Technical Paper by M.S.S. Almeida, J. Spada and M. Ehrlich

GEOTEXTILE FILTRATION TESTS ON TWO BRAZILIAN SOILS AND CURRENT FILTER CRITERIA

ABSTRACT: This paper presents results of filtration tests with geotextiles in combination with a uniform fine sand and a clayey fine sand. The tests with the clayey sand were long term tests during which the pH, electrical conductivity and turbidity of the percolation water were monitored with time. These observations, together with a detailed measurement of permeability values, indicate that the three geotextiles performed adequately with regard to drainage and soil particle retention. It is shown that current geotextile filter design criteria are conservative and only one among six criteria was able to predict the behavior of all the geotextiles tested.

KEYWORDS: Geotextile, Filtration Tests, Sands, Permeability, Filter Criteria.

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1 INTRODUCTION

Geotextiles used in soils for filtration purposes must fulfill drainage and particle retention requirements. In addition, the soil must not clog the geotextile, thereby reducing flow. These requirements can be assessed using a number of filter criteria methods. The requirement that clogging (short or long term) should not occur can be verified using two laboratory test procedures. The gradient ratio test, reported by Calhoun (1972) and Haliburton and Wood (1982), was originally developed for cohesionless soils and woven monofilament geotextiles. Halse et al. (1987) reported that for other soils or geotextiles the test is not well behaved. Long term flow tests, described by Rollin et al. (1989) and Merwe and Horak (1989), are the second option to evaluate clogging potential. However, interpretation of long term performance data is complicated by clogging and biological growth rather than particle movement.

This paper reports a study of the long and short term drainage, particle retention and clogging behavior of three geotextiles in combination with two Brazilian soils using filtration equipment developed by Spada (1991). Three test programs were performed. The soil tested in the first program was a uniform sand. Its filtration behavior is quite simple due to the high degree of internal stability of the material as compared to some finer soils. The second and third programs tested erodible clayey fine sands. In these two programs, flow rate and water turbidity were measured with time. Turbidity was measured to determine the loss in mass of the soil. In addition, pH and electrical conductivity were monitored. Finally, the performances of the geotextiles are compared and filter criteria methods are assessed.

2 EQUIPMENT DEVELOPED

Various types of filtration equipment have been developed based on: permeability (Calhoun 1972; Haliburton and Wood 1982; Rycroft and Jones 1982; Christopher and Holtz 1985; Wey et al. 1985; Faure et al. 1986; Qureshi et al. 1990); consolidation (Faure et al. 1986; Sato et al. 1986); and, triaxial tests (Williams and Abouzakhm 1989). Each type of equipment subjects the soil-geotextile system to different flow and boundary conditions. The equipment based on the permeability test is the one most widely used and consists of a vertical filtration column subjected to constant head downward flow with the geotextile filter placed under the soil. The basic advantages of this permeameter type equipment are simplicity, low cost and the possibility of collecting both the fines passing through the geotextile and the tail water. On the other hand, the main limitations of the permeameter type equipment are difficulties in achieving saturation, no control of the soil stress state, and the possibility of preferential water paths between the specimen and the cylinder wall, particularly in the case of fine grained soils. As far as the present studies are concerned, it is considered that the advantages out-weigh the limitations, thus preference is given to permeameter type equipment.

The filtration equipment developed by Spada (1991) is based on the proposal for standardization presented by Christopher and Holtz (1985) for the gradient ratio test methodology originally described by Calhoun (1972). The permeameter shown in Figure 1 consists of: an upper chamber, where the soil and the geotextile are placed; a lower chamber (to allow collection and quantification of the particles passing through the

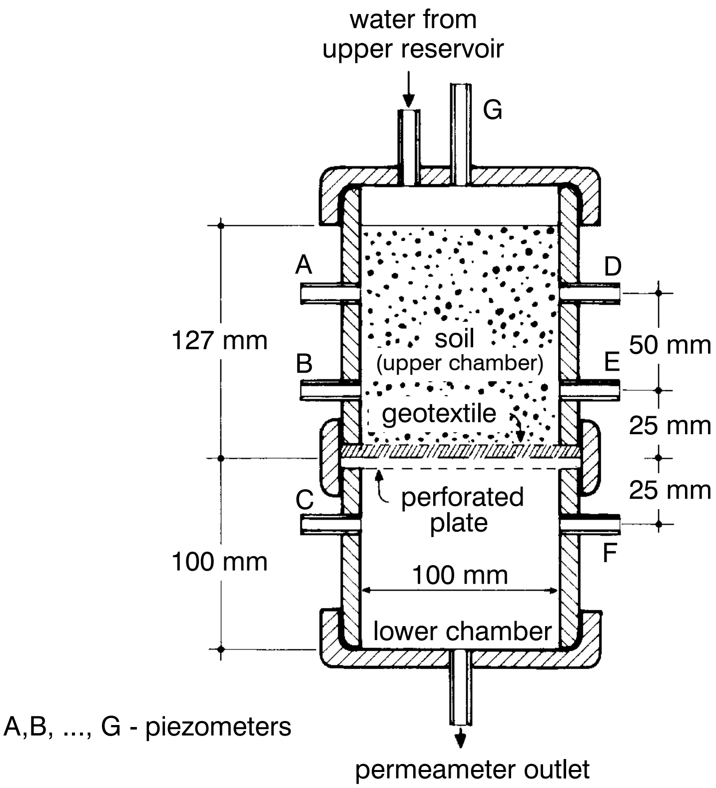

Figure 1. Permeameter developed for filtration tests.

geotextile and to keep it submerged); a perforated plate to support the geotextile-soil system; a nipple to assemble the above parts; a top cap; and a bottom cap. All the above parts are made of polyvinyl chloride (PVC) to minimize physicochemical interaction between the equipment and the soil. The permeameter design also allows the use of a granular filter. In this case, the perforated plate is not necessary and the granular filter is placed directly inside the lower chamber.

