Opening sizes and filtration behaviour of nonwoven geotextiles under confined and partial clogging conditions

E. M. Palmeira[1] and H. L. Trejos Galvis[2]

[1]*Professor, Department of Civil and Environmental Engineering, University of Brasília, Brasília, DF, Brazil, E-mail: palmeira@unb.br (corresponding author)*
[2]*Civil Engineer, Geotecnica S.A.S., Sabaneta-Antioquia, Colombia, E-mail: heydytrejos@gmail.com*

Received 13 June 2016, revised 02 August 2016, accepted 08 August 2016, published 23 September 2016

ABSTRACT: Nonwoven geotextiles have been used as filters for over four decades in geotechnical and geoenvironmental works. These products have a complex fibre matrix and their behaviour as filters depends on how this matrix interacts with fluids and soil particles. Therefore, uncertainties still exist regarding prediction of geotextile filter performance under severe and critical situations. This paper investigates how confinement and partial clogging influence the dimensions of openings in nonwoven geotextiles. Bubble point (BBP) tests were carried out on six nonwoven geotextiles under unconfined and confined (equivalent vertical stresses of up to 1000 kPa) conditions with and without partial clogging of the geotextile. The results obtained show significant influences of confinement and partial clogging on geotextile opening dimensions and retention capacity. The results of O_{95} from bubble point tests on unconfined and virgin specimens compared well with results from hydrodynamic tests. Comparisons between BBP results and data from filtration tests under confinement are also presented and discussed. The repercussions of reductions in opening size caused by confinement and partial clogging on geotextile clogging potential and filter criteria are discussed.

KEYWORDS: Geosynthetics, Geotextiles, Opening sizes, Filtration, Confinement, Clogging, Bubble point test

REFERENCE: 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**, No. 2, 125–138. [http://dx.doi.org/10.1680/jgein.16.00021]

1. INTRODUCTION

Geotextiles have been used extensively as filters in geotechnical and geoenvironmental engineering. The main reasons for such intense use are consequences of them being quick and easy to install, their less specialised labour requirements and environmental benefits from avoiding or reducing the exploitation and use of natural filter materials. Additional environmental benefits reported in the literature are fewer impacts to the environment in comparison with their natural counterparts. Frischknecht *et al.* (2012) report that the use of a geotextile filter in a pavement may produce over 85% less impact than a traditional granular filter with respect to parameters such as acidification, eutrophication, emissions of gases that contribute to global warming and energy (renewable or not) and water demands.

There are a variety of situations, some of them very complex, critical or severe that may lead to clogging of either geotextile or granular filters (Koerner and Koerner 2015). Despite their general use, the specification of a geotextile filter is still based on heavily empirical approaches regarding retention, clogging and permeability criteria. Most criteria were developed based on the results of filtration tests that did not necessarily reproduce actual filter conditions. Important theoretical contributions to the prediction of relevant filter properties are available in the literature (Laflaive and Puig 1974; Fayoux and Evon 1982; Masounave *et al.* 1980a, 1980b; Faure *et al.* 1989; Giroud 1996), but their accuracies are still to be properly demonstrated in a wide range of field situations.

Some aspects that may influence the filter characteristics of a geotextile that are not considered in current filter criteria are confinement, partial clogging and bedding conditions. Confinement reduces the size of the geotextile pores, so tests under unconfined conditions may be viewed as conservative in the sense that the filter will present less retention capacity than when confined by soil. Results of filtration tests under confinement (Palmeira *et al.* 1996; Gardoni 2000; Gardoni and Palmeira 2002; Palmeira and Gardoni 2002) have shown that the size of soil particles capable of passing through the geotextile filter can be significantly reduced due to confinement.

However, the reduction in pore size also has repercussions for filter clogging potential. Regarding the latter, the geotextile filter has to allow the passage of some amount of soil particles without compromising the system stability in order to avoid filter blinding or internal clogging. In the case of applications where biological clogging may take place, such as in landfill drainage systems, the reduction of geotextile pore size is likely to accelerate biological clogging.

Partial clogging is another mechanism that can increase geotextile retention capacity and reduce the available pore space. Partial clogging can take place during spreading and compaction of soil on the geotextile filter layer and is more relevant for fine-grained cohesionless soils (Palmeira and Gardoni 2000). Values of geotextile impregnation levels (λ), defined as the ratio between the mass of soil particles in the geotextile voids and the mass of geotextile fibres (Palmeira *et al.* 1996), ranging between 0.2 and 15 can be found in the literature under laboratory and field conditions (Palmeira and Gardoni 2000; Palmeira *et al.* 2005, 2010; Moraci *et al.* 2016), although in most of the cases reported λ values are typically smaller than 4. Thus in the field, when water flow starts, the geotextile filter will be under different conditions to those present in current laboratory tests. Partial clogging can also take place during the life of the work due to the action of seepage forces, which carry soil particles that become entrapped in the geotextile pores. Geotextile bedding conditions can also influence their retention capacity. Sagging of the geotextile filter in the voids between particles of coarse drainage materials (gravels or stones) can increase geotextile openings and reduce their retention capacity, as observed by Palmeira *et al.* (2012) in tests on nonwoven geotextile filters overlying different bedding materials.

Several experimental procedures are available for the measurement of geotextile opening sizes in the laboratory. The most commonly used are sieving techniques (ASTM D4751-12, ISO 12956-2012 (ISO 2009), CGSB 148.1 No. 10-94 (CGSB 1994), for instance) because they are less expensive, easy and quick to perform. However, large scatter among test results can be obtained depending on the product characteristics and experimental technique employed (Rigo *et al.* 1990; Fischer 1994; Bhatia and Smith 1996a, 1996b; Dierickx and Myles 1996; Blond *et al.* 2015). Blond *et al.* (2015) present and discuss advantages and limitations of different experimental techniques for the determination of geotextile opening sizes. More complex experimental procedures include the use of image analysis (Elsharief and Lovell 1996; Aydilek *et al.* 2002; Gardoni and Palmeira 2002) and fluid intrusion methods (Bhatia and Smith 1995; Fischer *et al.* 1996; Veermersch and Mlynarek 1996; Elton *et al.* 2006; Eun and Tinjium 2011), which are more time consuming or require the use of more sophisticated equipment.

The bubble point test (BBP) is one testing technique available for determining the constriction size distribution curves of geotextiles. In this test, the equivalent diameters of the constrictions are obtained based on measurements of the fluid pressures required to overcome the capillary attraction of the fluid in the pores. The advantages of the BBP test in comparison with other testing techniques are that it is quick to perform, simulates the flow of fluid in the geotextile flow channels, and its results are repeatable (Fischer *et al.* 1996). Geotextile normal permeability coefficient can also be obtained in BBP tests, whose results have compared well with those from conventional permittivity tests (Palmeira and Gardoni 2002).

This paper investigates the variation in geotextile pore dimensions of nonwoven geotextiles under confined and partial clogging conditions using the Bubble point test (BBP). The study aimed at contributing to a better understanding of the influence of factors that may affect the performance of geotextile filters in the field. In the following sections the experimental methodology and test results are presented and discussed.

2. EXPERIMENTAL

2.1. Equipment

Bubble point test (BBP) equipment was manufactured and employed in the test programme. Figure 1 presents the equipment, which consists of a testing cell and peripheral components including a data acquisition system, pressurised air supply system, pressure control valves, water head columns and a flow meter. The testing cell had an internal diameter of 60 mm and was made of stainless steel. During a test, the geotextile specimen was placed on a perforated plate. For each specimen, dry and saturated tests were carried out. Denatured alcohol (with a surface tension of 22.1 mN/m at 20°C) was used to saturate the specimens and the tests were carried out as per ASTM 6767. In dry tests, the air pressure was incrementally increased and the air flow rate measured with the flow meter. To increase accuracy, water head columns were used for measuring low pressures.

Before the tests with geotextiles, the accuracy of the results obtained with the equipment was evaluated by testing steel meshes with known aperture dimensions.

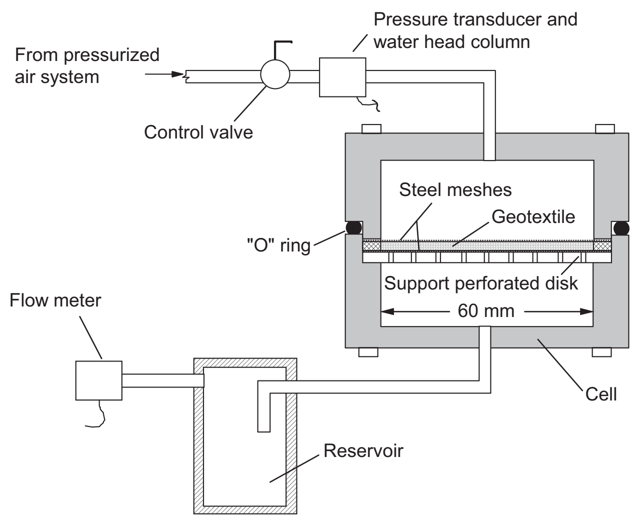

Figure 1. Bubble point test equipment used

Tests were performed on meshes with apertures of 0.075 mm and 0.090 mm (Silva 2014; Trejos-Galvis 2016). The differences between actual aperture dimensions and BBP test measurements were smaller than 5%, which can be considered quite satisfactory for the purposes of the study. The repeatability of the results of BBP tests on geotextiles was assessed by repeating tests on some of the geotextiles used in the research. Coefficients of variation obtained for these results were smaller than 1.5%.

