Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 49 No. 4 December 2018 ISSN 0046-5828

Performance of Nonwoven Geotextiles as Separators for Pavement Applications

Maria P.S. Susunaga[1], Ennio M. Palmeira[2,*] & Gregório L.S. Araújo[3]
[1]*University of Ibagué, Ibagué, Colombia*
[2, 3]*University of Brasilia, Department of Civil and Environmental Engineering, Brasilia, Brazil*
[1]*E-mail*: maria.salazar@unibague.edu.co
[2]*E-mail*: palmeira@unb.br
[3]*E-mail*: gregorio@unb.br

ABSTRACT: Geosynthetics can be used in several applications in geotechnical and geoenvironmental engineering, being geotextiles the most traditional and versatile type of geosynthetic. One of the applications of geotextiles is in separation between good and poor quality soils. This situation may occur in geotechnical structures such as roads and railways constructed on soft saturated subgrades. The presence of a geotextile separator avoids or minimize the contamination of the good quality base or ballast material with fines from the subgrade, increasing the life of the road and reducing maintenance costs. Despite its importance, very few studies on the behaviour of geotextiles in separation can be found in the literature compared to other applications of these materials. This paper investigates the performance of nonwoven geotextiles in separation. Laboratory tests on geotextiles with masses per unit area ranging from 200 g/m^2 to 600 g/m^2 were executed using an apparatus capable of applying repetitive loading to simulate traffic conditions. Measurements of surface displacements and pore pressures in the subgrade soil and the evaluation of geotextile mechanical damages at the end of the tests were carried out. The results obtained showed that the three geotextiles tested were effective separators, avoiding contamination of the base soil and accelerating the dissipation of excess pore pressures in the subgrade soil. However, significant mechanical damage was observed in the lighter geotextile used.

1. INTRODUCTION

Geotextiles are very versatile geosynthetics and can be used in several applications in geotechnical and geoenvironmental engineering. They can be used for filtration, drainage, reinforcement, separation and for the protection of other geosynthetics against mechanical damages. A very important, but commonly underestimated, application of geotextiles is as separators. In this case the primary function of the geotextile is to avoid or minimize the contamination of a good quality fill material with fine particles from a neighbouring soil, as schematically shown in Figure 1. This is particularly relevant in road pavements and railways, where the separation provided by the geotextile can significantly increase the life of the structure and reduce maintenance costs.

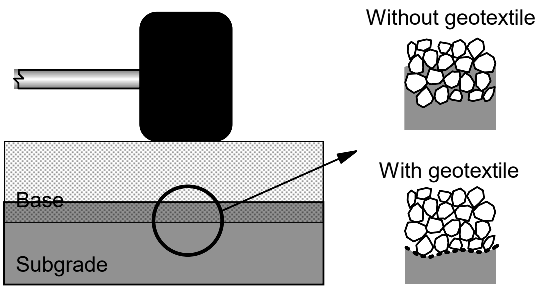


Figure 1 Geotextile separation mechanism

Several researchers have observed the benefits in using geotextile separators in railways, paved and unpaved roads (Palmeira 1981, Friedli and Anderson 1982, Schaeffner and Khay 1982, Christopher and Holtz 1985, Brorsson and Eriksson 1986, Tsai *et al.* 1993, Nishida and Nishigata 1994, Holtz 1996, Collins and Holtz 2005, for instance). Intermixture of the base-subgrade material takes place due pumping of fines from the subgrade caused by excess pore pressures and penetration of base soil particles in the weak foundation material caused by high vertical stresses at the interface between these materials. Geotextiles can dissipate excess pore pressures and retain soil particles from the subgrade, minimizing base soil impregnation and its detrimental effects on road and railway performance.

The resistance against mechanical damages and degradation mechanisms is of utmost importance in applications of geotextiles as separators. Hoare (1982) stated that mechanical damages at the points of contact between base soil particles and the geotextile may be the major cause of failure of geotextile separators in reducing base soil contamination. Palmeira *et al.* (2012) also discussed the influence of mechanical damages at the points of contact with coarse fill materials on the performance of geotextile filters. Holtz (1996) observed different levels of mechanical damages in field experiments with different types of geotextiles as separators. However, for the site conditions and materials employed, the mechanical damages did not affect pavement performance. Fernandes *et al.* (2008) described mechanical damages consisting of holes and cuts in a light weight geotextile used as separator in a heavily trafficked railway. Christopher and Holtz (1985), Koerner (1998), Wilmers (2007) and Vaitkus *et al.* (2006) highlight important aspects to be considered for the use of geotextiles as separators. AREA (1985) and Holtz *et al.* (1997) present survivability requirements for a satisfactory performance of geotextile in separation applications.

Due to the complexity of the problem, the specification of geotextiles for separation purposes is still highly empirically based. The following aspects must be considered in design: retention criterion, tensile strength, burst strength, impact/tear strength and resistance to mechanical damages and degradation. A geotextile must retain satisfactorily the particles of the subgrade soil in order to fulfill the separation function, i.e., it must allow free drainage but avoiding the passage of a significant amount of subgrade soil particles. According with Holtz *et al.* (1997), under cyclic or pulsating loads the retention criterion to be met by the geotextile should be:

$$FOS/D_{85} < 0.5 \quad (1)$$

Where *FOS* is the geotextile filtration opening size (assumed in this paper to be equal to O_{95}, which is the pore diameter for which 95% of the remaining pores are smaller than that value) and D_{85} is the soil particle diameter for which 85% of the remaining soil particles have smaller diameters than that value.

The geotextile separator must not fail or deform significantly under operational conditions. Currently, the tensile force mobilized in the geotextile separator is compared to its grab tensile strength in routine design procedures. The mobilized geotextile tensile force can be estimated by (Koerner 1998):

$$T = p' \, d_v^2 \, f(\varepsilon) \quad (2)$$

Where T is the mobilized tensile force in the geotextile, p' is the vertical stress on the geotextile, d_v is the characteristic value of the diameter of the voids between base soil particles and $f(\varepsilon)$ is a function of the level of intrusion of the geotextile in the base soil voids.