Three pairs of piezometers are positioned at three different levels on the permeameter wall, plus an additional one at the top (see Figure 1). In order to avoid soil entering the piezometer outlets, they are protected by pieces of 75 μm size mesh. These seven piezometers allow the determination of four permeability values: k_1 at the soil-geotextile interface, k_2 and k_3 at the middle and upper third of the permeameter, respectively (thus values within the soil); and k, the average value of the entire system.

Other parts of the equipment are shown in Figure 2 and include upper and lower water reservoirs (to provide the head necessary for the descending flow). The lower reservoir was placed above the permeameters to avoid the trapping of bubbles in the soil. Water was not deaired prior to the tests, only filtered, as the long term tests would require a costly deairing system. A total of eight permeameters were manufactured and used in

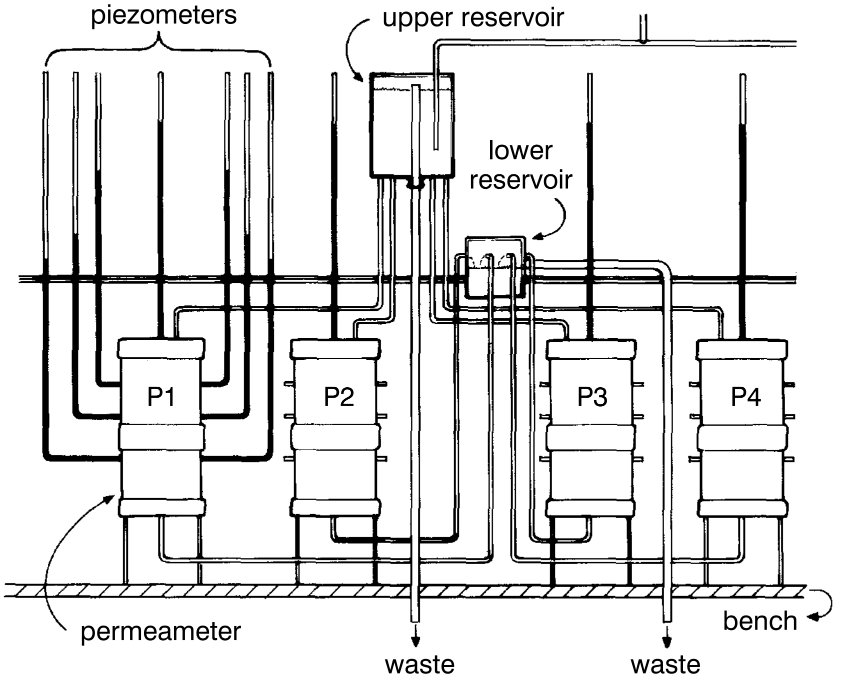

Figure 2. Filtration equipment arrangement.

parallel during the test programs. These permeameters have been divided into two groups of four permeameters, so that a set of upper and lower reservoirs could be used for each group, as shown in Figure 2. Permeameters P1 to P4 correspond to one set of lower and upper reservoirs and permeameters P5 to P8 to another set.

3 SOILS, GEOTEXTILES AND WATER

Two soils have been used, a uniform sand and a clayey sand. Grain size distributions for these soils are shown in Figure 3 and soil index properties are shown in Table 1. The uniform sand was used previously at COPPE by Oliveira (1987) and consists of quartz grains, subrounded to subangular in shape, and a small amount of biotite mica particles. The clayey sand is made up of 76% fine sand (with rounded grains), 20% clay, and hence, virtually no silt. It originates from the weathering of the Caiuá sandstone deposited during the Cretaceous period and is called Caiuá soil. This soil is quite common in vast areas of central and southern Brazil. Chemical and mineralogical analyses of the Caiuá soil have been performed to allow a better understanding of its physicochemical behavior during filtration. Results of the chemical analyses are shown in Table 2 together with the mineralogical composition as percentages of oxides. Analysis of these data indicates that the Caiuá soil is virtually inorganic and is an acidic soil, but is chemically stable as the pH(H_2O) is close to the pH(KCl). Kaolinite is the predominant clay mineral.

Table 1. Soil properties (Oliveira-Filho 1987).

Uniform sand	
d_{85} (μm)	290
$C_u = (d_{60} / d_{10})$	1.53
Specific gravity of soil particles	2.64
e_{min} - minimum void ratio (Miura and Toki's method)	0.56
e_{max} - maximum void ratio (Kolbuzewski's method)	0.82
Caiuá soil	
d_{85} (μm)	190
$C_u = (d_{60} / d_{10})$	75
Specific gravity of soil particles	2.67
Liquid Limit (%)	20
Plasticity Index (%)	7
Proctor maximum dry unit weight (kN/m^3)	20.5
Proctor optimum water content (%)	9.4

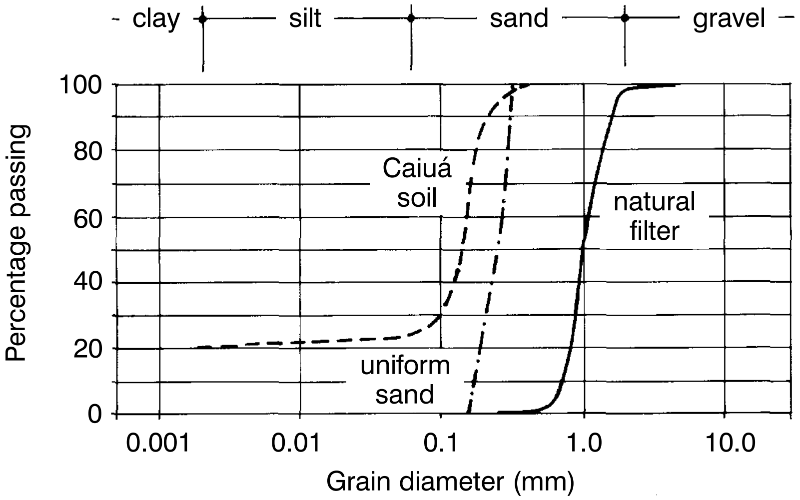

Figure 3. Grain size distribution of soils and natural granular filter.