2.2. Sample preparation

To simulate the conditions of the geotextile specimen under confinement, initially a series of compression tests on the geotextiles used in the experiments was conducted to measure the variation of geotextile thickness with normal stress for virgin and partially clogged geotextiles. Some results obtained in tests on virgin specimens are presented in Figure 2a. Figure 2b shows the results for partially clogged specimens of geotextile G3 for different levels of impregnation λ (the ratio between masses of entrapped soil particles and of geotextile fibres). Thus, in the BBP test equipment, the geotextile specimen was installed compressed between two rigid wire meshes with a given thickness. The normal stress yielding to that geotextile thickness could then be obtained from the thickness versus the normal stress relationship for the geotextile (e.g. Figure 2). The top and bottom wire meshes were tied to each other by seaming at specific points along the meshes' edges.

The test procedure was the same for virgin and partially clogged geotextiles. For the latter tests, the geotextile specimens were impregnated with glass beads. To partially clog the geotextile, the beads were uniformly distributed on the surface of the specimen, which was then subjected to vibration to favour the penetration of the beads into the geotextile voids. Different amounts of beads and vibration durations resulted in different values of λ.

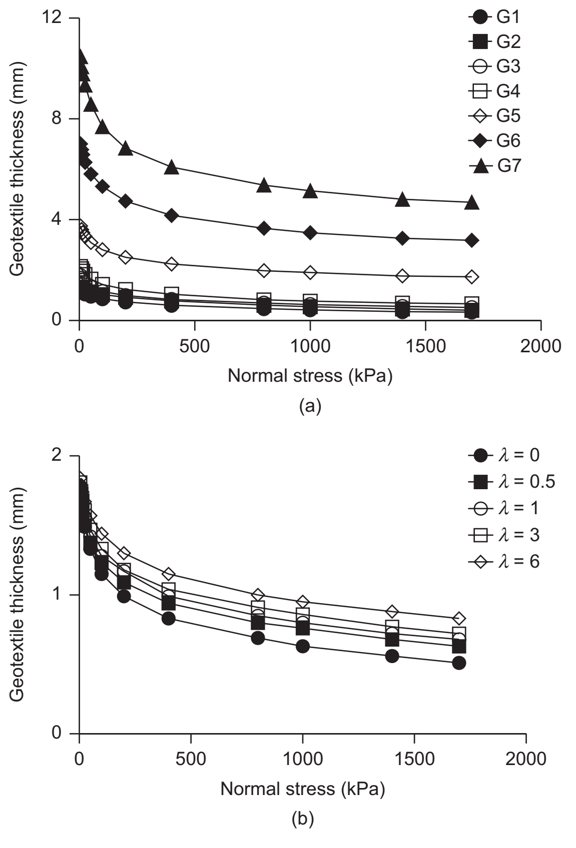

Figure 2. Results of uniaxial compression tests on virgin and partially clogged geotextile specimens. (a) Virgin geotextiles; (b) Partially clogged – Geotextile G3

2.3. Materials

Seven nonwoven geotextiles (codes G1 to G7) were tested as part of the research programme. Table 1 presents the main properties of these geotextiles. A wide range of geotextile mass per unit area (M_A) was investigated (200 g/m^2 to 1800 g/m^2). Geotextiles G1 and G2 were manufactured from polypropylene fibres, while the others were manufactured from polyester fibres. The thickness of the geotextiles under 2 kPa normal stress varied between 1.2 mm and 11 mm. The filtration opening size (FOS) of geotextiles G1 to G5 obtained in hydrodynamic sieving tests (CFG 1986, CGSB 148.1 No. 10-94 (CGSB 1994)) varied between 0.06 mm and 0.130 mm, according to the manufacturer's catalogue. To investigate the behaviour of thicker geotextiles, geotextiles G6 (1200 g/m^2) and G7 (1800 g/m^2) were assembled by stacking two and three layers of geotextile G5 (600 g/m^2), respectively.

The diameters of the glass beads used to impregnate the geotextile voids for tests on partially clogged specimens varied between 0.04 mm and 0.137 mm, with a coefficient of uniformity of 1.3. Values of λ in the range 0.5 to 3 were obtained, which is compatible with measurements in other laboratory studies and in geotextile specimens exhumed in the field (Palmeira and Gardoni 2000). The thicker the geotextile, the harder it is to obtain larger values of λ. For the geotextiles with greater mass per unit area (G5, G6 and G7) particle impregnation was concentrated close to the surface of the specimen, not uniformly distributed along its thickness. Therefore, only values of λ less or equal to 1 were obtained for those geotextiles with the impregnation technique employed. Figure 3 shows images of some partially clogged geotextile specimens for different values of λ.

3. RESULTS

3.1. Tests on virgin geotextiles

Figure 4 shows some typical results of distribution of geotextile opening dimensions for different geotextile thicknesses or corresponding normal stresses for geotextiles G1 and G4. As expected, geotextile openings decrease in size with increasing normal stress. Similar results were obtained for the other geotextiles tested. From curves such as those shown in Figure 4, one can obtain some characteristic values of geotextile opening diameters, of which the most commonly used in practice regarding filtration criteria are O_{95} and O_{98}.

Table 1. Properties of the geotextiles tested

Code	Polymer[1]	$M_A^{(2)}$ (g/m^2)	t_{GT} (mm)	FOS (mm)	k_n (cm/s)	ψ (s^{-1})
G1	PP	200	1.2	0.130	0.4	2.8
G2	PP	300	1.4	0.110	0.4	1.9
G3	PET	200	1.9	0.180	0.4	2.0
G4	PET	300	2.3	0.110	0.4	1.5
G5	PET	600	4.0	0.060[3]	0.4	0.9
G6	PET	1200	7.3	NA[4]	NA	NA
G7	PET	1800	11.0	NA	NA	NA
GTY	PET	180	1.9	0.140	0.4	2.1

Notes: (1) PP, polypropylene; PET, polyester; (2) M_A, mass per unit area; t_{GT}, geotextile thickness at 2 kPa vertical stress; FOS, geotextile filtration opening size from hydrodynamic sieving tests (AFNOR G38017; CFG 1986); k_n, normal coefficient of permeability; ψ, permittivity; (3) Average value of FOS of 0.095 mm in later manufacturer's catalogue; (4) NA, not available; All data from manufacturer's catalogue.

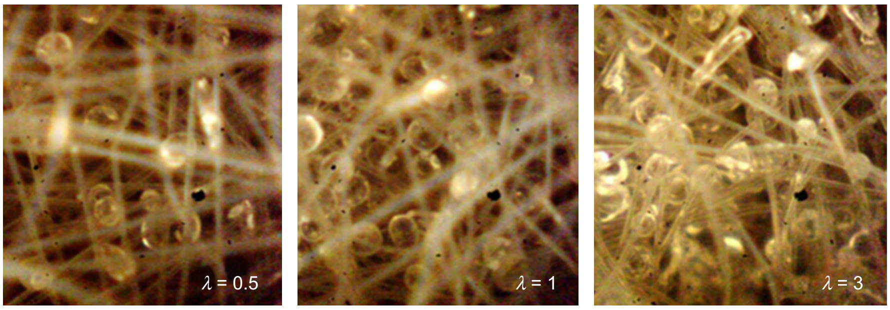

Figure 3. Images of partially clogged geotextile specimens for λ between 0.5 and 3 (enlarged 200 times)

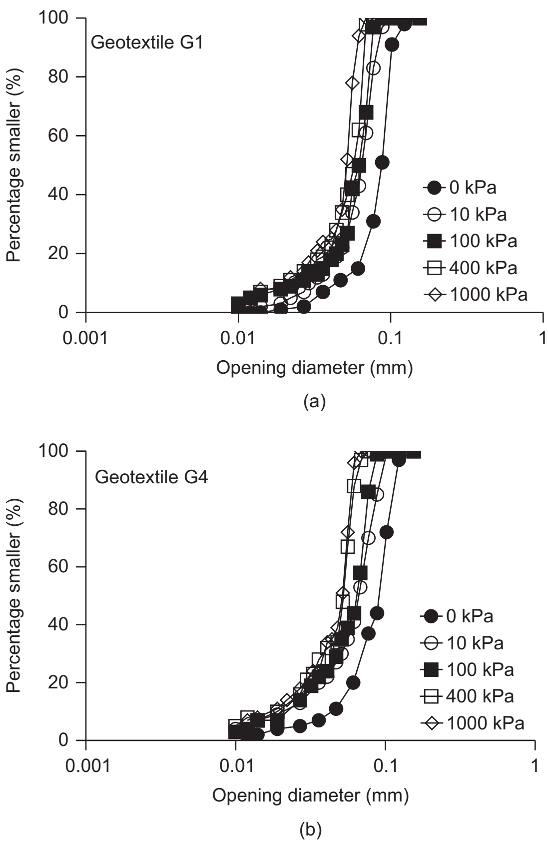

Figure 4. Pore size distribution curves for geotextiles G1 and G4. (a) G1; (b) G4

Figure 5a and b present the variation of O_{95} and O_{98} normalised by the geotextile fibre diameter (d_f, equal to 0.027 mm for geotextiles G3 to G7 and 0.037 mm for geotextiles G1 and G2) with normal stress for virgin geotextile specimens. A significant reduction of opening dimensions can be noted up to confining stresses of 100 kPa, and the lighter the geotextile the greater the relative reduction in opening diameters. Ratios O_{95}/d_f and O_{98}/d_f between 2.5 and 5.4 and 2.7 and 5.6, respectively, can be observed for tests without confinement depending on the geotextile considered. For the test under the largest vertical stress applied (1000 kPa), those ranges were 1.7 to 2.7 and 1.7 to 2.8. Therefore, the ranges of variation of O_{95}/d_f and O_{98}/d_f for the products tested were close. The ratio between O_{98} and O_{95} obtained for the geotextiles tested varied between 1.03 and 1.08, with O_{98}/O_{95} below 1.05 in 70% of the cases.