A burst failure mechanism has also to be considered, which depends on the dimensions of the voids of the base soil at the base soil-subgrade interface. According to Giroud (1984), the burst pressure to be resisted by the separator can be estimated by:

$$p_b = \frac{p' d_v}{d_s} \tag{3}$$

Where p_b is the geotextile burst strength and d_s is the diameter of the specimen in burst strength tests (equal to 30 mm as per ASTM D3786).

Mechanically aggressive base soil particles may cause puncture of the geotextile. According to Koerner (1998), the puncture force acting on the geotextile can be estimated by:

$$F_p = p' D_{50}^2 S_1 S_2 S_3 \tag{4}$$

Where F_p is the puncture force, D_{50} is the average base soil particle diameter, S_1 is a penetration factor (= z/d, where z is the penetrating depth of the base soil particle in the subgrade and d is the diameter of the penetrating particle), S_2 is a scale factor to account for geometrical equivalence between laboratory and field conditions ($S_2 = d_{test}/D_{50}$, where d_{test} is the diameter of the puncturing element in the laboratory test) and S_3 is a shape factor to account for the difference between the puncturing element in the laboratory and the soil particles in the field. Koerner (1998) presents values of S_3 as a function of the soil type and particle shape.

The resistance of the geotextile against tear and impact resistance must also be verified. The latter mechanism may occur when coarse base soil particles are dropped on the geotextile layer during construction. However, this type of mechanism was not simulated in the experiments described in the present work. One can obtain information on geotextile specification for impact mechanism in Koerner (1998). It should be pointed out that in design appropriate reduction and safety factors must be applied to available and required strengths.

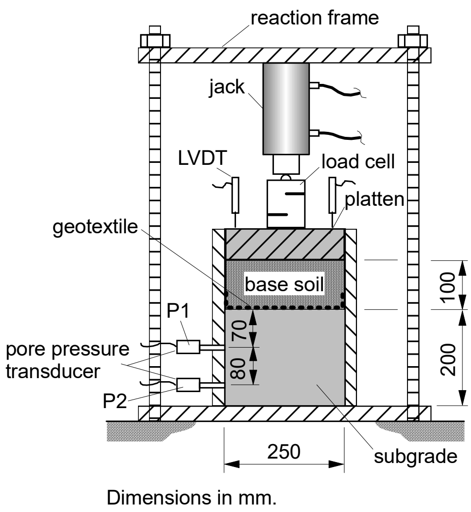
Due to the relevance of the theme, this paper investigates the behaviour of nonwoven geotextiles as separators between gravel material and a fine-grained subgrade soil under cyclic loading, aiming at improving the knowledge of this type of geotextile function. In the following sections the methodology employed and results obtained are presented and discussed.

2. EQUIPMENT AND MATERIALS

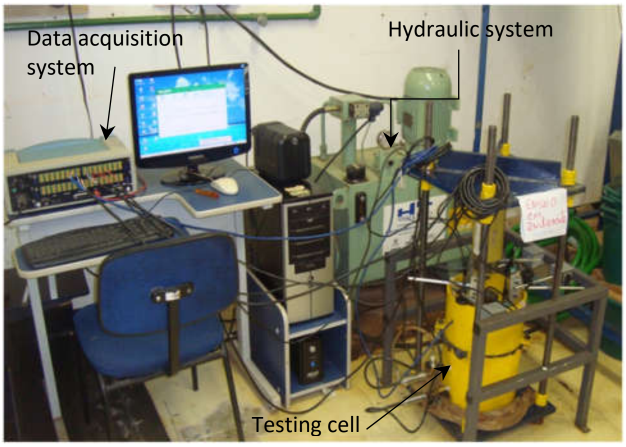
2.1 Equipment

The equipment used in the tests consisted of a rigid steel cell, loading platen, reaction frame and hydraulic and data acquisition systems. Figure 2(a) shows main characteristics of the equipment used in the tests and Figure 2(b) presents a view of the equipment during one of the tests performed. The testing cell has a diameter of 250 mm, with a total height of 370 mm. The subgrade soil is placed in the bottom half of the cell, whereas the base material (100 mm thick) is placed in the upper half of the cell. The geotextile separator is installed between these materials. The internal walls of the cell were lubricated with double layers of plastic film and oil to minimize friction. A rigid loading platen was employed to apply the vertical stress on the soils. A hydraulic cylinder connected to a hydraulic system provided the necessary load on the platen. The maximum vertical stress used was equal to 200 kPa and was applied at a frequency of 1 Hz. Similar testing devices were employed by Hoare (1982) and Nishida and Nishigata (1994).

The load applied was measured by a load cell and the platen displacements were measured by three displacement transducers installed at different point on the platen. The excess pore water pressure developed in the subgrade soil during testing was assessed by two pore pressure transducers located at 70 mm and 150 mm below the geotextile specimen (Fig. 2a). A data acquisition system and a microcomputer acquired and processed the data from the instrumentation.



(a) Characteristics of the equipment used.



(b) View of the equipment during one of the tests.

Figure 2 Equipment used in the tests

2.2 Soils

The base material tested consisted of a uniform gravel with soil particle diameters varying between 5 mm and 25 mm and average particle size diameter of 14 mm. The base soil layer was compacted in the test cell by tamping to reach a dry unit weight of 16.4 kN/m^3. The main base soil properties are summarised in Table 1.

A local fine grained soil was used as subgrade material and its properties are also presented in Table 1. It can be noted that a much finer characterization of the soil can be obtained if dispersing agent is used, which is a typical behaviour for this type of soil. The subgrade soil was prepared under two different conditions. In the first series of tests (Medium Subgrade – MS tests) the subgrade material was compacted with a moisture content of 25% (2% above the optimum value) using static compaction (in 3 layers). The soil was then submerged for a period of 5 days before testing to increase its saturation degree. A degree of saturation of 84% was reached after the submersion period. The California Bearing Ratio of the subgrade soil prepared under such condition was equal to 2%. In the second series of tests (Very Soft Subgrade – SS tests) a much softer subgrade material was employed. In this case the subgrade soil was initially saturated by boiling in deaired water and poured in the testing cell under saturated conditions, as suggested by Kuerbis and Vaid (1988). Then, consolidation under self-weight under submerged conditions was allowed for 7 days, before the loading stage of the test started.