Three types of geotextiles and a granular filter were used in the study presented here. The details of the geotextiles tested are summarized in Table 3. The Bidim and Propex products are the only geotextiles produced on a large scale in Brazil. The third, Typar, is from the United Kingdom. It was decided to test a granular filter since the behavior of natural filters is well known and allows a comparison to be made with geotextiles. The granular filter was therefore used as a reference for the analysis of geotextile performance and consisted of a medium quartz sand with subrounded grains and grain size distribution as shown in Figure 3. This sand has d_{15} = 750 μm and permeability k = 2 x 10^{-3} m/s. The water used in all the tests was tap water passed through two filters. The first, a sand filter, was used to retain larger particles and the second, a carbon activated filter, was used to retain the colloidal particles present in the water.

4 METHODOLOGY

4.1 Specimen Preparation

Both soils were first dried and specimens were then prepared by the air pluviation technique described by Miura and Toki (1982). As local experience with the air pluviation technique was previously acquired with the uniform sand (Oliveira 1987) the preparation of these specimens was straightforward. However, as this technique had not been used previously for finer soils, some studies were performed with the Caiuá soil. The first study was the assessment of repeatability of the specimen preparation in terms of unit weight, which proved to be satisfactory. In addition, the homogeneity of the specimens was preliminarily verified by visual inspection using a transparent cylinder. Subsequently, small samples were taken along different horizontal and vertical planes within a specimen and subjected to grain size analyses. These analyses showed that the specimen was homogeneous.

The dry unit weight of the Caiuá soil specimens was about 14 kN/m^3 which was low compared to the maximum Proctor value of 20.5 kN/m^3. Recently, Brandon et al. (1991) reported that the air pluviation technique applied to silty sand soils also results in specimens with very high void ratios. The low unit weight of the laboratory specimens is a condition more critical than the field one. If filtration tests under these conditions show a satisfactory behavior, then even better behavior can be expected under field conditions. The granular filter that was used as the reference condition was also placed in the lower chamber of the permeameter by air pluviation.

4.2 General Test Procedures

The first step in setting up the tests for Caiuá soil consisted of filling the permeameter with water in order to saturate the filters and the lower chamber. Following this, the specimen was prepared by air pluviation. In order to expel as much air as possible, upward flow of water was applied to the specimen for 120 hours before the actual downward flow test started. Tests with the uniform sand specimens began immediately with downward flow. During the tests the permeameters were continuously monitored for air bubbles. When piezometers indicated anomalous readings, the permeameters were carefully deaired. The readings recorded herein were taken after equilibrium of water

Table 2. Chemical and mineralogical analyses of Caiuá soil.

Chemical analysis	
loss on ignition (1000°C)	3.08%
pH (H_2O)	4.10
pH (KCl)	4.36
SiO_2	6.9%
Al_2O_3	6.8%
Fe_2O_3	4.85%
TiO_2	0.50%
Residual	78.53%
Mineralogical analysis	
Kaolinite	15%
Gibbsite	1%
Goethite	6.5%
TiO_2	0.5%
Quartz	78.5%

Table 3. Geotextile properties.

Geotextile	Properties			
	Polymer Classification	Thickness (mm)	Permeability (m/s)	O_{95} (μm)
Typar 3267	polypropylene nonwoven heat-bonded	0.41	0.13×10^{-2}	250 (D_w = 240)
Propex 4004	polypropylene woven slit-film	0.40	6.4×10^{-2}	400
Bidim OP-20	polyester nonwoven needle-punched	2.9	0.22×10^{-2}	130

Note: D_w = effective opening size.

heads. Measurements taken during the tests consisted of flow rates and piezometric levels at each of the seven piezometers shown in Figure 1. Permeability values have been computed from the average piezometric level at each elevation, i.e. A and D, B and E, and C and F, as shown in Figure 1, provided these readings were similar in magnitude. When a piezometer gave unexpectedly high readings, apparently indicating a preferential flow path along the permeameter wall, these readings were disregarded. For the computations of k_1 and k, the thickness of the geotextile was not added to the drainage length, since the permeability of the geotextile is much greater than that of the soil.

4.3 Test Procedures for the Caiuá Soil

Two test programs were performed with fine clayey sands, a preliminary short term test for the purpose of checking the performance of the equipment with fine grained soils and the actual long term tests. However, results of the preliminary program will not be presented here. Two fine soils, susceptible to field erosion, were tested in the preliminary program: the Caiuá soil described above; and one with similar granulometry, but of Cenozoic origin. Bidim OP-20 was the only geotextile used in this preliminary program. The hydraulic gradient was increased in three steps giving values of 1.0, 2.5 and 4.0 in an attempt to simulate long term conditions. The total duration of the test was 190 hours. Results of this preliminary program were entirely satisfactory and only small changes in test procedure had to be made for the long term tests.

Three water quality parameters of the outflow were monitored: pH, electrical conductivity and turbidity. Turbidity is expressed as a UTF (universal turbidimetric factor). The UTF calibration consisted of suspending a known mass of soil in a known volume of water and measuring its turbidity. Subsequent dilution steps and measurements of the respective turbidity allowed establishment of the correlation shown in Figure 4 and this was used to calculate the amount of soil that had escaped from the specimen.

4.4 Test Procedures for the Uniform Sand

The test procedures for the uniform sand were basically the same as for the Caiuá soil, but with the following differences: there was no monitoring of the water quality during the tests; the position of the top piezometer was used as a bleed; the natural filter was not used; and the hydraulic gradient adopted was about 0.45, suitable for the measurements planned.