3.2. Tests on partially clogged geotextiles

The variation of normalised pore opening diameters (O_{95}/d_f and O_{98}/d_f) with level of impregnation (λ) obtained in tests without confinement ($\sigma = 0$) are depicted in Figure 6a and b. The opening diameters decrease as the impregnation level of the geotextile increases. The result of a test on geotextile G3 for which a value of λ of 6 was achieved is also presented, which suggests a smaller rate of decrease in O_{95}/d_f and in O_{98}/d_f with increasing values of λ under unconfined conditions.

The combination of confinement and partial clogging reduces the pore dimensions even further. Figure 7 shows the variation of O_{95}/d_f with normal stress for different impregnation levels in tests on geotextile G3

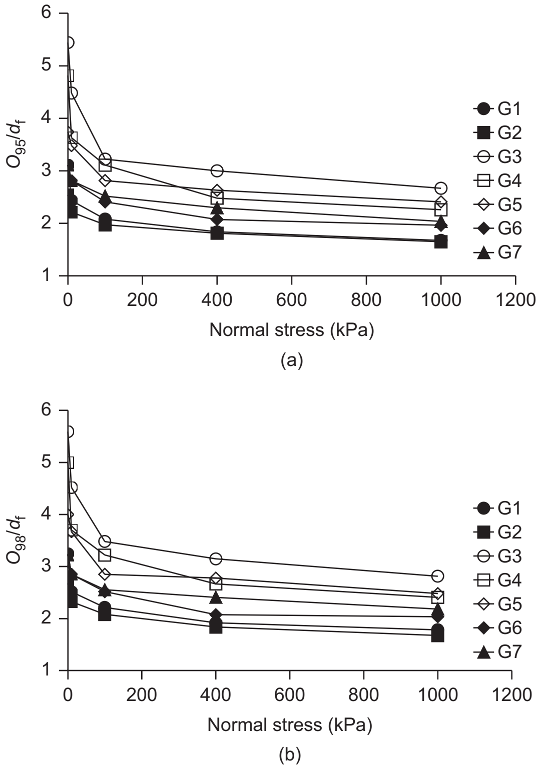

Figure 5. Variation of O_{95}/d_f and O_{98}/d_f with normal stress for virgin geotextile specimens. (a) O_{95}/d_f versus normal stress; (b) O_{98}/d_f versus normal stress

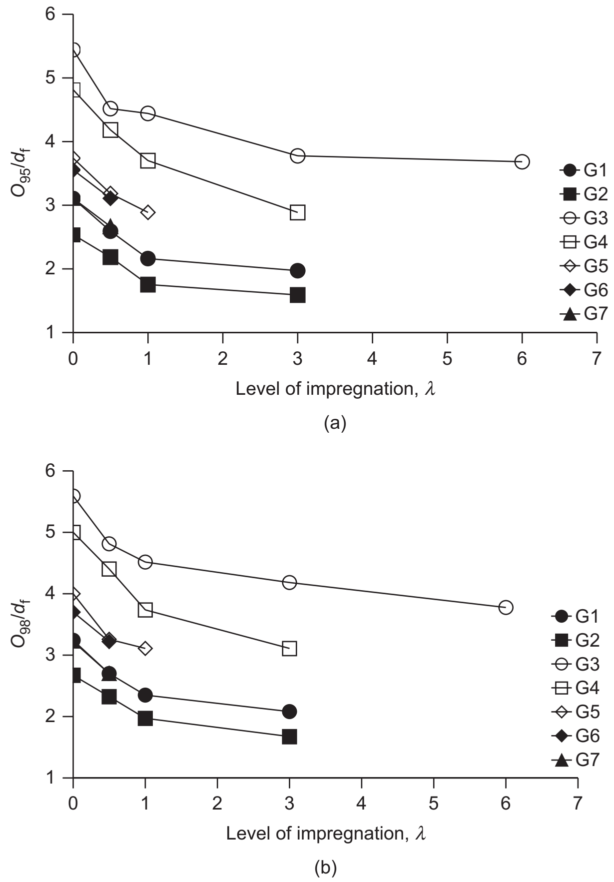

Figure 6. Variation of O_{95}/d_f and O_{98}/d_f with geotextile impregnation level – unconfined specimens, (a) O_{95}/d_f vs. λ; (b) O_{98}/d_f vs. λ

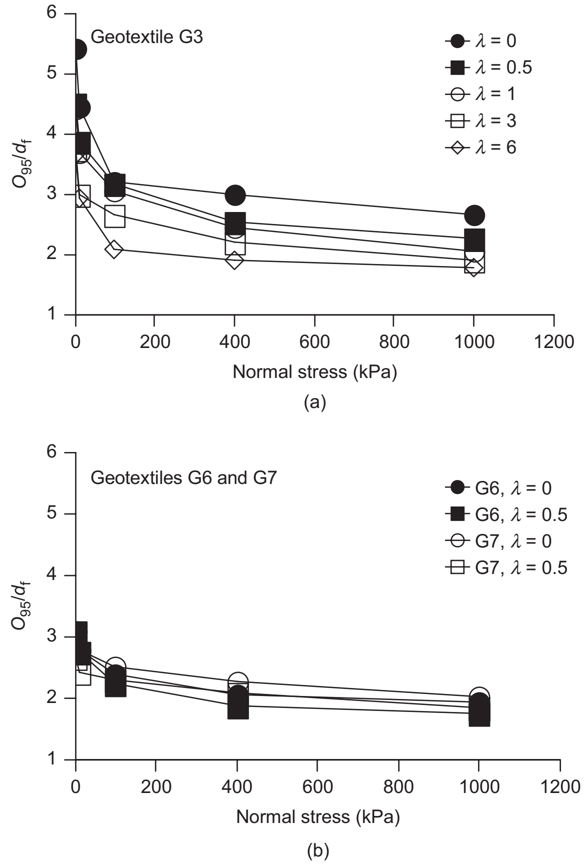

Figure 7. Influence of partial clogging and confinement, (a) geotextile G3; (b) geotextiles G6 and G7

($M_A = 200$ g/m^2) and geotextiles G6 ($M_A = 1200$ g/m^2) and G7 ($M_A = 1800$ g/m^2). The results show that the combined effect of confinement and partial clogging was more significant for the light and thin geotextile (Figure 7a). As mentioned before, impregnation of thicker geotextiles was concentrated close to the surface and only low values of λ were achieved. So, there were no significant differences between the results of tests with geotextiles G6 and G7, as shown in Figure 7b. In the case of partially clogged geotextiles, the ratio between O_{98} and O_{95} varied typically between 1.03 and 1.12, with O_{98}/O_{95} below 1.1 in 93% of the cases.

3.3. Comparisons between predicted and measured geotextile opening dimensions

3.3.1. *Virgin geotextiles*

Giroud (1996) presented the following equation for the prediction of geotextile filtration opening size as a function of some of its physical properties:

$$\frac{O_F}{d_f} = \frac{\delta}{\sqrt{1-n}} - 1 + \frac{\xi n}{(1-n)t_{GT}/d_f} \qquad (1)$$

where O_F is the geotextile filtration opening size, d_f is the fibre diameter, n is the geotextile porosity, t_{GT} is the geotextile thickness and δ and ξ are empirical parameters.

Equation (1) was proposed by Giroud (1996) based on an extension of geometrical models for geotextile filters simulated as multidirectional fibre arrangements (Laflaive and Puig 1974; Fayoux and Evon 1982). In the geometrical models, δ can vary between 0.89 and 1.65, depending on the model considered. Giroud (1996) adopted a value of δ equal to 1 in equation (1). Based on comparisons between predictions by equation (1) and the results of hydrodynamic sieving tests, Giroud suggested a value of ξ equal to 10. Gardoni and Palmeira (2002) found best agreement between predictions by equation (1) and measurements of maximum diameters of particles that piped through nonwoven geotextiles in gradient ratio tests for ξ equal to 15.

The comparison between filtration opening sizes predicted by equation (1) and measured values (assumed as O_{98}) in BBP tests on virgin specimens showed that best agreement was achieved with different values of δ in equation (1), depending on the polymer used in the geotextile manufacture and on the geotextile mass per unit area. Figure 8a shows comparisons between predicted O_F/d_f and measured O_{98}/d_f values under varying levels of confinement for the lighter ($M_A \leq 300$ g/m^2) geotextiles tested. Reasonably good agreement between predictions and measurements was achieved when $\delta = 1$ and $\xi = 12.5$ were adopted for the polypropylene geotextiles G1 and G2 and $\delta = 1$ and $\xi = 15$ were adopted for the polyester geotextiles G3 and G4. For the heavier polyester geotextiles ($M_A \geq 600$ g/m^2) G5 to G7, best agreement between predictions and measurements was obtained for δ equal to 1.34 and ξ equal to 15, as shown in Figure 8b. Therefore, the results suggest that polymer type and thickness (or mass per unit area) influence the values of δ and ξ to be used in equation (1). Less scatter can also be noticed in predictions for thicker geotextiles (Figure 8b), which may be a consequence of greater uniformity in fibre distribution in thicker nonwoven geotextile products in comparison with lighter ones.