Table 1 Properties of the soils tested

Property	Base Soil	Subgrade soil
D_{10} (mm)(1)	9.7	0.0031/0.0054(2)
D_{50} (mm)	14	0.0075/0.043
D_{85} (mm)	19	0.025/0.132
Coefficient of uniformity	1.6	3.1/11.3
Soil particle density (kN/m^3)	26.64	26.98
Dry unit weight (kN/m^3)	16.4	14.6(3)
Liquid limit (%)	NA	56
Plasticity limit (%)	NA	36
Optimum moisture content (%)	NA	23
Moisture content (%)(4)	0	35
California bearing ratio (%)	---	0 – 2(5)
Los Angeles abrasion test (%)	15.6	NA(6)
Particle shape index	0.6	NA

Notes: (1) D_n = soil particle diameter for which n % in mass is smaller than that diameter; (2) Numbers on the left and on the right are values obtained in grain size analysis tests with and without the use of dispersing agent, respectively; (3) In MS tests; (4) Moisture content in SS tests; (5) Range of variation, depending on the subgrade preparation procedure used; (6) NA = not applicable.

2.3 Geotextiles

Three nonwoven, needle-punched, geotextiles made of polyester were used in the tests. The mass per unit area of the geotextiles varied between 200 g/m^2 and 600 g/m^2. The main properties of the geotextiles tested are summarised in Table 2. The geotextile products tested cover a wide range of values of filtration and tensile strength properties.

Additional information on materials and testing methodology can be found in Susunaga (2015).

Table 2 Properties of the geotextiles tested

Property	GT1	GT2	GT3
Mass per unit area (g/m^2)	200	400	600
Thickness (mm)	2.9	3.8	5.9
Filtration opening size (mm)(1)	0.147/ 0.083(2)	0.130/ 0.076	0.101/ 0.073
Permeability coefficient (cm/s)	0.22	0.22	0.22
Permittivity (s^{-1})	0.76	0.57	0.37
Porosity (%)	93	92	91
Tensile strength (kN/m)(3)	10.6	13.0	24.3
Tensile stiffness at 5% strain (kN/m) (3)	17.2	22.2	47.9
Maximum tensile strain (%)(3)	64	73	67
Grab tensile strength (kN)(4)	0.8	1.8	2.4
Puncture strength (kN)(5)	2.6	5.2	8.0
Burst strength (MPa) (6)	2.2	4.5	6.0

Notes: (1) From Bubble Point Tests as per ASTM D6767 (Palmeira & Trejos-Galvis 2017 and Silva 2014); (2) Numbers separated by slashes are the values of O_{95} obtained in Bubble Point Tests under no confinement and under 200 kPa vertical stress, respectively (Palmeira & Trejos-Galvis 2017 and Silva 2014); (3) From wide strip tensile tests as per ASTM D4595; (4) ASTM D4632; (5) ASTM 6241; (6) ASTM D3786.

3. RESULTS OBTAINED

3.1 Settlements of the system

Figure 3 presents results of settlement of the loading plate versus number of load repetitions (N) for tests without and with geotextile separator for the medium subgrade soil (MS tests). A total settlement of the loading plate of 5.5 mm was obtained in the test without geotextile at the end of the test (N = 150000). In this test the rate of increase of plate settlement with number of load cycles was significantly greater up to N = 3000, but still increasing at a rather constant rate afterwards. On the other hand, the settlements obtained in the tests with geotextile separator reached their maximum values (less than 0.46 mm) at the early stages of the tests, remaining constant afterwards. This difference between results of tests with and without geotextile separator can be attributed to penetration of base soil particles in the subgrade soil. The geotextile separator prevented effectively this mechanism and for the range of displacements measured differences between results can be considered within the scatter expected in this type of test.

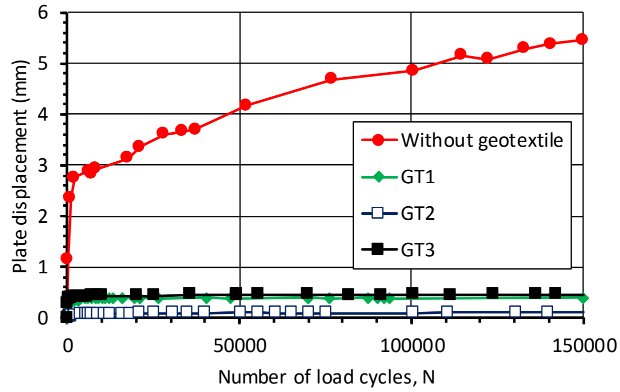


Figure 3 Plate settlement versus number of load cycles – MS tests

The results of loading plate settlements versus number of load repetitions in the case of the very soft subgrade (SS tests) are depicted in Figure 4. As expected, significantly greater vertical displacements of the plate were obtained in comparison with MS tests (Fig. 3), with a value of 52 mm having been reached at the end of the test (N = 15000) without geotextile separator. The settlements in the tests with geotextile separator in SS tests were also significantly greater than those obtained in MS tests. A maximum settlement of the order of 40 mm was reached at the end of the tests with geotextile, with some influence of the geotextile type for values of N up to 50000. Very little increase in plate settlement in tests with and without geotextile can be noted after 50000 load cycles. The results in Figure 4 show a reduction of approximately 25 % in the loading plate settlement for the tests with geotextile separator, which was also a consequence of less penetration of base soil particles in the soft subgrade.