5 TEST RESULTS FOR THE UNIFORM SAND

The details of the tests on the uniform sand are shown in Table 4. Initial values of void ratio (e_i) were in the range 0.56 to 0.58, thus the specimens had relative densities close to 100% (according to the minimum void ratio value given in Table 1). Final values of void ratio (e_f) were in the range 0.53 to 0.58, thus small reductions in void ratio occurred during the tests. The above values of void ratio may be slightly in error since it was noticed during the air pluviation process that a very small amount of sand was sometimes able to get into the geotextile.

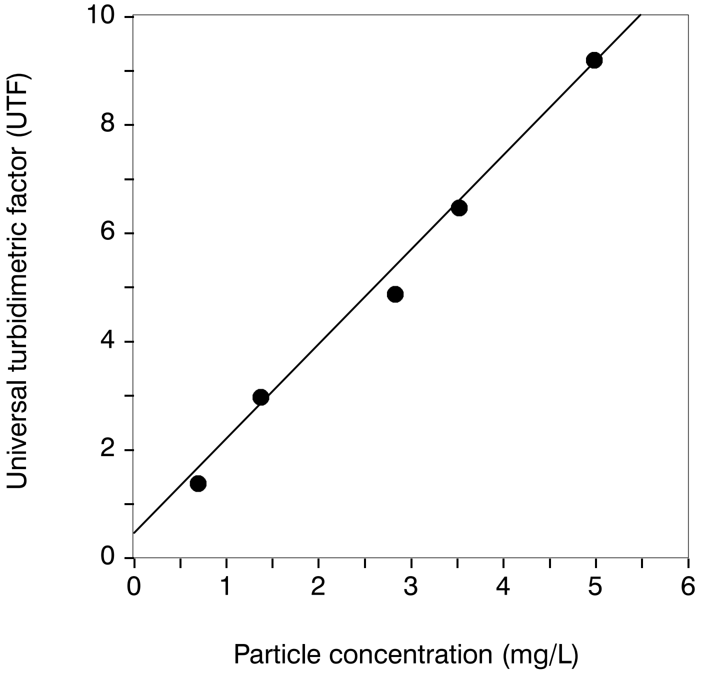

Figure 4. Correlation between turbidity and particle concentration in suspension for Caiuá soil.

Variations of the permeabilities k_1 and k_2 with time are presented in Figure 5 for tests P5 to P7. Permeability values shown have been corrected to the reference temperature of 20°C. As expected, values of k_1 are either greater than or close to k_2 values, as the greater permeability of the geotextile (k_g) renders the permeability k_1, of the soil-geotextile system, greater than the soil permeability k_2. Values of k_1 show great variations during the first 100 hours of testing as a consequence of particle rearrangement as well as air expulsion from the soil voids. Following this period, values of k_1 varied in the range 10×10^{-5} to 20×10^{-5} m/s without a clear trend. Values of k_2 after the first 100 hours of the test, vary in the narrow range 9×10^{-5} to 13×10^{-5} m/s. These data can be compared to the value 9×10^{-5} m/s, computed using the equation $k(\text{cm/s}) = 0.35\,[d_{15}\,(\text{mm})]^2$ proposed by Sherard et al. (1984).

6 TEST RESULTS FOR THE CAIUÁ SOIL

6.1 Events Observed During the Tests

For each filter material two parallel tests were performed in two different permeameters, as shown in Table 5. Values of void ratio of the specimens prior to the tests are also

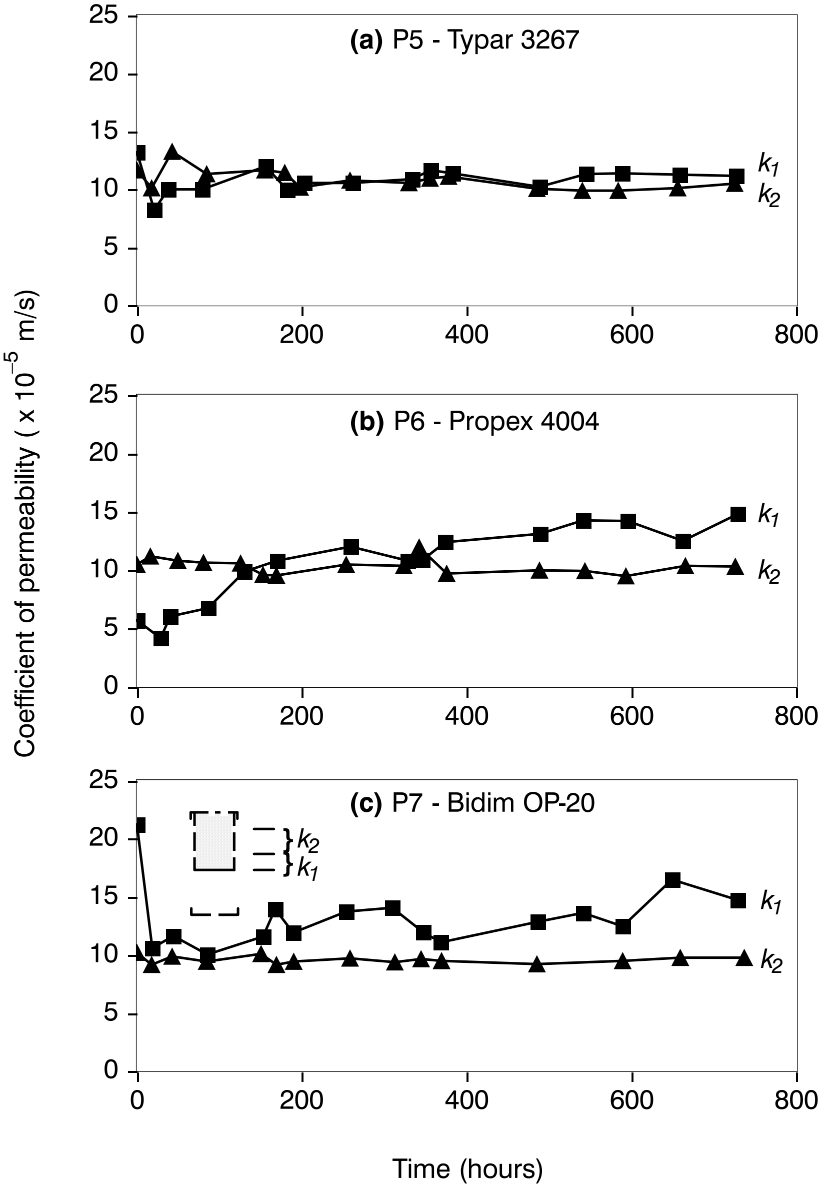

Figure 5. Permeability versus time for tests with uniform sand.