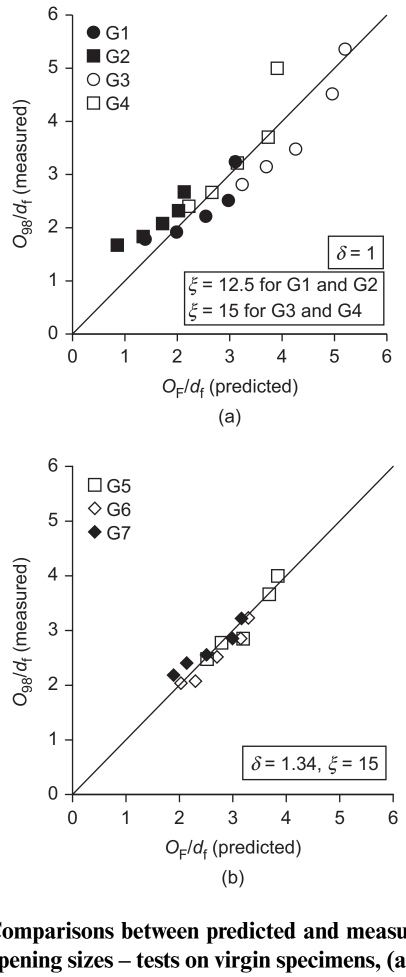

Figure 8. Comparisons between predicted and measured geotextile opening sizes – tests on virgin specimens, (a) geotextiles G1 to G4; (b) geotextiles G5 to G7

3.3.2. *Partially clogged geotextiles*

An interesting exercise would be to assess how accurate equation (1) would be if used to predict the filtration opening sizes of partially clogged geotextiles. In this case, the value of the filter porosity used in that equation was the one obtained considering the presence of the glass beads in the geotextile voids. This value of porosity is given by:

$$n' = 1 - (1 - n)\left(1 + \frac{\rho_f}{\rho_s}\lambda\right) \tag{2}$$

where n' is the remaining average filter porosity taking into account the presence of the solid particles (glass beads) in the geotextile voids, n is the porosity the geotextile would have for the same thickness not considering the presence of the solid particles in its voids, λ is the geotextile impregnation level, ρ_f is the geotextile fibre density and ρ_s is the density of the solid particles (equal to 2500 kg/m^3 for the glass beads used in the tests).

Figure 9a and b show comparisons between predictions using equations (1) and (2) and measurements from bubble point tests on partially clogged geotextiles under different levels of confinement and λ. Figure 9a presents the results for lighter geotextiles (G1 to G4), where best agreement was obtained for polypropylene geotextiles G1 and G2 for values of δ and ξ of 1.25 and 12.5, respectively. For the polyester geotextiles G3 and G4, best agreement was achieved for δ equal to 1 and ξ equal to 15, which are the same values obtained for virgin specimens. Figure 9b shows that good agreement between predictions and measurements for geotextiles G5 to G7 was obtained for values of δ equal to 1.38 and ξ equal to 15, which are very close or equal to those obtained for virgin specimens ($\delta = 1.34$ and $\xi = 15$).

Figure 8 and Figure 9 show values of O_{98}/d_f between 1.6 and 5.6 for virgin geotextiles and between 1.2 and 4.8 for partially clogged geotextiles. These ranges yield to values of O_{98} between 0.043 mm and 0.151 mm for virgin geotextiles and between 0.032 mm and 0.130 mm for partially clogged ones. These opening dimensions fall within the range of particle sizes of silts and fine sands (particle diameters between 0.002 mm and 0.2 mm). This explains to some extent why cohesionless silts and fine sands can cause clogging of geotextile filters, and highlights the need for due care in the specification of geotextile filters in contact with such cohesionless fine-grained soils and internally unstable soils where particles with diameters within those ranges may be carried towards the filter layer. Koerner and Koerner (2015)

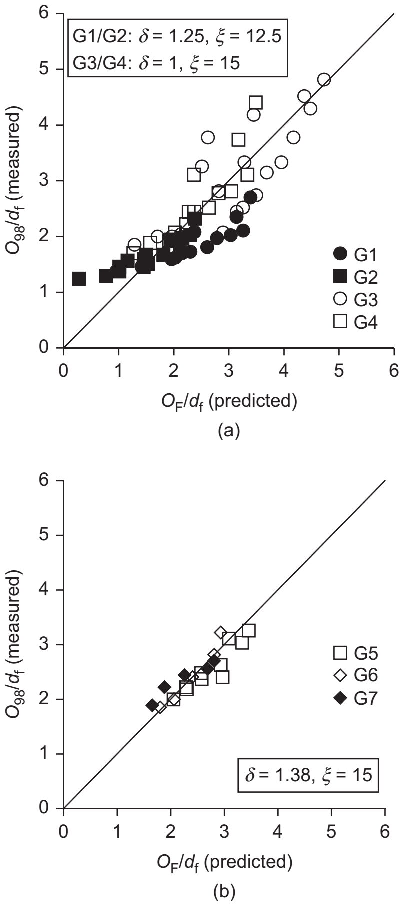

Figure 9. Comparisons between predicted and measured geotextile opening sizes – tests on partially clogged specimens, (a) geotextiles G1 to G4; (b) geotextiles G5 to G7

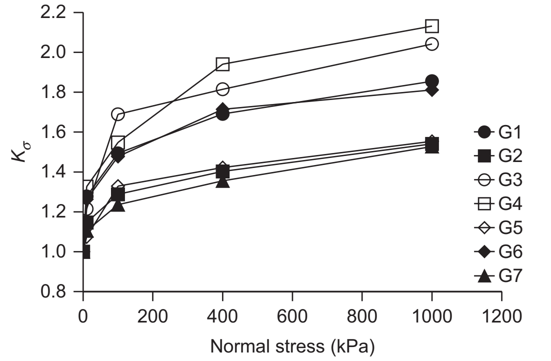

Figure 10. Reduction factor for confinement versus vertical stress

present and discuss some case histories of clogging of geotextile filters in contact with fine-grained cohesionless soils.

3.4. Reduction factors for confinement and partial clogging

Palmeira and Gardoni (2002) proposed that under confined and partially clogged conditions, the largest opening size of a nonwoven geotextile (assumed equal to O_{95}) could be expressed as:

$$O_{95}^{*} = \frac{O_{95}}{K_{\sigma} K_{\text{pc}}} \tag{3}$$

where O_{95}^{*} is the geotextile opening size under confinement and partial clogging, O_{95} is the geotextile opening size under unconfined ($\sigma = 0$) and virgin ($\lambda = 0$) conditions, K_{σ} is a reduction factor to account for confinement and K_{pc} is a reduction factor to account for partial clogging.

The results obtained in the bubble point tests reported in this work can be used to assess the values of K_{σ} and K_{pc}. Figure 10 shows the results of K_{σ} as a function of the vertical stress from tests on virgin geotextiles. The value of K_{σ} increases with vertical stress at a greater rate up to 100 kPa, which is consistent with a more compressible behaviour of the geotextile under such a stress level (Figure 2). The results show that for the lighter geotextiles G1 to G4, the value of K_{σ} varied between 1.2 and 2.13 in the range of vertical stress of 10 kPa to 1000 kPa. For the thicker geotextiles G5 to G7, the value of K_{σ} varied between 1.07 and 1.81 for the same stress range.

The products $K_{\sigma}K_{\text{pc}}$, taking into account confinement and partial clogging versus vertical stress for geotextiles G3 (300 g/m^2) and G5 (600 g/m^2), are shown in Figure 11a and b. Similar results were obtained for the other geotextiles tested. The combined effect of confinement and partial clogging resulted in $K_{\sigma}K_{\text{pc}}$ values between 1 and 3 depending on the geotextile, vertical stress and impregnation level considered. The value of $K_{\sigma}K_{\text{pc}}$ increases at a greater rate for values of vertical stress

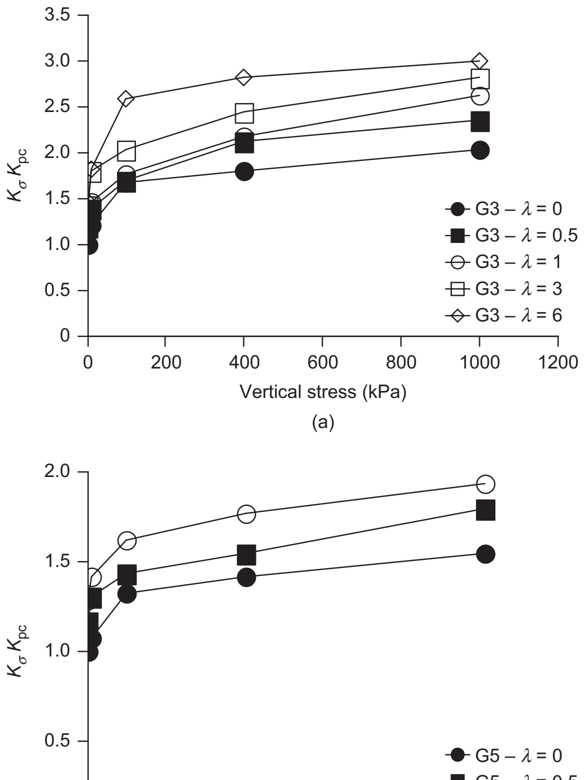

Figure 11. $K_{\sigma}K_{\text{pc}}$ versus vertical stress, (a) geotextile G3; (b) geotextile G5

up to 100 kPa, below which the geotextile is more compressible (Figure 2).