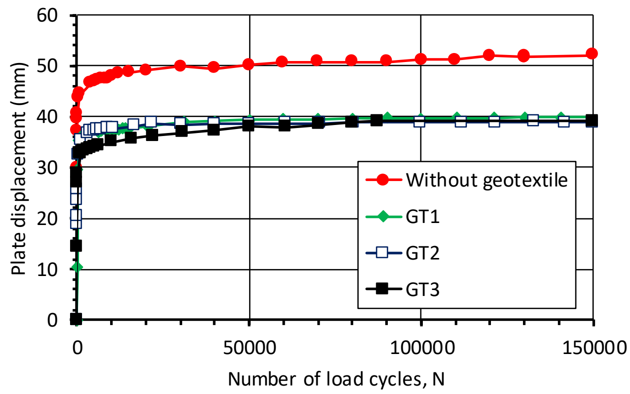


Figure 4 Plate settlement versus number of load cycles – SS tests

3.2 Excess pore pressures

Figure 5 shows the variation of excess pore pressure (Δu) as measured by the pore pressure transducer (P1) closest to the interface between base and subgrade soils in MS tests. A sharp increase in Δu can be noted at the early stages of the tests. A similar development of excess pore pressure was also observed by Bell *et al.* (1982), Hoare (1982) and Christopher and Schwarz (2010). The results show reductions in Δu with N at greater rates for tests with geotextile separator than for the reference test in the initial stages of the experiments, particularly in the tests with geotextiles GT1 and GT3. Negative values of Δu were obtained in the test with geotextile GT1, but within the range of accuracy of the measurements. However, the unloading stages of the test can cause suction in the subgrade soil, yielding to negative pore pressures, as observed in experimental and numerical studies on fine grained soils subjected to cyclic loadings under oedometric conditions performed by Elgohary (1973), Gu *et al.* (1995), Alobaidi and Hoare (1998a) and Müthing *et al.* (2016). In addition, it should be noted that saturation of the subgrade was not achieved in MS tests, which certainly influenced the pore pressure generation in this case. Another limitation to be raised is that the pore pressure transducers were installed at the cell wall. Although the pore stone was flushed with the internal cell wall, friction between subgrade soil and pore stone or even some level of clogging of the pore stone may have influenced the results obtained. Because of these limitations, the values of pore pressure measured should be preferably viewed in qualitative rather than quantitative terms.

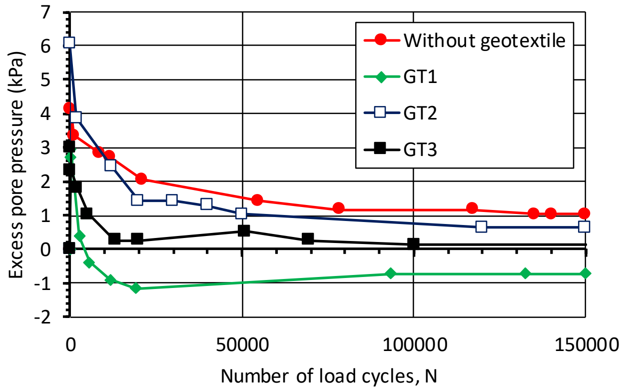


Figure 5 Excess pore pressure at piezometer P1 versus number of load cycles – MS tests

The values of excess pore pressure measured by the deeper pore pressure transducer (P2) in MS tests are shown in Figure 6. Again, greater rates of pore pressure reduction with N can be noted in tests with geotextile separators. The values of Δu remained quite constant in tests with geotextiles after N equal to 20000. Excess pore pressure values measured by P2 were greater than those measured by P1. This is a consequence of the greater distance of P2 from the top drainage boundary.

Figure 7 shows the variation of Δu with N in pore pressure transducer P1 in tests with the soft subgrade soil (SS tests). Significant pore pressure reductions can be noted up to N equal to 20000 in tests without and with geotextile, with negative values being observed in the tests with geotextiles (low in modulus for GT2 and GT3) since the early stages of the tests. Some considerations on these patterns of pore pressure variation can be made. Firstly, faster pore pressure reductions would be expected due to the proximity of transducer P1 to the drainage boundary. Bell *et al.* (1982), Hoare (1982) and Nishida and Nishigata (1994) observed similar fast dissipations of excess pore pressures close to the geotextile layer. Secondly, as can be noted in Figure 4, because of the large settlements of the base material in SS tests the distance between the pore pressure transducer and the base-subgrade soil interface decreased significantly already at the earlier stages of the test (N < 20000). It would be expected the reduction in this distance to be more influential in the case of geotextile GT1, due to its low tensile stiffness and strength, which would favour gravel particles of the base soil to penetrate deeper in the subgrade soil. Base soil particles penetrating deeper in the soft subgrade close to the pore pressure transducer can influence the value of excess pore pressure, as also observed by Hoare (1982). In addition, the penetration depth of an intruding base soil particle into the subgrade close to P1 can be more intense in one test than in another. It can be noted in Figures 4 and 7 that the reductions in Δu with N at greater rates for N up to 20000 are consistent with the more significant plate settlements at that stage of the tests. The influence of other aspects on pore pressure measurements, as mentioned earlier in this paper, cannot be ruled out either.

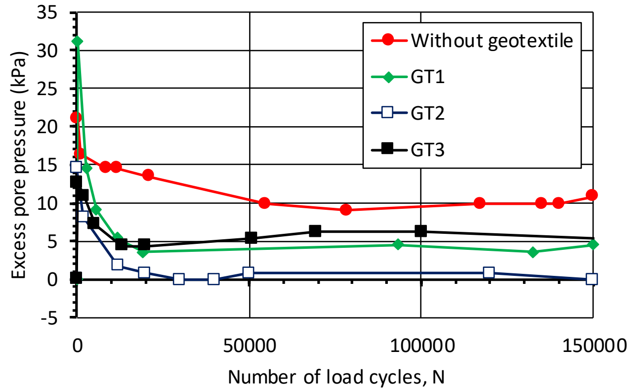


Figure 6 Excess pore pressure at piezometer P2 versus number of load cycles – MS tests

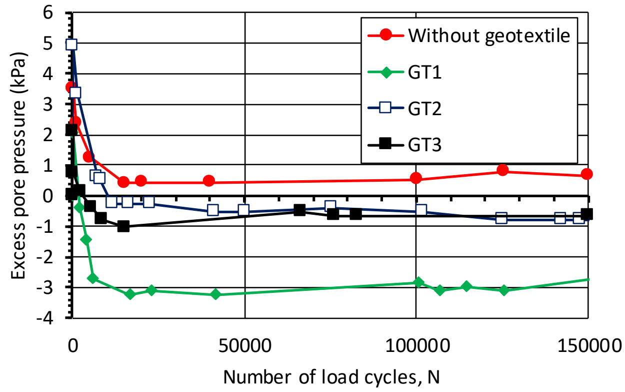


Figure 7 Excess pore pressure at piezometer P1 versus number of load cycles – SS tests

The variation of excess pore pressure in pore pressure transducer P2 with the number of loading cycles in SS tests is presented in Figure 8. As in the MS tests, the presence of the geotextile at the base-subgrade interface reduced more significantly the values of Δu measured by the deeper pore pressure transducer. Similar patterns of pore pressure development under cyclic loading were obtained by Overy (1982), Gu *et al.* (1995), Alobaidi & Hoare (1996, 1998a and 1998b) and Gebretsadik (2012).