shown in Table 5. They vary in the range 0.96 to 1.00 for the permeameters with geotextiles, and are lower (0.91 and 0.95) for the two permeameters with natural filters. The different methodology adopted to determine the mass of the specimens in the latter case may be the reason for the lower values obtained.

Table 4. Details of tests with uniform sand.

Permeameter	Filter	e_i	e_f	i
P1	Typar 3267	0.56	0.53	0.43
P2	Propex 4004	0.56	0.56	0.43
P3	Bidim OP-20	0.58	0.58	0.43
P5	Typar 3267	0.56	0.54	0.44
P6	Propex 4004	0.57	0.55	0.44
P7	Bidim OP-20	0.58	0.56	0.44

Table 5. Details of tests with Caiuá soil.

Permeameter	Filter	e_i(1)	i	w (%)	GR_{max}
P1	Typar 3267	1.00	1.0	35	1.88
P2	Propex 4004	0.99	1.0	36	1.08
P3	Bidim OP-20	1.04	1.0	35	0.40
P4	natural filter	0.91	1.0	35	1.35
P5	Typar 3267	0.96	1.0	35	1.00
P6	Propex 4004	1.02	1.0	34	0.76
P7	Bidim OP-20	1.06	1.0	35	1.76
P8	natural filter	0.95	1.0	33	1.81

Note: (1) Zero initial water content for all specimens (oven dried soil).

Final water content data from all tests are presented in Table 5 and are in the range w = 33% to 36%. Measuring the final volume and mass of the specimens was difficult due to the presence of iron precipitates on the top of the specimens as described below. Therefore, it was not possible to compute the final values of void ratio, e_f, and degree of saturation, S_r. However, assuming S_r= 100% indicates that void ratios have decreased 6% on average. On the other hand, assuming no change in void ratio during the tests ($e_i = e_f$) yields S_r values in the range 88% to 97%. Actual values are probably between these limits.

6.2 Presence of Iron Sediments in Long Term Tests

After 1125 hours of testing, iron precipitates were observed inside the upper water reservoirs and at the top of the specimens and it was decided to stop tests P5 to P8 for two hours in order to remove the sediments from inside the reservoir and also from the top of the specimens. However, after restarting the tests, it appeared that these measures were ineffective as permeability values remained unaltered and iron precipitates continued to be deposited. Following this, periodic cleaning of the reservoirs was performed up to the end of the testing program.

A biological analysis of the iron precipitates taken from inside the upper reservoir of permeameters P5 to P8 indicated the presence of micro-organisms with a predominance of iron bacteria. Chemical analyses confirmed the presence of iron. Iron precipitation inside reservoirs is a common phenomenon and the conditions for this occurrence are good aeration and iron in solution (as an ion) or in suspension (as a colloid). The air-water interface ensures good aeration making the reservoir an oxidizing environment and thereby favoring precipitation. The precipitate is composed of amorphous iron hydroxide ($Fe(OH)_3$) which is slowly transformed into FeO(OH), plus clay. When the iron precipitates, the colloidal clay particles are deposited both by mechanical dragging with iron and by charge neutralization. These reactions can be summarized by:

$$Fe^{2+} \Leftrightarrow Fe^{3+} + e^{-};\ Fe^{3+} + 3\ OH^{-} \Leftrightarrow Fe(OH)_3\mathbf{B}_{\mathrm{gel}} \xrightarrow[\text{ageing}]{-H_2O} FeO(OH)\mathbf{B}_{\mathrm{crystalline}} \qquad (1)$$

The chemical analysis of the water entering the permeameter did not indicate the presence of iron in solution (accuracy of $5\mathrm{x}10^{-6}$ g/L of iron).

6.3 Variation of Permeability With Time

Variations of permeability values with time for tests P5 to P8 in the Caiuá soil are shown in Figure 6. Each pair of tests with the same filter type gave the same order of magnitude of permeability values, thus, just one test of each pair is presented. Inspection of Figure 6 shows an initial increase in permeability due to air expulsion for some specimens. This process takes about 100 hours and is followed by a decrease in permeability. It is also possible that the soil (at its low unit weight) was slightly compacted leading to a decrease in its permeability. After this period, in most cases, there is a general trend to stable measurements indicating a stable soil-filter system.

Values of k_1 (the soil-geotextile system permeability) generally show some oscillation, apparently due to particle rearrangement. It is also noticed that values of k_1 are, with the exception of P8, the highest ones. The trend for P8 is apparently due to particle transportation. The permeability of the mid-third of the specimen, k_2, is the highest in test P8 with the natural filter. Unlike the other permeability values, k_2, showed only small oscillations and appeared to be little affected by the events taking place at the extremities of the specimen.

Typical permeability calculations for the top of the specimen (k_3) are shown in Figure 7 for test P8. It can be noted that k_3 starts to drop at a time corresponding to about when the iron precipitates were first noticed at the top of the specimens. However, in some tests, values of k_3 and k were observed to drop earlier in the test but the reason for this behavior is not clear.