From the value of the product $K_\sigma K_{pc}$ the value of K_{pc} alone can be estimated. However, the value of K_σ for a partially clogged geotextile is also needed in the calculations. This value can be estimated using equation (1) to predict O_{95} for the geotextile with the same thickness under virgin conditions (porosity calculated not considering the presence of the entrapped particles) and the value of O_{95} for the geotextile under unconfined ($\sigma = 0$) and virgin ($\lambda = 0$) conditions. Thus, the value of K_{pc} can be estimated with the predicted K_σ and the product between reduction factors (Figure 11). It should be pointed out that the accuracy of this exercise is bounded by the accuracy of predictions by equation (1).

Figure 12a–c present the values of K_{pc} estimated as described above for geotextiles G3, G4 and G5. As expected, the smaller the values of λ, the smaller the values of K_{pc}. The value of K_{pc} is greater for the lighter and thinner geotextiles G3 and G4. Figure 13 shows the ranges of variation of K_{pc} for the geotextiles tested and for the ranges of values of λ and σ used. For the lighter geotextiles G1 to G4, the value of K_{pc} varied between 1 and 1.9 for λ in the range 0 to 3 and vertical stresses between 0 and 1000 kPa. For the thicker geotextiles G5 to G7, K_{pc} varied between 1 and 1.3 for λ in the range 0 to 1 and vertical stresses between 0 and 1000 kPa. It should be noted that the value of K_{pc} decreased with the increase in geotextile mass per unit area for both types of polymeric products tested (G1 and G2, polypropylene geotextiles, and G3 to G7, polyester geotextiles). The lower values of K_{pc} for the thicker geotextiles are associated to some extent with lesser impregnation of glass beads into these geotextiles, besides the impregnation having been concentrated close to the surface of the geotextiles as mentioned earlier in this paper.

The results in Figures 10–13 suggest that a reduction factor to be applied to the opening size of a virgin and unconfined geotextile to account for confinement may reach as much as 2.2. Regarding the influence of partial clogging, the reduction factor to account for this mechanism may reach as much as 2.2, depending on the geotextile type, characteristics and level of impregnation.

It should be pointed out that a reduction in the geotextile filtration opening size will increase its retention capacity, reducing or avoiding conditions for piping in the base soil in contact with the filter. However, a reduction in geotextile openings may raise uncertainties with respect to the clogging potential of the filter, particularly in the case of internally unstable base soils. Fine movable particles of the soil may not be able to pass through the filter as initially assumed in the design phase, and may further increase the impregnation of the geotextile or cause blinding.

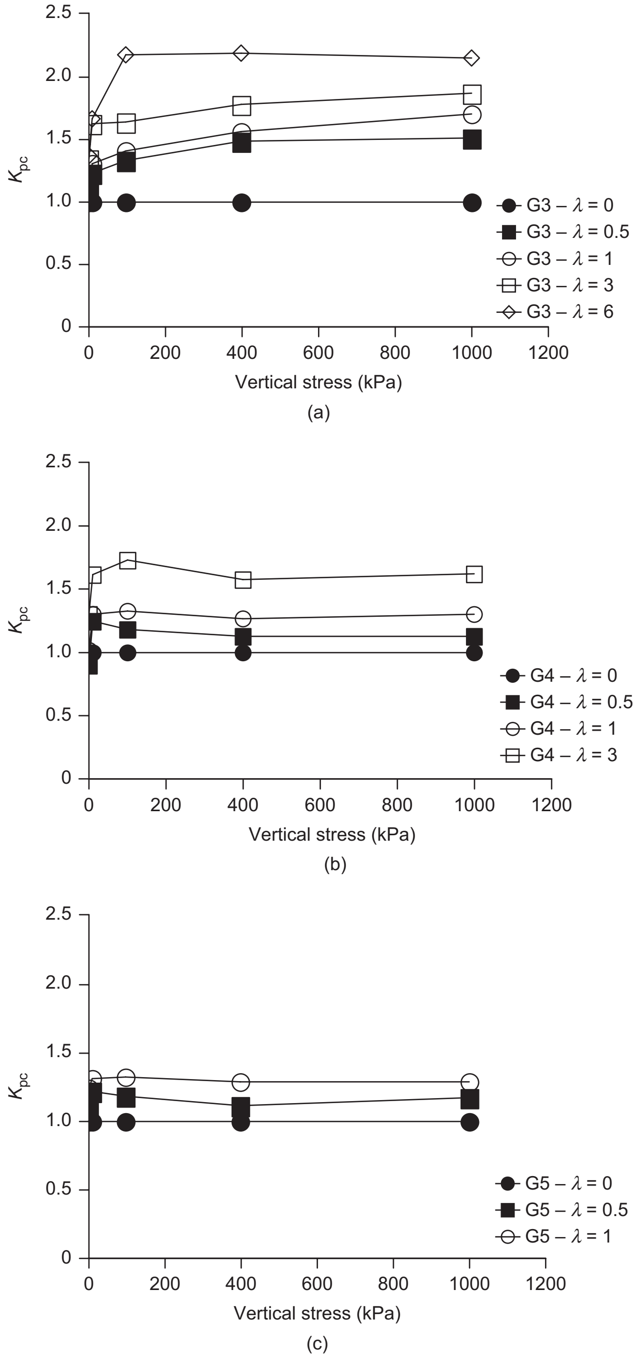

Figure 12. K_{pc} versus geotextile impregnation level, (a) geotextile G3; (b) geotextile G4; (c) geotextile G5

3.5. Comparisons with results from other testing techniques

3.5.1. *Comparisons with results from hydrodynamic sieving tests*

Figure 14 shows the results of bubble point and hydrodynamic sieving tests carried out on geotextiles G3, G4 and G5 (virgin specimens). In this case the diameter O_{95} from bubble point tests was employed to be consistent with the 95% percentage value used to determine the FOS value in hydrodynamic sieving tests. The FOS values are those reported by Palmeira *et al.* (1996), Gardoni and Palmeira (2002), Bessa da Luz (2004) and Palmeira *et al.* (2010). Despite some scatter, in general a good comparison can be observed between the results from both types of tests for the products tested and the testing procedures employed. It should be pointed out that the scatter in this figure may actually be smaller because the value of FOS equal 0.060 mm for geotextile G5 from Bessa da Luz (2004), as shown in the figure, may

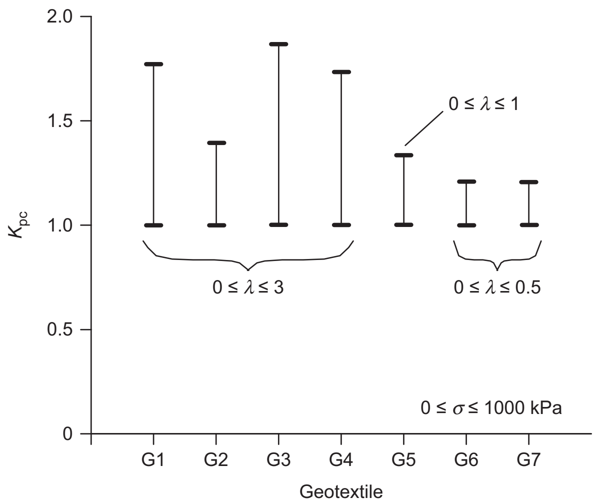

Figure 13. Estimated ranges of variation of K_{pc}

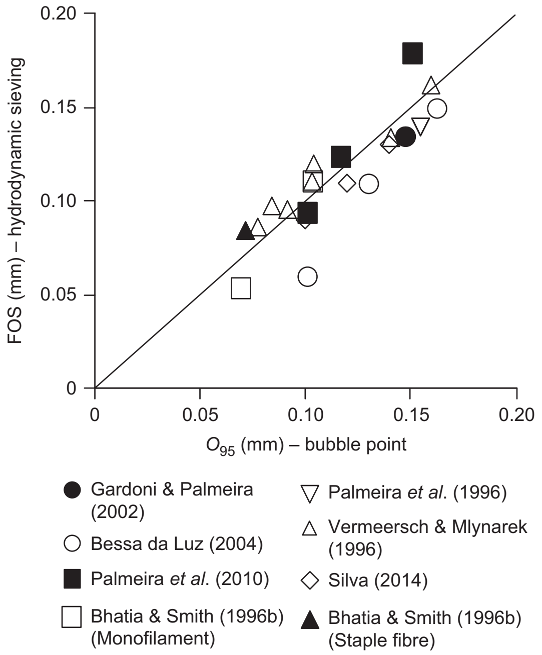

Figure 14. Comparisons between bubble point and hydrodynamic sieving tests – virgin geotextile specimens

actually be equal to 0.095 mm. The reason for this is that later on the geotextile's manufacturer provided a range of variation of FOS for G5 yielding an average value of 0.095 mm instead of 0.06 mm presented in earlier product catalogues. However, it was not possible to assess if this change in value of FOS was due to changes in the product or not. Therefore, the authors decided to use the original FOS value of 0.60 mm in Figure 14.