Figures 5 to 8 show that the three geotextiles tested reduced the pore pressures in the subgrade soil. However, because of the aforementioned limitations regarding pore pressure measurements under the conditions of the tests, the results in these figures do not allow a proper identification of the geotextile that most effectively reduced the pore pressures.

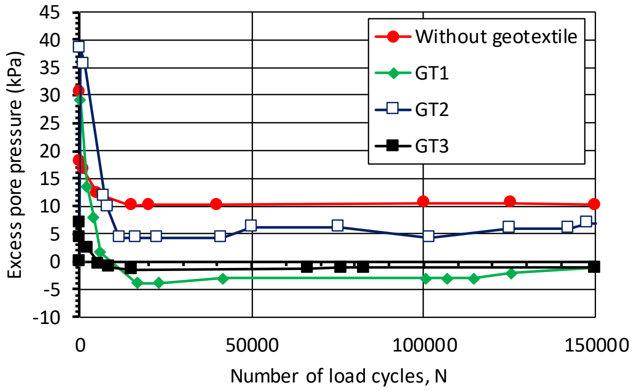


Figure 8 Excess pore pressure at piezometer P2 versus number of load cycles – SS tests

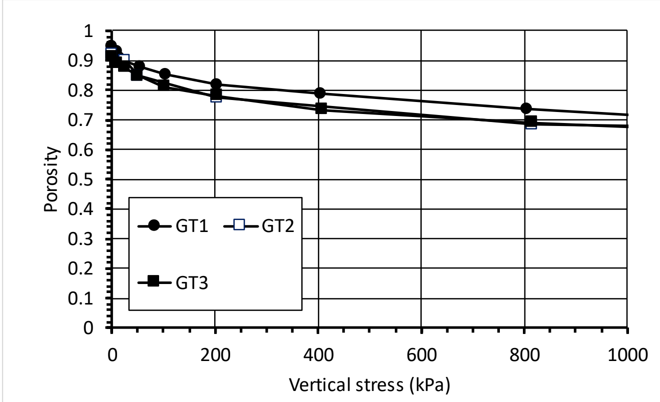


Figure 10 Geotextile porosity versus vertical stress

3.3 Impregnation of the geotextile and of the base soil

The mass of the particles from the subgrade soil that impregnated the geotextile separator at the end of the test was measured. Figure 9 shows the results obtained in terms of impregnation level (λ) of the geotextile, defined as the mass of soil particles entrapped in the geotextile divided by the mass of geotextile fibers. The values of λ varied between 0.44 and 0.8, depending on the geotextile considered and were higher in SS tests, due to the soft nature of the subgrade soil in this case. The thicker (and less open) the geotextile the smaller the impregnation level, because less particles are capable of intruding the pores of geotextiles with smaller values of filtration opening size.

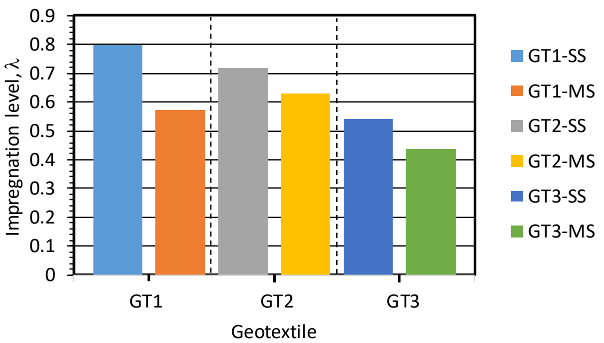


Figure 9 Impregnation levels of the geotextiles

The fraction of geotextile open voids at the end of the test can be estimated as a function of its impregnation level and physical properties by the following equation (Palmeira *et al*. 2010):

$$FOV = 1 - \frac{\rho_f}{\rho_s}\left(\frac{1-n}{n}\right)\lambda \qquad (5)$$

Where *FOV* is the fraction of geotextile open voids, ρ_f is the density of the geotextile fibers, ρ_s is the density of entrapped soil particles, n is the geotextile porosity and λ is the geotextile impregnation level.

A realistic value of n to be used in equation 5 must be that for the geotextile under the vertical stress used in the tests. Figure 10 shows the variation of n with vertical stress obtained in one dimensional compression tests on the geotextiles used in the experiments reported in this paper. It can be note that for the maximum vertical pressure employed in the tests (200 kPa) the geotextile porosity varies between 0.78 and 0.82, depending on the geotextile considered. Using the values of n obtained in the compression tests, *FOV* values can be calculated (equation 5) and are presented in Figure 11. This figure shows that after 150000 load cycles the fraction of open voids of the geotextile separator remained considerably high (between 89% and 94%).