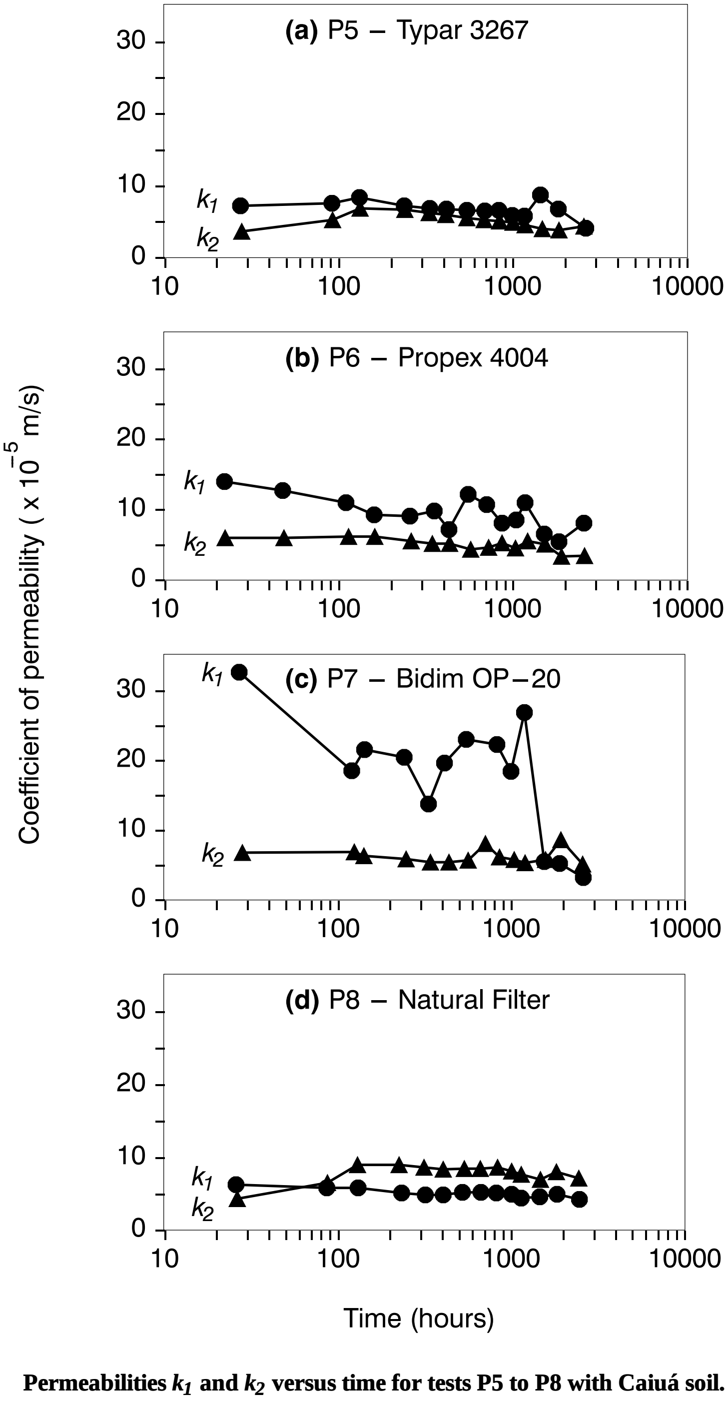

Figure 6. Permeabilities k_1 and k_2 versus time for tests P5 to P8 with Caiuá soil.

6.4 Water Quality Monitoring During the Tests

Results of pH and electrical conductivity measurements are reported in Table 6. At the start of the test a general decrease in the permeameter outlet pH is observed when compared to the reservoir pH. However, final pH values at the permeameter outlet increase and approach those of the reservoir inlet. The reason for these changes is that when the water passes through the soil it takes up protons. With the continuation of the process the available amount of hydrogen is exhausted and the pH of the permeameter outlet becomes close to that of the reservoir. An analogous explanation may be given for the electrical conductivity. Following the initial water-soil contact the electrical conductivity drops from 90 μS/cm to 70 μS/cm (microsiems/cm) due to physicochemical equilibrations (cation exchange, absorption and chemical reactions). As equilibrium is reached the electrical conductivity at the permeameter outlet approaches that of the reservoir.

The results presented in Figure 8 have been calculated from the turbidity measurements using the calibration curve from Figure 4. The results are presented in terms of $\overline{p}$, the accumulated weight of the fines passing through, normalized by the initial weight of the soil, versus $\overline{v}$, the accumulated volume of the water passing through, normalized by the initial volume of voids. These results allow assessment of the performance of the geotextiles with regard to their particle retention capability. It is seen that at the beginning of the tests there is an increase in the amount of fines passing through due to the pre-filter formation process. This is followed by a trend of stabilization of the amount of fines passing through as observed in all long term tests. The total percentage of fines is never greater than 0.1% of the initial weight of the soil. In these tests the granular filter returned the most effective performance with respect to particle retention capability. Although the loss of fines is small in all filtration tests, Typar 3267 and the natural filter show less long term loss of fines than Bidim OP-20 and Propex 4004, as can be clearly seen from the plot of the ratio $\overline{p} / \overline{v}$ against time in Figure 9.

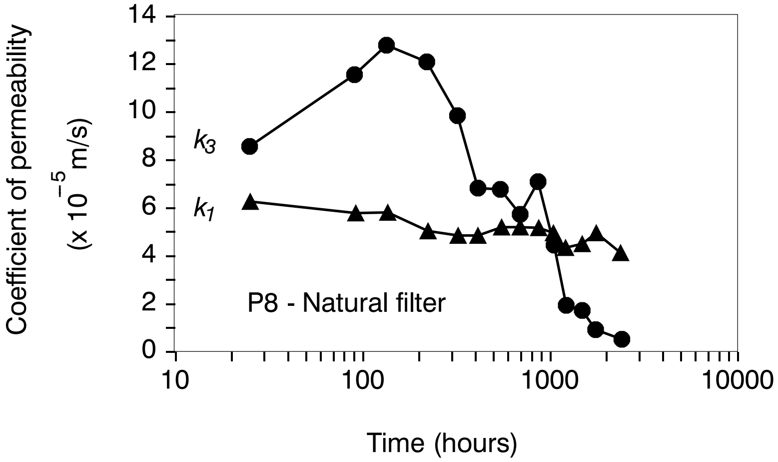

Figure 7. Permeabilities k_1 and k_3 versus time for test P8 with Caiuá soil.

