GCL A, under dry and hydrated conditions, in terms of mobilised shear stresses and mobilised tensile loads in the carrier geotextile.

The results obtained showed that the mixture of the alternative materials used in this research programme with bentonite can increase the internal shear strength of an alternative low cost GCL made with those mixtures, but degraded some other important parameters for barrier applications, such as GCL expansibility and permittivity. Increases in the cost of manufacturing the alternative GCLs should also be taken into account before assuming that the use of less bentonite alone will result in a cheaper GCL, particularly for the case o mixtures involving bentonite and sand. Some practical aspects also need investigation, such as the possibility of segregation of the alternative material used in the GCL during transportation, handling and installation in the field. This segregation can be minimised or avoided depending on the manufacturing process used to produce the GCL, but this can also yield to additional costs to produce the alternative GCL product.

Despite presenting greater permittivity and lower expansibility than conventional GCLs, alternative products with mixtures of bentonite and tire grains may be considered for less critical barrier systems and as bedding/protective layers underneath geomembranes, particularly under confining stresses above 100 kPa, which are easily reached in waste disposal areas. In addition, this type of use of tire grains provides a more environmentally friendly use of wasted tires. However, despite some encouraging results obtained in this work, further research is required for a better understanding on the behaviour of alternative GCL products.

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