Figure 14 also shows comparisons between BBP and hydrodynamic sieving test results reported by Vermeersch and Mlynarek (1996) and Bhatia and Smith (1996b). Good agreement can also be noticed regarding results from Vermeersch and Mlynarek (1996), although these authors have reported poor comparisons for two geotextiles with larger FOS values. In these cases, the poor comparison may be a result of the BBP apparatus used to measure the low pressures required for large pore diameter calculations being less accurate. The results from Bhatia and Smith (1996b) were obtained in hydrodynamic sieving tests with glass bead mixtures on two monofilaments (needle-punched and heat bonded products), geotextiles, and on a staple fibre nonwoven geotextile. In general, a satisfactory comparison in terms of average values can also be observed. It should be pointed out that Bhatia and Smith (1996b) obtained a significant difference between BBP and hydrodynamic test results for the nonwoven needle-punched product when glass bead fractions were used in the latter test type. The results reported above, though rather limited in number, show satisfactory comparisons between BBP and hydrodynamic sieving test results for measurement of the geotextiles' largest pore diameter, with the advantages of the former being much quicker to perform, presenting less scatter of results and being less sensitive to operational conditions.

3.5.2. *Comparisons with results from filtration tests*

Despite the satisfactory agreement between BBP and hydrodynamic sieving results commented on above, a better assessment of test accuracy for filter design purposes would be obtained with results from field tests or from filtration tests more closely simulating field situations. To the knowledge of the authors, there is no information on the size of particles that piped through geotextile filters in the field. However, there are studies that measured the diameters of soil particles that passed through geotextile filters during filtration tests such as the Gradient Ratio Test (Palmeira *et al*. 1996, 2005, 2010; Gardoni 2000; Gardoni and Palmeira 2002; Palmeira and Gardoni 2002; Bessa da Luz 2004; Beirigo 2005). In these studies, piped particle diameters were measured using a laser beam grain size analyser immediately after soil sample preparation, at the end of the loading stages in filtration tests carried out under confinement (for different values of normal stress on the soil–geotextile system) and/or at the end of the test. Sample preparation in these filtration tests consisted of submerged pluviation in the case of uniform soils and slurry deposition in the case of broadly graded soils followed by vibration as per Vaid and Negussey (1988) and Kuerbis and Vaid (1988), respectively. Table 2 summarises the main properties of the soils (and glass beads) used in the aforementioned filtration tests. Among the test results reported in the works above, only those for soils with $D_{85} > O_{98}$ (where D_{85} is the particle diameter of the base soil for which 85% of the remaining particles are smaller than that value) were considered because for finer soils the largest piped particle diameter would certainly be smaller than O_{98}. A significant variety of soils can be noted in Table 2, ranging from uniform glass beads and sands to iron mine tailings.

The geotextiles employed in the tests with the soils listed in Table 2 were the same geotextiles G3, G4 and G5 used in the bubble point tests reported in this paper. In a few filtration tests a needle punched geotextile (code GTY), made of polyester, from the same manufacturer but with different value of mass per unit area (180 g/m^2) from G3,

Table 2. Properties of soil in filtration tests

Soil code	Soil type	$D_{10}^{(1)}$ (mm)	D_{15} (mm)	D_{50} (mm)	D_{85} (mm)	$C_U^{(2)}$	$C_C^{(3)}$	$I_D^{(4)}$ (%)
UGGB2(5)	Uniform glass beads	0.057	0.072	0.116	0.140	2.2	1.2	83
UGS(5)	Uniform sand	0.124	0.154	0.226	0.266	2.0	1.4	85
BGSS1(5)	Silty sand	0.009	0.020	0.214	0.257	25	9.6	84
BGSS2(5)	Silty sand	0.002	0.005	0.158	0.251	105	0.9	85
FA(7)	Iron mine tailings	0.044	0.066	0.128	0.251	3.7	0.9	50
SB(8)	Sand	0.053	0.085	0.42	0.61	11.5	1.6	NA
SF(8)	Uniform sand	0.089	0.093	0.11	0.18	1.4	1.0	NA

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) coefficient of curvature (= $D_{30}^2/D_{60}D_{10}$); (4) relative density; (5) from Palmeira *et al.* (1996) and Palmeira and Fannin (1998); (6) from Palmeira *et al.* (2005) and Bessa da Luz (2004); (7) from Beirigo (2005) and Palmeira *et al.* (2010); (8) from Palmeira and Gardoni (2000) and Gardoni (2000); NA, not available; the soil codes are the same as in the original works.

G4 and G5 (200 g/m^2, 300 g/m^2 and 600 g/m^2, respectively) was also tested (Table 1). For the former, the values of O_{98} were obtained from extrapolations of BBP results obtained for G3, G4 and G5 as a function of their masses per unit area. It should be pointed out that the r^2 value for the best curve (hyperbolic decline equation: $O_{98}/d_f = a(1 + bM_A)^c$) fitting the relation between O_{98}/d_f obtained in BBP tests and mass per unit area (M_A) was greater than 0.99.

Figure 15a shows the ratio between maximum particle diameter (D_{max}, assumed equal to D_{85}) passing through the geotextile after sample preparation and maximum geotextile opening diameter (O_{98}) obtained in bubble point tests (virgin specimens) for geotextiles G3, G4, G5 and GTY. This figure shows that the ratio D_{max}/O_{98} can be significantly smaller than 1, depending on the soil considered and despite the vibration process used for soil compaction in the filtration tests. It should be pointed out that during sample preparation, the soil was initially deposited in a loose state on the geotextile by submerged pluviation or slurry deposition followed by vibration. Despite the gentle sedimentation of soil particles on the geotextile, it is likely that pores of the geotextile were obstructed by soil particles. This partial clogging reduced the available pores for the passage of additional particles during vibration.

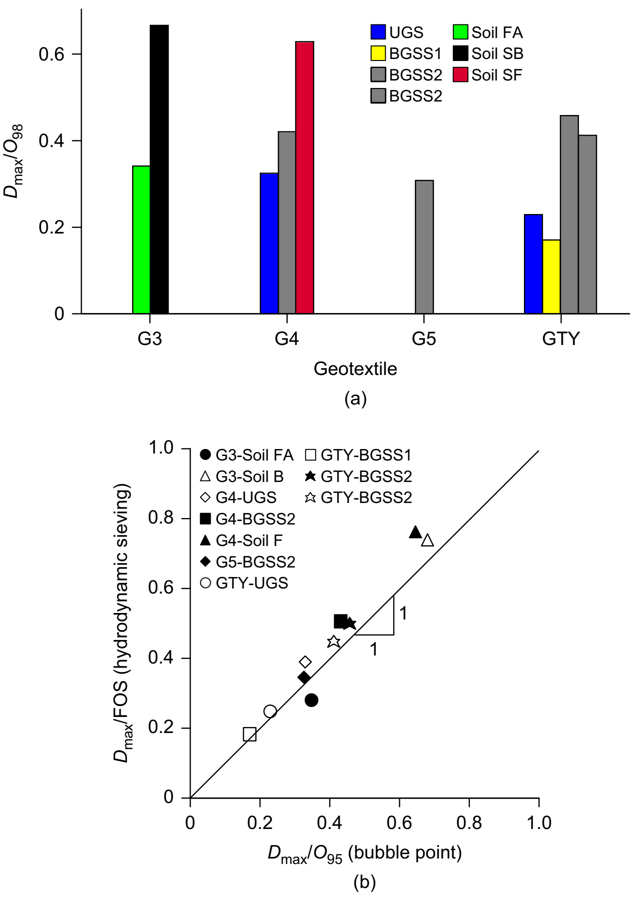

Figure 15. Ratio between maximum particle diameter and maximum pore diameter after sample preparation in filtration tests, (a) D_{max}/O_{98} for O_{98} from BBP tests; (b) bubble point test against hydrodynamic test

As observed in Figure 15a, previous works in the literature have also shown that particles that are capable of passing through the geotextiles can be significantly smaller than the geotextile filtration opening size obtained from hydrodynamic sieving tests (FOS), either during sample preparation or during seepage in filtration tests (Palmeira *et al.* 1996; Gardoni 2000; Gardoni and Palmeira 2002; Palmeira and Gardoni 2002). However, Figure 15b shows that similar ratios of D_{max}/O_{95} and D_{max}/FOS are obtained in BBP and in hydrodynamic tests with respect to soil particles that passed through the geotextile filter after sample preparation (submerged pluviation or slurry deposition followed by vibration). Some scatter can be noted, but in general a consistent correlation between the results from both testing techniques can be observed.

It should be noted that the results in Figure 15 were obtained for geotextile filters under unconfined conditions. A similar comparison can be made for tests under confined conditions. Palmeira and Fannin (1998) presented the results of tests under confinement using a testing cell where the soil–geotextile system was first subjected to a vertical stress followed by vibration. After the end of the vibration period, the diameters of the particles that piped through the geotextile filter were measured for the determination of D_{max}. Regarding filtration tests, Beirigo (2005) reports measurements of soil particle diameters that passed through the geotextile filter at the end of seepage stages in Gradient Ratio Tests under confinement.