Table 6. Physicochemical properties of percolation water (Caiuá soil).

Permeameter outlet	pH		electrical conductivity microsiems/cm (μS/cm)	
	initial	final	initial	final
P1	5.3	6.6	70	107
P2	5.7	6.5	73	110
P3	5.9	6.5	73	86
P4	5.8	6.8	71	80
P5	6.1	6.6	73	92
P6	6.5	6.7	79	101
P7	6.5	6.7	81	114
P8	6.3	6.4	75	83
reservoir	6.7	6.7	90	90

7 ASSESSMENT OF FILTER CRITERIA METHODS

The design specification for a particular geotextile can be made using one of several filter criteria methods which can be found in publications from several organizations: the Comité Français des Géotextiles et Géomembranes, CFGG (1986); the Franzius Instituts, Hannover (FIH), as described by Saathoff and Kohlhase (1986); Giroud (1982, 1988); the Federal Highway Administration (FHWA), as described by Christopher and Holtz (1985); IRIGM (Grenoble) in association with Ecole Polytechnique de Montréal (EPM), as described by Faure et al. (1986); and Mlynarek et al. (1990). The corresponding equations (for the current study) are shown in Table 7. All use a characteristic pore size of the geotextile which depends on the measurement technique. The techniques used in the above criteria are: AOS (apparent opening size); FOS (filtration opening size); and D_w (effective opening size). These measurement techniques have been described by Gourc and Faure (1990).

The above filter criteria have been applied to the materials used in this study and the results are presented in Table 7. All geotextiles proved to be efficient as far as their particle retention capabilities are concerned. This should lead in principle to the conclusion that they fulfill the criteria outlined above. However, application of the criteria according to CFGG, FHWA and FIH showed that this is not the case for the uniform sand. Only the criteria stipulated by IRIGM/EPM and by Giroud were satisfied by all three geotextiles tested. The IRIGM/EPM criteria is also the best one when used for the Caiuá soil

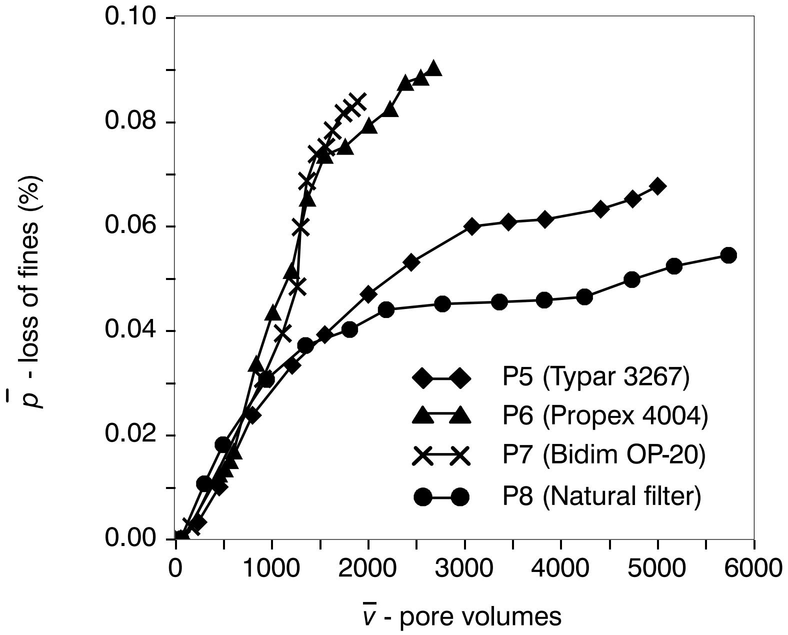

Figure 8. Loss of fines versus pore volumes.

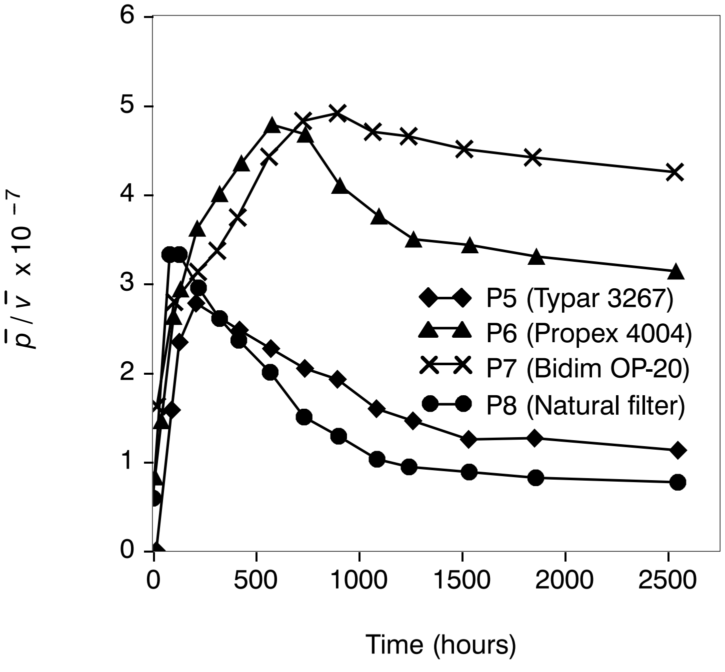

Figure 9. Variation of the ratio $\bar{p} / \bar{v}$ with time.

(Table 7). The remaining criteria are not satisfied by at least two of the geotextiles tested.

