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ABSTRACT

A series of tests were carried out on three types of geotextiles to investigate the effects of biaxial tensile loading on their permeability and filtration opening sizes. A woven slit-film and two nonwoven needle punched geotextiles were tensioned either equally in both directions or unequally. The tensile forces exerted were small, less than 10% of the geotextiles' tensile strength. And a tensile loading frame was designed for this purpose. An attempt to measure the effect on the permeability was made using a large diameter permeameter that was subjected to an upward water flow. A hydrodynamic sieving mechanism (HSM) was used to investigate the effect on the opening sizes of the geotextiles. Certain aspects of the hydrodynamic test method were also investigated.

The most significant results were obtained with the HSM. There was a marked decrease in the filtration opening size (FOS) with progressively larger loads. For the woven geotextile, a 28% reduction occurred in FOS under a load equal to 8% of the minimum tensile strength. A 43% reduction in its permeability also occurred when the HSM was used as a falling head permeameter. The results for the nonwoven geotextile showed a 9% reduction in FOS for a load equal to 10% of the multidirectional tensile strength.

When considering geotextile filter design, these reductions would probably result in an improvement in the retention characteristics of geotextile filters. However, the combination of a reduction in permeability and FOS will increase the possibility of clogging and thus failure of the geotextile filter.

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

PC Adolio
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28th day of May 1997

AN INVESTIGATION OF THE EFFECTS OF TENSILE STRESS ON THE PERMEABILITY CHARACTERISTICS AND OPENING SIZES OF GEOTEXTILES

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A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Engineering

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can be evaluated.

The mercury intrusion porosimetry method is outlined in the draft Standard Test Method for Determination of Pore Volume (ASTM) and Pore Volume Distribution of Geotextiles by Mercury Intrusion Porosimetery. Mercury intrusion porosimetry is based on the theory of the Washburn equation, which relates the pressure required to force a non wetting fluid (mercury) into the pores of a geotextile to the radius of the pores intruded. As a result, the pore-size distribution of the geotextile can be evaluated.

Image analysis (Rollin et al., 1977; Faure et al., 1990; Bhatia et al., 1993, 1994) is a technique used for the direct measurement of pore spaces within a cross-sectional plane of a geotextile. This is done by measuring pore sizes from enlarged scanning electron microscope (SEM) photographs. In determining pore sizes, assumptions are necessary regarding how the pore between fibres will be defined, for instance equivalent circle, smallest dimension, average rectangular dimension, etc.

A few attempts have been made at developing a mathematical model of the structure of a geotextile. Goure and Faure (1992) expand on the theoretical model called the convex-grain Boolean scheme (Rollin 1978). Consideration is given to the circle of diameter d that can be inscribed in the pore and the distribution of inscribed circles between fibres is determined (assuming the fibres to be arranged uniformly and parallel to the sheet plane). The C_{max}, which is the conduit diameter characterising the maximum diameters of the conduits, is calculated and can be considered as a theoretical approach to the filtration opening size.

The Canadian draft standard *Filtration Opening Size of geotextiles* (CAN/CGSB-148.11) gives a description of the hydrodynamic sieving method. This method also uses a mixture of glass beads. Four tests are usually run at the same time. The apparatus consists of four cylinders that are attached to a frame which is in turn connected to a pneumatic device. The geotextile samples are attached to the bottom of the cylinders and the mixture of glass beads is placed upon them. The cylinders and geotextiles are then immersed and withdrawn from the water pans. This action allows the glass beads to be forced through the openings of the geotextiles when the water flows from the cylinders. After a specified number of cycles, the glass beads that have passed through the geotextile are collected and oven dried. Their distribution is determined and the O_{95} is calculated. Hydrodynamic sieving evaluates the so called filter opening size (FOS) of a geotextile.

The bubble point test is outlined in Method B of The Standard Test Methods for Pore size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Tests (ASTM F-316). It combines the measurement of capillary pressure with measurements of air flow through the specimen and it is based on:

(1) a dry porous material will pass air through all its pores when any amount of air pressure is applied to one side of the material; and

(2) a saturated porous material will only allow a fluid to pass when the pressure applied exceeds the capillary attraction of the fluid in the largest pore. The pressure required to extract a certain volume of liquid is measured and this provides information on the pore volume which in turn is related to the opening sizes. Since smaller and smaller pores pass air as the air pressure is increased, the largest opening, O_{95}, and pore-size distribution of the geotextile

basically the same thing but with a few differences. The major difference is that the BS measures the apparent pore size for which 90% of the glass beads are on and within the geotextile. The AOS on the other hand is defined as the size of bead that has only 5% passing through the geotextile. Another difference is that the ASTM standard starts the sieving using the smallest sized beads and then moves onto progressively larger sizes. The BS starts with the coarsest beads followed by progressively smaller sizes.