Figure 16a presents the results of the ratio D_{max}/O_{95} versus vertical stress with D_{max} obtained in tests on geotextiles G3, G4, G5 and GTY using soil FA (Beirigo 2005) and glass beads (Palmeira and Fannin 1998) as base soils. O_{95} values were obtained in BBP tests on virgin specimens under the same stresses as those applied in filtration tests under confinement. The general trend is of a reduction of D_{max}/O_{95} with increasing vertical stress, with large scatter for vertical stresses up to 75 kPa. To some extent, this scatter may be a consequence of uncertainties related to particle diameter measurements in grain size analyses. However, it should be noted that sample preparation of the loose glass bead samples (UGGB2, in Figure 16) in the tests performed by Palmeira and Fannin (1998) was achieved by submerged pluviation, followed by vertical stress application and vibration. Some level of partial clogging certainly occurred during bead pluviation caused by the first beads reaching the geotextile layer. The value of λ after pluviation should depend on the the relative sizes of the beads and geotextile openings. For vertical stresses below 100 kPa, virgin and partially clogged geotextiles are more compressible (Figure 2). So, further reduction of geotextile thickness and accommodation of entrapped beads in the geotextile would be expected to take place during the application of a vertical load before vibration of the soil–geotextile system. This further thickness reduction and remaining opening sizes depend on geotextile type, the vertical stress applied and λ (Figure 2). These different values of λ for different geotextiles and further geotextile compression may also explain to some extent the scatter of test results for stresses in the range 0 to 75 kPa.

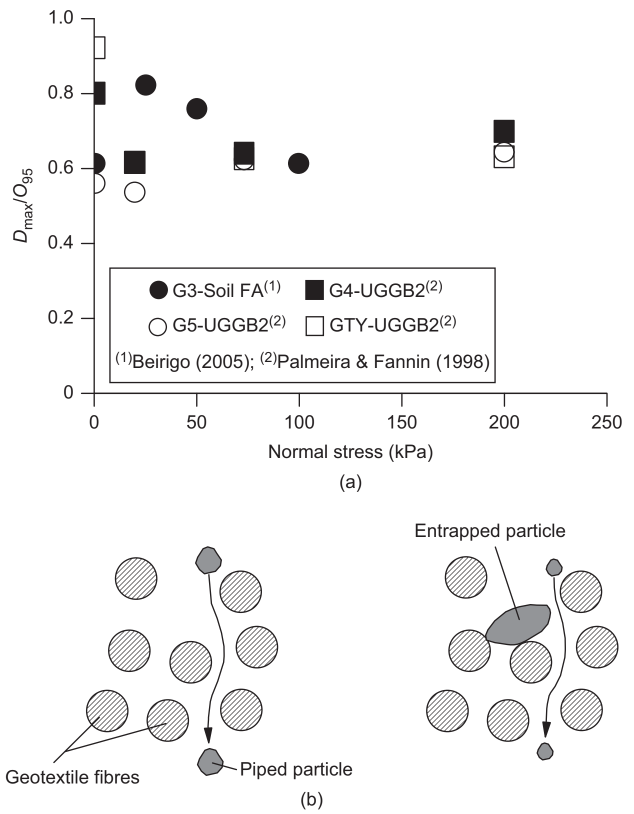

Figure 16. Ratio between maximum particle diameter and maximum pore diameter under confinement, (a) D_{max}/O_{95} under confinement; (b) reduction of piped particle size due to partial clogging

Figure 5 and Figure 7 show that most of the reductions in O_{95} values of virgin and partially clogged geotextile specimens occur for vertical stresses up to 100 kPa, and that the value of vertical stress beyond which O_{95} becomes less dependent on confinement is a function of λ. This may explain the lesser variation of D_{max}/O_{95} with confinement in Figure 16 for vertical stresses greater than 100 kPa. The results in this figure are consistent with the pattern of variation of O_{95} of the geotextiles with vertical stress obtained in BBP tests (Figure 5 and Figure 7).

The results obtained suggest that in soil sample preparation in filtration tests or under field conditions the first soil particles to be retained by the filter during spreading and compaction of the soil on the geotextile or during water flow will limit the diameter of further particles capable of piping through the geotextile filter, as schematically shown in Figure 16b. This will be more relevant for fine cohesionless soils (silts and fine sands). Under such conditions, the diameters of piped particles are likely to be influenced by the soil type and gradation and how it is deposited and compacted on the filter. For uniform soils where submerged pluviation is used during sample preparation in filtration tests, the largest soil particles will settle first on the geotextile (according to Stokes' law the settling velocity is proportional to the particle diameter squared), which may favour the closure of the largest geotextile pores. Even if particles with the same diameter as the geotextile maximum opening diameter pass through the geotextile, in most cases their masses will be smaller than the sum of the masses of the finer piped particles. As a consequence, the value of D_{max} (usually assumed as D_{85} of the soil) obtained from the gradation curve of the entire mass piped through the geotextile will be smaller than the geotextile filtration opening size. Compaction in the field and in the laboratory can displace entrapped particles laterally in the fabric matrix to positions they would not reach by the action of seepage forces alone, making the prediction of the diameters of particles capable of piping through the partially clogged filter even more complex.

4. CONCLUSIONS

This paper presented and discussed the results of bubble point tests on confined and partially clogged nonwoven geotextiles. Comparisons between the results from such tests and from other testing techniques have also been presented and discussed. The main conclusions from this investigation are presented below.

The bubble point test proved to be a very useful and repeatable technique for the measurement of the opening sizes of nonwoven geotextiles. The test provided consistent results for virgin and partially clogged geotextiles with and without confinement. Confinement and partial clogging had a marked effect on geotextile opening dimensions. The product of reduction factors to account for the effects of confinement and partial clogging on the value of O_{95} varied between 1 and 3, depending on the geotextile, vertical stress and level of partial clogging. The geotextile retention capacity increases due to opening size reductions caused by confinement and partial clogging. However, the conditions for geotextile blinding and internal clogging are also changed to a state not accounted for by current filter criteria. The values of O_{98} obtained for the stress and the partial clogging levels used in the tests fell within the range of particle diameters for silts and fine sands. This highlights the importance of proper investigation and analysis in the specification of a geotextile filter for cohesionless fine sands and silts. The same applies in the case of internally unstable soils, in which particles in the silt and fine sand diameter ranges can be carried towards the filter layer by seepage forces.

Predictions using the empirical equation derived by Giroud (1996) compared well with bubble point test results on virgin geotextile specimens with and without confinement after some adjustments in the values of the empirical coefficients (δ and ξ) of that equation with respect to those originally proposed. These coefficients depended on the polymer used in the manufacture of the geotextile. The values of δ and ξ were back-analysed for the prediction of the maximum opening sizes of partially clogged geotextiles. The results showed that the equation presented by Giroud (1996) can be a useful tool for estimating the maximum geotextile opening size under confinement and partial clogging conditions in preliminary analyses of filter performance.

For tests on unconfined geotextile specimens, the results obtained in the bubble point test compared well with those from hydrodynamic sieving tests. Good comparisons between both techniques were also obtained with respect to the dimensions of particles that piped through the geotextile during sample preparation in filtration tests. The dimensions of the largest particles that piped through the geotextile filter in filtration tests under confinement varied between 0.5 and 0.92 times the value of O_{95} obtained in bubble point tests under the same vertical stress.

Fortunately, clogging of geotextile filters is rare but when it occurs it may lead to serious consequences in a geotechnical or geoenvironmental work. Despite being rare, and even after decades of research on the performance of geotextile filters, clogging of these filters remains a very complex subject and further research is certainly necessary for the development of more accurate and reliable filter criteria for geotextiles.

ACKNOWLEDGEMENTS

The authors are indebted to the following institutions that supported the research programme described in this paper in different ways: University of Brasília, CNPq-National Council for Scientific and Technological Development and CAPES-Brazilian Ministry of Education.

NOTATION

Basic SI units are given in parenthesis.

a, b, c	fitting coefficients
C_c	soil coefficient of curvature (dimensionless)
C_U	soil coefficient of uniformity (dimensionless)
D_{max}	diameter of the largest particle that piped through the geotextile (m)
D_n	diameter for which n% in mass of the remaining soil particles are smaller than that diameter (m)
d_f	geotextile fibre diameter (m)
FOS	geotextile filtration opening size obtained in hydrodynamic sieving tests (m)
I_D	soil relative density (percentage)
K_{pc}	reduction factor for partial clogging (dimensionless)
K_σ	reduction factor for confinement (dimensionless)
M_A	geotextile mass per unit area (kg/m^2)
n	geotextile porosity (dimensionless)
n'	average geotextile porosity taking into account the presence of the solid particles in the geotextile voids (dimensionless)
O_F	geotextile filtration opening size (m)
O_n	geotextile opening diameter for which n% of the remaining openings are smaller than that value (m)
t_{GT}	geotextile thickness (m)
δ	empirical coefficient in the equation by Giroud (1996) (dimensionless)
λ	geotextile level of impregnation (dimensionless)
ψ	geotextile permittivity
ρ_f	density of geotextile fibres (kg/m^3)
ρ_s	density of soil particles entrapped in the geotextile (kg/m^3)
σ	vertical stress (Pa)
ξ	empirical coefficient in the equation by Giroud (1996) (dimensionless)

ABBREVIATIONS

BBP	Bubble point
FOS	Filtration opening size
GR	Gradient ratio
PET	Polyester
PP	Polypropylene

REFERENCES

ASTM 4751-12 Standard test method for determining apparent opening size of a geotextile. 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.

Aydilek, A. H., Oguz, S. H. & Edil, T. B. (2002). Digital image analysis to determine pore opening size distribution of nonwoven geotextiles. *ASCE Journal of Computing in Civil Engineering*, **16**, No. 4, 280–290.