In addition, some filter criteria require that the permeability of the geotextile, k_g , be at least N times greater than the soil permeability k_s , hence:

$$k_g > Nk_s \tag{2}$$

Table 7. Assessment of filter criteria methods.

Uniform sand			
Criterion	Geotextile		
Origin [equation]	Typar 3267	Propex 4004	Bidim OP-20
CFGG [$FOS < C_1\ C_2\ C_3\ C_4\ d_{85}$]	250 < 273 (Y)	400 < 273 (N)	130 < 273 (Y)
FHWA [$AOS < B\ d_{85}$]	250 < 273 (Y)	400 < 273 (N)	130 < 273 (Y)
IRIGM/EPM [$FOS < 1.5\ d_{85}$]	250 < 405 (Y)	400 < 405 (Y)	130 < 405 (Y)
Giroud [$AOS < 2(C'_u)^{0.3}\ d_{85}$]	250 < 624 (Y)	400 < 624 (Y)	130 < 624 (Y)
FIH [$D_w < d_{90}$]	240 < 287 (Y)	400 < 287 (N)	130 < 287 (Y)
Mlynarek [$2d_{15} < AOS < 2d_{85}$]	340<250<546 (n)	340<400<546 (Y)	340<130<546 (n)
Caiuá soil			
Criterion	Geotextile		
Origin [equation]	Typar 3267	Propex 4004	Bidim OP-20
CFGG [$FOS < C_1\ C_2\ C_3\ C_4\ d_{85}$]	250 < 122 (N)	400 < 122 (N)	130 < 122 (N)
FHWA [$AOS < B\ d_{85}$]	250 < 190 (N)	400 < 190 (N)	130 < 190 (Y)
IRIGM/EPM [$FOS < 1.5\ d_{85}$]	250 < 285 (Y)	400 < 285 (N)	130 < 285 (Y)
Giroud [$AOS < 2(C'_u)^{0.3}\ d_{85}$]	250 < 230 (N)	400 < 230 (N)	130 < 230 (Y)
FIH [$D_w < d_{90}$]	240 < 200 (N)	400 < 200 (N)	130 < 200 (Y)
Mlynarek [$2d_{15} < AOS < 2d_{85}$]	2<250<380 (Y)	2<400<380 (N)	2<130<380 (Y)

Note: (Y) criterion satisfied; (N) criterion not satisfied; (n) criterion not satisfied at the lower limit; $C'_u = d'_{60}/d'_{10}$.

Table 8. Values of the maximum gradient ratio, *GR*.

Permeameter	Filter	Uniform sand	Caiuá soil
P1	Typar 3267	1.0	1.88
P2	Propex 4004	0.5	1.08
P3	Bidim OP-20	0.8	0.40
P4	natural filter	-	1.35
P5	Typar 3267	0.9	1.00
P6	Propex 4004	0.8	0.76
P7	Bidim OP-20	0.6	1.76
P8	natural filter	-	1.81

This equation has been adopted by CFGG, FHWA and Giroud with each assigning a particular value for the factor N dependent on the hydraulic gradient of interest and soil type. For the CFGG, N is also dependent on the geotextile thickness. The application of these three criteria and corresponding recommended N value, demonstrates that all of them are satisfied for all tests presented here.

The gradient ratio (*GR*), (Calhoun 1972; Haliburton and Wood 1982) has been used as a direct measure of the clogging potential of granular soils. It is defined as $GR = i_1/i_2$, where i_1 and i_2 are the hydraulic gradients to compute k_1 and k_2 respectively. Maximum values of *GR* observed during filtration tests are shown in Table 8. They are in the range 0.50 to 1.00 for the uniform sand, 0.40 to 1.88 for the Caiuá soil, and are smaller than the critical value of 3.0 for severe applications. Thus it is confirmed that clogging is not a problem for the uniform sand. Although the assessment of the clogging potential by means of *GR* values is not strictly applicable to clayey fine sands, the values obtained confirm the results of long term filtration tests in which clogging did not occur.

8 CONCLUSIONS

The studies reported here regarding long term filtration tests with a uniform sand and a clayey fine sand (Caiuá soil) have shown that the three geotextiles investigated performed adequately with respect to drainage, particle retention and clogging. The clayey fine sand was tested at a rather low density corresponding to a state more critical than the field condition. Water quality analysis of the percolated water and the variation of the permeability of the soil-geotextile system suggests that a pre-filter was formed in the tests with the Caiuá soil.

The current view that geotextile filter criteria are generally conservative was confirmed in this study. Six criteria were assessed. The criteria proposed by IRIGM/EPM was best able to predict the performance of all the tests with geotextiles. Long term tests appear to be an effective tool to assess clogging potential of fine soils. However, a sound interpretation of the test results will require parallel chemical and bacteriological studies.

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NOTATIONS

Basic SI units are given in parentheses.

D_w = effective opening size (m)
e_f = final void ratio (dimensionless)
e_i = initial void ratio (dimensionless)
i = hydraulic gradient (dimensionless)
k = average permeability of entire system (m/s)
k_g = geotextile permeability (m/s)
k_s = soil permeability (m/s)
k_1 = permeability at soil-geotextile interface (m/s)
k_2 = soil permeability at middle of permeameter (m/s)
k_3 = soil permeability at upper third of permeameter (m/s)
$\overline{p}$ = portion of soil lost through geotextile (%)
$\overline{v}$ = pore volumes (dimensionless)

ABBREVIATIONS

AOS: apparent opening size (m)
CFGG: Comité Français des Géotextiles et Géomembranes
COPPE: Coordenação dos Programas de Pós-Graduação de Engenharia
EPM: Ecole Polytechnique de Montréal
FHWA: Federal Highway Administration
FIH: Franzius Instituts, Hannover
FOS: filtration opening size (m)
GR: gradient ratio (dimensionless)
IRIGM: Institut de Recherche Interdisciplinaires de Géologie et Mécanique
PVC: polyvinyl chloride
UTF: universal turbidimetric factor