The basic process though remains the same. A geotextile specimen is placed in a sieve frame, and 50 g of sized glass beads(a set of glass beads of a certain size is called a glass bead designation) are placed on the geotextile surface. The geotextile and frame are shaken laterally for ten minutes so that the jarring motion will induce the beads to pass through the test specimen. In the case of the ASTM test, progressively larger sized glass beads are sieved through a geotextile until a particle size designation has been found for which 5% or less, by mass, passes through. The BS test continues until the designation and mean particle size are reached for which more than 95% of the beads pass through the test specimen.

The wet sieving technique (Saathoff and Kohlhase 1986) is very similar to dry sieving, but with two fundamental differences. Firstly, a continuous water spray is applied while the sieving takes place. Secondly, a glass bead mixture, as opposed to a number of designated glass bead sizes, is used. The glass beads that pass through the geotextile are collected and oven dried. A particle size distribution analysis is carried out on these beads and the O_{95} is then evaluated by calculating the 95% finer by mass point on the curve.

NF G38-017-89	Hydrodynamic sieving using soil particles - France
SM-G8.2	Hydrodynamic sieving using soil particles - International Union of Testing and Research Laboratories for Materials and Structures (RILEM)
SW 640550-83	Wet sieving with soil particles - Switzerland
CNR-1986	Wet sieving with soil particles - a draft standard in Italy
BAW-FGSV 6.12 UFH	Wet sieving with soil particles - recommended in Germany
ISO/TC38/SC21/N-9	Hydrodynamic sieving using soil particles - in development

2.3 Descriptions of Available Techniques for Measuring O_{95}

The standard methods are thus all based on the three types of sieving, i.e. wet, dry and hydrodynamic. Many of the other techniques are in the development stage and a description of all the available methods are described below.

The United States and Britain both use dry sieving with glass beads to determine the opening sizes of geotextiles. The USA has the *Standard Test Method for Determining the apparent Opening Size (AOS) of a Geotextile* (ASTM D-4751-87). The British on the other hand, have the *British Standard Methods of test for Geotextiles Part 2. Determination of the apparent pore size distribution by dry sieving* (BS 6906:Part2:1989). These are both describing and O_{95}.

The difficulty in measuring the opening sizes of geotextiles is borne out by the fact that there are so many different methods used. Some methods are able to measure the entire pore size distribution, while others can only measure the largest effective opening size: the O_{95}. Numerous measurement techniques have been developed. There are the indirect methods such as dry sieving (Calhoun, 1972; Gerry and Raymond, 1983), hydrodynamic sieving (Fayoux, 1977), wet sieving (Saathoff and Kohlhase, 1986), the bubble point method (Andrei et al., 1982; Dennis and Davies 1984; Miller et al., 1986; ASTM F-316; Vermeersch and Mlynarek 1996), and mercury intrusion porosimetry (Prapaharan et al., 1989; ASTM D-4404). There are also the direct methods such as image analysis (Rollin et al., 1977; Faure et al., 1990; Bhatia et al., 1993, 1994), and mathematical models (Rollin et. al. 1978 and 1982; Goure 1982; Witmann 1982; Goure and Faure 1992).

2.2 Standardized Methods

Some of the above methods have become standardized:

ASTM D 4751-87	Dry sieving using glass beads - USA
BS-6906-1989	Dry sieving using glass beads - UK
NBN S 29001	Dry sieving using natural soil particles - Belgium
CAN/CGSB-148.1-10	Hydrodynamic sieving using glass beads - Canada

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Geotextiles are used in numerous filtration applications, such as in landfill leachate collection systems, in pipe underdrains, behind rigid retaining walls, in earth dams, and beneath erosion control structures. When geotextiles are used as filters, proper design is essential. Three basic filter criteria are used for design: a retention criterion, a permeability criterion and a clogging criterion. The ability of a geotextile to meet existing design criteria is considered to be a function of the effective pore openings of a geotextile. Depending on the design technique, one usually uses either the O_{95} or the O_{50}. These are defined as the measure of the effective pore openings of a geotextile. The classification is similar to that of soil. The O_{95} is the value which has 95% of the geotextile openings smaller than it. Similarly, the O_{50} is the opening size that has 50% of the geotextile pores smaller than it. This opening size is then related to a particular size on the particle size distribution curve of the soil that is in contact with the geotextile. Note that the O_{95} is usually referred to as the largest effective opening size or the filtration opening size, while the O_{100} is obviously the largest effective opening size. Due to the fact that this value is difficult to measure, parameters that are closely related to it are measured and are used as approximate values of O_{100}. Such typical parameters are O_{90}, O_{95}

the smallest sized beads, each bead size was added as the test progressed. The hydrodynamic sieving mechanism was also used for a test of the through flow capacity or permeability of the geotextiles.

calculated. The two geotextiles that were tested were subjected to a total of four tests each. Apart from an untensioned test, they were also subjected to one equally loaded and two unequally loaded tests.