Beirigo, E. A. (2005). *Filter Behaviour of Geotextiles in Tailings Dams*, MSc thesis, Graduate Programme of Geotechnics, University of Brasilia, Brasilia, Brazil, 192 p (in Portuguese).

Bessa da Luz, D. W. (2004). *Compatibility of Soil–geotextile systems in Filtration Tests Under Stress*, MSc thesis, University of Brasilia, Brasilia (in Portuguese), 139 p.

Bhatia, S. K. & Smith, J. L. (1995). Application of the bubble point method to the characterization of the pore-size distribution of geotextiles. *Geotechnical Testing Journal*, **18**, No. 1, 94–105.

Bhatia, S. K. & Smith, J. L. (1996a). Geotextile characterisation and pore-size distribution: part II – a review of test methods and results. *Geosynthetics International*, **3**, No. 2, 155–180.

Bhatia, S. K. & Smith, J. L. (1996b). Geotextile characterization and pore-size distribution: part III. Comparison of methods and application to design. *Geosynthetics International*, **3**, No. 3, 301–328.

Blond, E., Veermersch, O. & Diederich, R. (2015). A comprehensive analysis of the measurement techniques used to determine geotextile opening size: AOS, FOS, O_{90}, and 'Bubble Point'. *Geosynthetics 2015*, Portland, Oregon, USA, 10 p.

CFG (1986). Recommendations générales pour la réception et la mise en oeuvre des géotextiles: norms Françaises d'essais. *Association Française de Normalization, French Committee on Geotextiles*, France, 32 p.

CGSB (Canadian General Standard Board) (1994). CGSB 148.1 n° 10-94: Filtration opening size of geotextiles. Canadian General Standard Board, Ottawa, Canada.

Dierickx, W. & Myles, B. (1996). Wet sieving as a European WN-Standard for determining the characteristic opening size of geotextiles. *Recent Developments in Geotextile Filters and Prefabricated Drainage Geocomposites*, ASTM STP 1281, Bhatia, S. K. & Suits, L. D., Editors, ASTM, West Conshohocken, PA, USA, pp. 54–64.

Elsharief, A. M. & Lovell, C. W. (1996). Determination and comparisons of the pore structure of nonwoven geotextiles. *Recent Developments in Geotextile Filters and Prefabricated Drainage Geocomposites*, Bhatia, S. S. & Suits, L. D., Editors, ASTM STP 1281, American Society for Testing and Materials, West Conshohocken, PA, USA, pp. 35–53.

Elton, D. J., Hayes, D. W. & Adanur, S. (2006). Bubble point testing of geotextiles: apparatus an operation. *Geotechnical Testing Journal*, **30**, No. 1, 1–18.

Eun, J. W. & Tinjium, J. M. (2011). Variation in air entry suction of nonwoven geotextiles with pore size distribution. *Unsaturated Soils: Theory and Practice*, Jotisankasa, A., Sawangsuriya, A., Soralump, S. & Mairaing, W., Editors, Kasetsart University, Bangkok, Thailand, pp. 553–558.

Faure, Y. H., Gourc, J. P. & Gendrin, P. (1989). Structural study of porometry and filtration opening size of geotextiles. *Geosynthetics: Microstructure and Performance*, Peggs, I. D., Editor, ASTM STP 1076, American Society for Testing and Materials, Philadelphia, PA, USA, pp. 102–119.

Fayoux, D. & Evon, E. (1982). Influence of the fibre size on the filtration characteristics of needled-punched geotextiles. *2nd International Conference on Geotextiles*, Las Vegas, USA, vol. 1, pp. 49–53.

Fischer, G. R. (1994). *The Influence of Fabric Pore Structure on the Behavior of Geotextile Filters*, PhD thesis, University of Washington, Seattle, WA, USA.

Fischer, G. R., Holtz, R. D. & Christopher, B. R. (1996). Evaluating geotextile pore structure. *Proc. Recent Developments in Geotextile Filters and Prefabricated Drainage Geocomposites*, Bhatia, S. S. & Suits, L. D., Editors, ASTM STP 1281, American Society for Testing and Materials, West Conshohocken, PA, USA, pp. 3–18.

Frischknecht, R., Stucki, M., Büsser, S. & Itten, R. (2012). Comparative life cycle assessment of geosynthetics versus conventional construction materials. *Ground Engineering*, **45**, No. 10, 24–28.

Gardoni, M. G. (2000). *A Study on the Drainage and Filtration Behaviour of Geosynthetics Under Compression*, PhD thesis, University of Brasilia, Brasilia.

Gardoni, M. G. & Palmeira, E. M. (2002). Microstructure and pore characteristics of synthetic filters under confinement. *Geotechnique*, **52**, No. 6, 405–418.

Giroud, J. P. (1996). Granular filters and geotextile filters. *GeoFilters '96*, Lafleur, J. & Rollin, A. L., Editors, Ecole Polytechnique de Montreal, Montreal, Canada, pp. 565–680.

ISO (2009). ISO 12956-2009: Geotextiles and geotextile-related products – determination of the characteristic opening size. ISO, Geneva, Switzerland.

Koerner, R. M. & Koerner, G. R. (2015). Lessons learned from geotextile filter failures under challenging field conditions. *Geotextiles and Geomembranes*, **43**, No. 3, 272–281.

Kuerbis, R. H. & Vaid, Y. P. (1988). Sand preparation – the slurry deposition method. *Soils and Foundations*, **28**, No. 4, 107–118.

Laflaive, E. & Puig, J. (1974). Emploi des textiles dans les travaux de terrassement et de drainage. *Bulletin de Liaison, Laboratoires des Ponts et Chaussées*, Paris, France, No. 69, January–February, pp. 61–79.

Masounave, J., Denis, R. & Rollin, A. L. (1980a). Prediction of hydraulic properties of synthetic fabrics used in geotechnical works. *Canadian Geotechnical Journal*, **17**, No. 4, 517–525.

Masounave, J., Rollin, A. L. & Denis, R. (1980b). Prediction of permeability of nonwoven geotextiles from morphometry analysis. *J. Microsc.*, **121**, No. 1, 99–100.

Moraci, N., Mandaglio, M. C. & Salmi, M. (2016). Long term behavior of woven and nonwoven geotextile filters. *GeoAmericas 2016*, Miami, FL, USA, vol. 1, pp. 740–749.

Palmeira, E. M., Beirigo, E. A. & Gardoni, M. G. (2010). Tailings-nonwoven geotextile filter compatibility in mining applications. *Geotextiles and Geomembranes*, **28**, No. 2, 136–148.

Palmeira, E. M. & Fannin, R. J. (1998). A methodology for the evaluation of geotextile pore opening sizes under confining pressure. *Geosynthetics International*, **5**, No. 3, 347–357.

Palmeira, E. M. & Gardoni, M. G. (2000). The influence of partial clogging and pressure on the behaviour of geotextiles in drainage systems. *Geosynthetics International*, **7**, No. 4–6, 403–431.

Palmeira, E. M. & Gardoni, M. G. (2002). Drainage and filtration properties of non-woven geotextiles under confinement using different experimental techniques. *Geotextiles and Geomembranes*, **20**, No. 2, 97–115.

Palmeira, E. M., Fannin, R. J. & Vaid, Y. P. (1996). A study on the behaviour of soil–geotextile systems in filtration tests. *Canadian Geotechnical Journal*, **33**, No. 4, 899–912.

Palmeira, E. M., Gardoni, M. G. & Bessa da Luz, D. W. (2005). Soil–geotextile filter interaction under high stress levels in the gradient ratio test. *Geosynthetics International*, **12**, No. 4, 162–175.

Palmeira, E. M., Tatto, J. & Araújo, G. L. S. (2012). Sagging and filtration behaviour of nonwoven geotextiles overlying different bedding materials. *Geotextiles and Geomembranes*, **31**, No. 1, 1–14.

Rigo, J. M., Lhote, E., Rollin, A. L., Mlynarek, J. & Lombard, G. (1990). Influence of Geotextile structure on pore size determination. *Geosynthetics: Microstructure and Performance*, ASTM STP 1076, Peggs, I. D., Editor, American Society for Testing and Materials, Philadelphia, PA, USA, pp. 90–101.

Silva, A. M. (2014). *Filtration Opening Size of Geotextiles Under Confinement*, MSc dissertation, Graduate Programme of Geotechnics, University of Brasília, Brasília, Brazil (in Portuguese).

Trejos-Galvis, H. (2016). *Evaluation of Geotextile Filtration Opening Size Under Confinement and Partial Clogging*, MSc dissertation, Graduate Programme of Geotechnics, University of Brasília, Brasília, Brazil (in Portuguese).

Vaid, Y. P. & Negussey, D. (1988). Preparation of reconstituted sand specimens. *Advanced Triaxial Testing of Soil and Rock*, Donague, R. T., Chaney, R. C. & Silver, M. L., Editors, American Society for Testing and Materials, Philadelphia, PA, USA, Special Technical Publication No. 977, pp. 405–417.

Veermersch, O. G. & Mlynarek, J. (1996). Determination of the pore size distribution of nonwoven geotextiles by a modified capillary flow porometry technique. *Proc. Recent Developments in Geotextile Filters and Prefabricated Drainage Geocomposites*, Bhatia, S. S. & Suits, L. D., Editors, ASTM STP 1281, American Society for Testing and Materials, West Conshohocken, PA, USA, pp. 19–34.

The Editor welcomes discussion on all papers published in Geosynthetics International. Please email your contribution to discussion@geosynthetics-international.com by 15 October 2017.