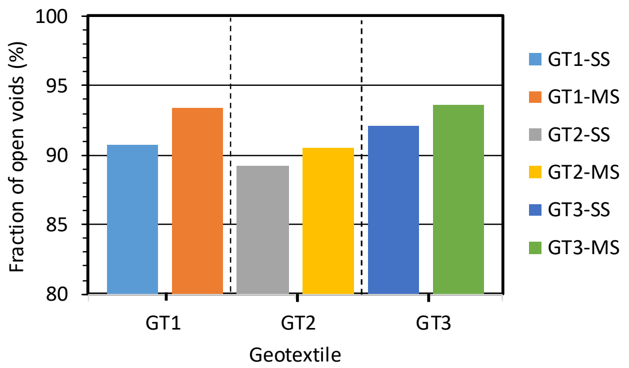


Figure 11 Geotextile fraction of open voids

Figures 12(a) and (b) show images of the base soil at the end of tests without geotextile on medium and soft subgrades, respectively. Significant contamination of the gravel material with fines from the base soil can be noted in both cases, but with a much more severe contamination in the test with the soft subgrade. The values of mass of the subgrade soil impregnating the base soil per unit area in MS and SS tests were equal to 2241 g/m^2 and 7130 g/m^2, respectively. As expected, a greater value of mass of impregnating particles per unit area was observed for the soft subgrade. The contamination of the base material in tests with geotextile separator was negligible, as shown in Figure 12(c), which confirms that all 3 geotextiles used performed well as separators. Negligible intermixing between base and subgrade soils was also observed in full-scale tests reported by Tsai *et al.* (1993) using different nonwoven geotextiles than the ones tested in the present paper.

3.4 Geotextile strength reduction

Wide strip tensile tests were performed on the geotextile specimens after the tests. Figure 13 show results of tensile strength before and after the tests under repetitive load for specimens tested on different subgrade conditions (MS and SS tests). It can be noted that after 150000 load repetitions significant strength reduction was observed only for the lighter geotextile (GT1) on soft (SS) subgrade. Tests on medium subgrade did not produced significant geotextile tensile strength reductions.

3.5 Assessment of requirements for geotextile separators

Equations 1 to 4 can be used to evaluate the capability of the geotextiles tested as separators for the conditions of the tests performed. The verification of the requirements expressed by those equations is presented below.

(a) Test with medium subgrade (MS test)

(b) Test with soft subgrade (SS test)

(c) Test with geotextile GT2 (SS test)

Figure 12 Images of the base soil after the tests

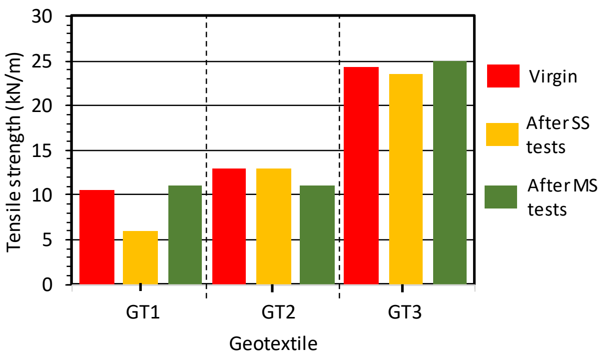
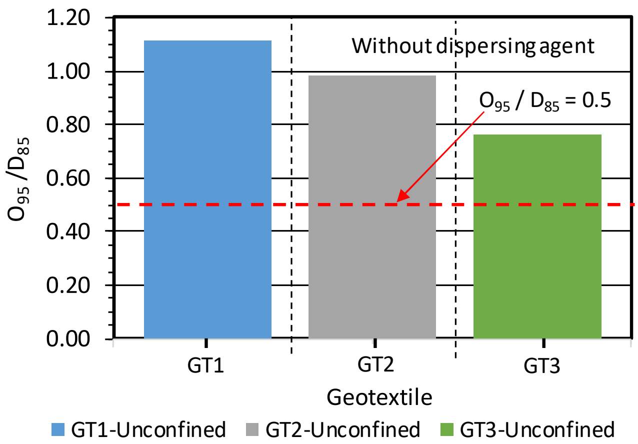


Figure 13 Geotextile tensile strength before and after the tests

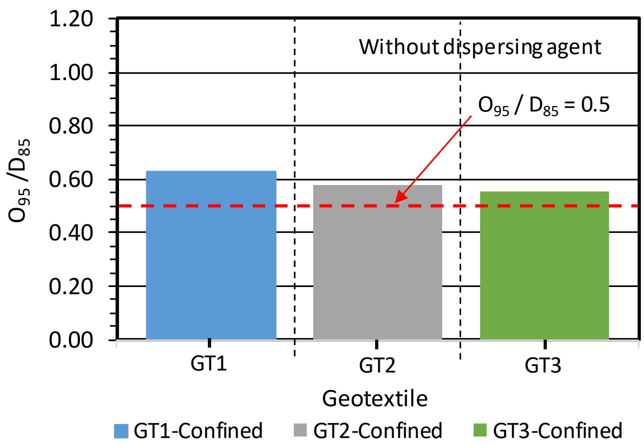
3.5.1 Geotextile retention capacity

Figure 14(a) shows the ratio O_{95}/D_{85} for the geotextiles tested for values of D_{85} obtained in grain size analysis tests without the use of dispersing agent and for values of O_{95} obtained in bubble point tests on unconfined geotextile specimens (Palmeira and Trejos-Galvis 2017). It can be noted in that figure that none of the geotextiles satisfied the criterion $O_{95}/D_{85} < 0.5$ (Holtz et al. 1997).

It could be argued that under cyclic loading the subgrade particles would be pushed against the geotextile filter under confined conditions, i.e., under varying vertical stresses that would reach the established maximum value of 200 kPa. Under such conditions, the value of O_{95} would be smaller than that obtained under unconfined conditions. Taking this into account, Figure 14(b) shows values of the ratio O_{95}/D_{85} with O_{95} obtained in bubble point tests with the geotextile specimens subjected to a vertical stress of 200 kPa (Silva 2014, Palmeira and Trejos-Galvis 2017). Even under these conditions the values of O_{95}/D_{85} were still slightly above the 0.5 limit, varying between 0.55 and 0.63. Had the results of grain size analysis using dispersing agent been used in these calculations the values of O_{95}/D_{85} would be significantly higher than those depicted in Figure 14, as shown in Table 3 for O_{95} measured under unconfined conditions. The results obtained and the negligible contamination of the base material by fines from the subgrade in tests with geotextile suggest that the retention criterion used may be quite conservative for conditions similar to those of the tests reported in this paper.