There are presently many different methods to measure the pore sizes of geotextiles. Some methods are able to measure the entire pore size distribution, while others can only measure the largest effective opening size, which is usually called the O_{95}. It was decided to use one of these methods, namely hydrodynamic sieving, to measure the change in the largest apparent opening size. Hydrodynamic sieving uses a glass bead mixture which is sieved through a geotextile by the force of alternating water flow. A particle size analysis test is performed on the beads that have passed through the geotextile and in this way the filter opening size is determined. The apparatus was modified to enable the testing of pretensioned geotextiles. Once again relatively small loads were used and a series of equally and unequally tensioned tests were performed on a woven slit-film and two nonwoven needle punched geotextiles.

The two nonwoven geotextiles were identical in their manufacturing process, but the one was thicker than the other. The thicker geotextile was used in only two tests in order to see the effect of thickness on FOS. The woven and the thinner of the two nonwoven geotextiles were subjected to the same loading patterns i.e. six equally tensioned tests and three unequally tensioned tests.

A variation of the standard hydrodynamic sieving test was also performed. Instead of adding the beads as a mixture at the start of the test, the beads were divided up according to the sieve size that they were retained on. Starting with

The growth in the use of geotextiles led to the International Conference on the Use of Fabrics in Geotechnics held in Paris in 1977. This resulted in a great deal of research into this rapidly expanding technology.

The aim of this dissertation was to investigate one particular aspect of geotextile behaviour. The topic under investigation was the effect of biaxial tensile loading on the permeability and opening sizes of geotextiles.

In certain applications, geotextiles can be subjected to in-plane tensile strain. For example they are used as filters or drains in leachate collection layers below landfills and as reinforcing layers beneath fills constructed on soft soils. It should be noted that the geotextiles are not in danger of failing in terms of their strength in these applications, but it is possible that a realignment of the fibres may occur and this in turn will affect the behaviour of the geotextile.

A method was thus developed in a previous study to investigate the effect of relatively small loads (less than 10% of the tensile strength of the geotextile) on the permeability and the largest apparent opening size of geotextiles. To simulate biaxial loading, a loading frame was built that enabled the geotextiles to be pretensioned either equally or unequally in two directions. The frame allowed a maximum load of 2.5 kN/m. To measure the effect of these tensile loads on the permeability of the geotextile, a large diameter constant head permeameter was used. The geotextile was placed in direct contact with a fine grained sand and the design was such that a pretensioned geotextile could be clamped into the permeameter without any loss in the strain. The flowrate of water through the permeameter was monitored by measuring the amount of water flowing out of the outlet spout and the permeability was subsequently

CHAPTER 1

INTRODUCTION

Geotextiles are defined as thin, flexible, permeable sheets usually of synthetic material used to stabilise and improve the performance of soil associated with civil engineering works. Correctly designed and installed, geotextiles have the ability to filter, drain, reinforce and separate soil. In many applications, geotextiles may be designed and selected to perform a combination of these functions.

Although there were some very early isolated applications of geotextiles dating back as far as 1926 (Bell et. al. 1977), it is only since the early 1970s that their impact has become significant. The first polymer-based geotextiles were woven industrial fabrics used beneath concrete block revetments in the late 1950s. Geotextile nets became established around 1968, but the development of the first nonwoven geotextile in France in 1968 widened the range of geotextiles and their applications. The first use of a geotextile filter in an earth dam was at Valcros Dam in France in 1970 (Giroud et. al. 1977). By 1971 three other lines of geotextile applications first appeared, i.e. fin drains, woven geotextile basal reinforcement beneath embankments and geotextile reinforced soil walls (John 1987). Improvements in manufacturing techniques have resulted in geotextiles being widely used as they often have an economic advantage over some of the traditional methods, e.g. geotextile filters are often cheaper than sand filters.

LIST OF SYMBOLS

Basic SI units are given in parentheses

AOS	=	Apparent Opening Size (m)
C_u	=	coefficient of uniformity (dimensionless)
C_u'	=	linear coefficient of uniformity (dimensionless)
C_{95}	=	the constriction size such that 95% of the geotextile constrictions are smaller than C_{95} (m)
d_x	=	particle size that corresponds to a percentage = x, i.e. the particle size which is such that x% by mass of the soil particles are smaller than d_x (m)
FOS	=	Filtration Opening Size (m)
i	=	hydraulic gradient (dimensionless)
k	=	coefficient of permeability of a permeable medium (m/s)
n	=	porosity of the filter material (dimensionless)
O_{50}	=	the opening size such that 50% of the geotextile openings are smaller than O_{50} (m)
O_{90}	=	the opening size such that 90% of the geotextile openings are smaller than O_{90} (m)
O_{95}	=	the opening size such that 95% of the geotextile openings are smaller than O_{95} (m)
O_{98}	=	the opening size such that 98% of the geotextile openings are smaller than O_{98} (m)
O_{100}	=	the opening size such that 100% of the geotextile openings are smaller than O_{100} (m)
μm	=	microns

Table 2.1 Retention criteria for geotextile filters (Giroud, 1982).