(a) For unconfined geotextile conditions



(b) For confined geotextile conditions

Figure 14 Geotextile retention criterion evaluation

Table 3 Required and available mechanical properties for separation

Test	Required value(1)	Available value(2) GT1	GT2	GT3
Filtration (FOS/D_{85})	< 0.5	5.9/1.1(3)	5.2/0.98	4.0/0.77
Grab tensile test (N)	2.2	800 (364)(4)	1800 (818)	2400 (1091)
Burst strength (MPa)	0.031	2.2 (71)	4.5 (145)	6.0 (194)
Puncture force (kN)	0.034	2.6 (76)	5.2 (153)	8.0 (235)

Notes: (1) No reduction or safety factors considered; (2) See Table 2; (3) Numbers on the left and on the right are values calculated using results from grain size analysis tests with and without dispersing agent, respectively, and for geotextile under unconfined conditions; (4) Numbers in parentheses are the ratios between available and required values.

3.5.2 Geotextile mechanical properties

Tensile strength

The mobilized tensile force in the geotextile can be estimated by equation 2. According to Koerner (1998), the value of the void diameter in the base soil can be assumed as one third of its average particle diameter. Adopting a ratio between geotextile penetration and void width of 0.4 leads to a value of $f(\varepsilon)$ equal to 0.51 (Giroud 1984). Thus:

$$T = p' d_v^2 f(\varepsilon) = 200\,x(0.014 / 3)^2\,x0{,}51 = 0.0022\,kN$$

According to Table 3 the calculated required tensile force is much smaller than the available tensile strength of the geotextiles obtained in grab tensile tests. This table also presents the ratio between available and required tensile strengths, which shows that the former is 364 to 1091 times greater than the latter, depending on the geotextile considered. Even if lager values of d_v and $f(\varepsilon)$ were used above, the mobilized tensile force would still be considerably smaller than the available tensile strength for all geotextiles tested.

Geotextile burst strength

The required burst strength can be estimated by equation 3:

$$p_b = \frac{p' d_v}{d_s} = \frac{200x(0.014/3)}{0.030} = 31.1kPa = 0.031MPa$$

The values of the burst strength of the geotextiles tested are also significantly greater than the required value, ranging from 71 to 194 times the latter value, as shown in Table 3.

Geotextile puncture force

Using equation 4 with S_1 equal to 0.4, d_{test} equal to 50 mm (ASTM 6241) ($S_2 = d_{test}/D_{50} = 50/14 = 3.57$) and S_3 equal to 0.6 (value for crushed rock particles, as per Koerner 1998) yields to:

$$F_p = p' D_{50}^2 S_1 S_2 S_3 = 200x0.014^2 x0.4x3.57x0.6 = 0.034kN$$

Again, the results in Table 3 show that the puncture strength of the geotextiles tested are 76 to 235 greater than the required value.

The values of ratios between available and required parameters presented in Table 3 exceed by far the product of reduction factors and factors of safety commonly used in practice. Thus, even the lighter geotextile (GT1) tested would be considered appropriate as a separator for the conditions of the test, but bearing in mind its significant reduction in tensile strength (Fig. 13). However, one should also bear in mind the maximum number of load repetitions reached in the tests (N = 150000). It should be pointed out that under field conditions the effects of impact forces and geotextile degradation mechanisms should also be taken into account, which were not considered in the present study.

Based on the calculations above, the retention criterion was not satisfied by the geotextiles used in the research programme reported in this paper. Nevertheless, all geotextiles performed well as separators, avoiding the contamination of the base soil. These results suggest that the retention criterion employed may be quite conservative.

4. CONCLUSIONS

This paper presented a study on the behaviour of nonwoven geotextiles as separators. The main conclusions obtained are summarized as follows.

The vertical displacements of the tests without geotextile were considerably higher than those where geotextile separator was used, particularly in the tests with the soft subgrade. This was a consequence of greater penetration of the base material particles in the subgrade.

Despite the complexity of the pore pressure generation under cyclic loading and difficulties in the measurements conducted due to the characteristics of the apparatus used, the results showed that the presence of the geotextile significantly accelerated the dissipation of excess pore pressure generated during the tests close to the base soil-subgrade interface.

All three geotextiles tested performed well as separators. Severe impregnation of the base soil was observed in the tests without geotextile, confirming the need of the latter as separator in this type of work. The amount of base soil particles that intruded in the geotextile voids was small, with 89% to 94% of open voids remaining at the end of the tests, depending on the geotextile and subgrade condition considered.

Significant reduction of tensile strength of the geotextile after the tests was observed only for the test with the lighter geotextile and the soft subgrade. However, no holes or cuts were visible in the geotextile specimens after the tests and the tensile strength reduction did not compromise the separation performance of the lighter geotextile.

The design of geotextiles as separators in road pavements and railway tracks is still a complex task. Therefore, further research is needed under laboratory and field condition for improvements in the design of geotechnical works using geotextile separators.

5. ACKNOWLEGEMENTS

The authors are indebted to the following institutions which contributed in different ways to the research activities described in this paper: University of Brasília, CNPq-National Council for Scientific and Technological Development and the geotextile manufacturers.

6. REFERENCES

Alobaidi, I. and Hoare, D.J. (1996). “The development of pore water pressure at the subrade-subbase interface of a highway pavement and its effect on pumping of fines”. Geotextiles and Geomembranes 14(2): 111-135.

Alobaidi, I. and Hoare, D.J. (1998a). “Qualitative criteria for anti-pumping geocomposites”. Geotextiles and Geomembranes 16(4): 221-245.

Alobaidi, I. and Hoare, D.J. (1998b). “The role of geotextile reinforcement in the control of pumping at the subgrade-subbase interface of highway pavements”. Geosynthetics International 5(6): 619-636.

AREA (1985). American railway engineering association manual. AREA, Lanham, MA, USA.

ASTM D3786. Standard test method for bursting strength of textile fabrics—diaphragm bursting strength tester method. American Society for Testing and Materials, West Conshohocken, PA, USA.

ASTM D4595. Standard test method for tensile properties of geotextiles by the wide-width strip method. American Society for Testing and Materials, West Conshohocken, PA, USA.

ASTM 4632. Standard test method for grab breaking load and elongation of geotextiles. American Society for Testing and Materials, West Conshohocken, PA, USA.

ASTM 6241. Standard test method for static puncture strength of geotextiles and geotextile-related products using a 50-mm probe. American Society for Testing and Materials, West Conshohocken, PA, USA.

ASTM D6767-12. Standard test method for pore size characteristics of geotextiles by capillary flow test. American Society for Testing and Materials, West Conshohocken, PA, USA.

Bell, A.L., McCullough, L.M. and Snaith, M.S. (1982). "An experimental investigation of sub-base protection using geotextiles". 2nd International Conference on Geosynthetics, Las Vegas, NV, USA, vol. 2, pp. 435-440.

Brorsson, L. and Eriksson, L. (1986). "Long-term properties of geotextiles and their function as separator in road construction". 3rd International Conference on Geosynthetics, Vienna, Austria, vol. 1., pp. 93-98.

Christopher, B.R. and Holtz, R.D. (1985). Geotextile engineering manual. Report No. FHWA-TS-86/203, Federal Highway Administration, Washington, DC, 1044 p.

Christopher, B.R. and Schwarz, L.G. (2010). "Performance of geogrids overlying geotextiles in roadway stabilization applications". 9th International Conference on Geosynthetics, Guarujá, Brazil, vol. 3, pp. 1451-1456.

Collins, B.M. and Holtz, R.D. (2005). Long-term performance of geotextile separators, Bucoda Test site – Phase III. Research Report WA-RD 595.1, Washington State Transportation Center, Seattle, Washington, USA, 234 p.

Elgohary, M.M.M. (1973). Consolidation of soils under cyclic loading. PhD. Thesis, MacMaster University, Ontario, Canada.

Fernandes, G., Palmeira, E.M. and Gomes, R.C. (2008). "Performance of geosynthetic-reinforced alternative sub-ballast material in a railway track". Geosynthetics International 15(5): 311-321.

Friedli, P. and Anderson, D.G. (1982). "Behavior of woven fabrics under simulated railway loading". 2nd International Conference on Geosynthetics, Las Vegas, NV, USA, vol. 2, pp. 473-478.

Gebretsadik, A.G. (2014). Shear resistance degradation of lime–cement stabilized soil during cyclic loading. MSc. Thesis, Royal Institute of Technology, Dept. of Civil, Architectural and the Built Environment, Stockholm, Sweden.

Giroud, J.P. (1984). Geotextiles and geomembranes, definitions, properties and designs. Industrial Fabrics Association International, IFAI, St. Paul, MN, USA.

Gu, X.Y., Xu, D.N. and Wey, D. (1995). "A computing model based on cyclic consolidation tests". 5th International Symposium on Land Subsidence, The Hague, The Netherlands, pp. 295-303.

Hoare, D.J. (1982). "A laboratory study into pumping clay through geotextiles under dynamic loading". 2nd International Conference on Geosynthetics, Las Vegas, NV, USA, vol. 2, pp. 423-428.

Holtz, R.D., Christopher, B.R. and Berg, R.R. (1997). Geosynthetic Engineering. BiTech Publishers, Richmond, BC, Canada.

Koerner, R.M. (1998). Designing with geosynthetics. Prentice-Hall, USA.

Kuerbis, R.H. and Vaid, Y.P. (1988). "Sand sample preparation – the slurry deposition method". Soils and Foundations 28(4): 107-118.

Müthing, N., Razouki, S.S. Datcheva, M. and Schanz, T. (2016). "Rigorous solution for 1-D consolidation of a clay layer under haversine cyclic loading with rest period". SpringerPlus 5: 1-13.

Nishida, K. and Nishigata, T. (1994). "The evaluation of separation function for geotextiles". 5th International Conference on Geosynthetics, Singapore, vol. 1, pp. 139-142.

Overy, R.F. (1982). The behaviour of anisotropically consolidated silty clay under cyclic loading. PhD. Thesis, University of Nottingham, UK.

Palmeira, E.M. (1981). The use of geotextile as reinforcement of embankments on soft soils. MSc. Dissertation, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, 282 p.

Palmeira, E.M., Berigo, E.A. and Gardoni, M.G. (2010). "Tailings-nonwoven geotextile filter compatibility in mining applications". Geotextiles and Geomembranes 28: 136-148.

Palmeira, E.M., Tatto, J. and Araújo, G.L.S. (2012). "Sagging and filtration behaviour of nonwoven geotextiles overlying different bedding materials". Geotextiles and Geomembranes 31:1-14.

Palmeira, E.M. and Trejos Galvis,H.L. (2017). "Opening sizes and filtration behaviour of nonwoven geotextiles under confined and partial clogging conditions". Geosynthetics International 24(2): 125-138.

Schaeffner, M. and Khay, M. (1982). "Mesure du pouvoir anticontaminant d'un géotextile sousmis à un trafic simulé". 2nd International Conference on Geosynthetics, Las Vegas, NV, USA, vol. 2, pp. 429-434.

Silva, A.M. (2014). Geotextile opening sizes under confinement. MSc. Dissertation, Graduate Programme of Geotechnics, University of Brasília (in Portuguese).

Susunaga, M.P.S. (2015). Geotextiles as separators of pavement layers. MSc. Dissertation, Graduate Programme of Geotechnics, University of Brasília, Brasília, Brazil (in Portuguese).

Tsai, W.-S., Savage, B.M., Holtz, R.D., Christopher, B.R. and Allen, T.M. (1993). "Evaluation of geotextiles as separators in a full-scale road test". Geosynthetics'93, Vancouver, BC, Canada, vol. 1, pp. 35-48.

Vaitkus, A., Cygas, D. and Laurinavicius, A. (2008). "Newly developed geotextiles selection system for layers separation in Lithuanian roads construction". 4th European Conference on Geosynthetics, Eurogeo 4, Eddingburgh, Scotland, paper 076, 7 p.

Wilmers, W. (2007). The use of geosynthetics as separators in civil engineering. Geosynthetics in Civil Engineering, R.W. Sarsby (editor), Germany.