	Relative density of soil	Linear coefficient of uniformity of the soil	
		$1 < C_u' < 3$	$C_u' > 3$
Loose soil	< 35%	$O_{95} < C_u' d_{50}$	$O_{95} < 9 d_{50}/C_u'$
Medium dense soil	35 - 65%	$O_{95} < 1.5 C_u' d_{50}$	$O_{95} < 13.5 d_{50}/C_u'$
Dense soil	> 65%	$O_{95} < 2 C_u' d_{50}$	$O_{95} < 18 d_{50}/C_u'$

The primary objective of these criteria is to ensure retention of the soil that is being filtered, i.e. to prevent migration of fine particles from the soil. Some of the above proposed design criteria have been incorporated into the design standards of various countries.

2.5.3 Permeability criterion

The permeability of a geotextile filter is addressed by considerations of relative permeability of the soil and the geotextile. Current drainage criteria require that the permeability of a geotextile should be some percentage of that of the retained soil, with suggested values varying between 10 and 1000% (Fischer et al. 1990). Giroud (1982) points out that the thickness of a geotextile filter is typically less than 1/100th that of a granular filter. The head loss across these two types of filters would therefore be of a similar magnitude if the permeability of the geotextile was 1/100th that of the alternative granular filter. Since the normal criterion for the coefficient of permeability of a granular filter is:

the d_{85}, which is the diameter such that 85% of the soil particles are smaller than that diameter. (As in soils, the O_{95} is used as opposed to the O_{100}, the largest opening size. This is because the measurement of the O_{100} is likely to fluctuate significantly from one sample to the next if there are only a few openings which may be present in one sample and not the other. The O_{95} is less likely to fluctuate due to the larger number of openings that have the O_{95} size in a geotextile sample.) The relationship is usually in the form:

$$\frac{O_{95}}{d_{85}} \leq x \tag{2}$$

, where x varies according to the design method. Typical values are 2-3 (Carrol 1983) and 1-2 (Christopher and Holtz 1985). Loudiere and Fayoux (1982) relate the O_{95} to the d_{50} with $x = 0.8$, Heerten (1982) the O_{90} to the d_{50} with $x = 1$. Ogink (1975), also relates the O_{90} to the d_{90} with $x = 1$ for woven geotextiles and $x = 1.8$ for nonwoven geotextiles.

The most complete relationship has been established by Giroud (1982), (see Table 2.1). It relates the O_{95}, the linear coefficient of uniformity C_u' and the d_{50} while taking into consideration the relative density of the material. For filtration applications, the central linear portion of the particle-size distribution is extrapolated and used to determine the linear coefficient of uniformity, C_u'. Thus, $C_u' = d_{60}'/d_{10}'$

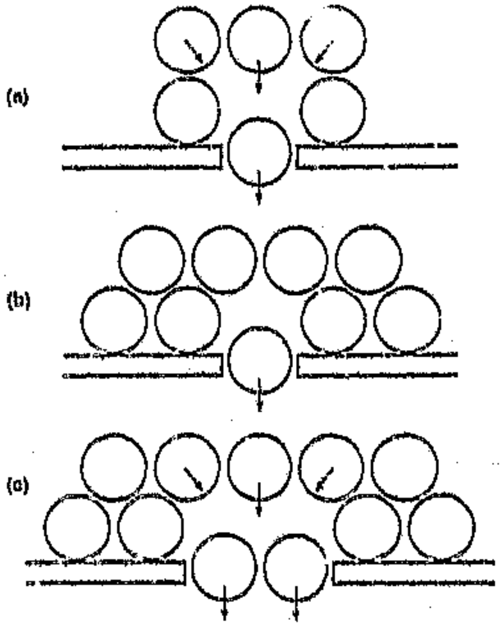

Figure 2.1 Filter opening size as a function of soil density.

It therefore appears that, in the case of a loose soil, the filter openings must be just smaller than the size of the particle that the filter is intended to retain, whereas, in the case of the same soil in a dense state, the filter openings can be twice as large as the particles the filter is intended to retain. This conclusion can be considered conservative, because soil particles are not spherical and it seems logical to expect non spherical particles to be less mobile, hence more stable, than spherical particles.

2.5.2 Retention criterion

The design of geotextiles according to the retention criterion usually involves relating the O_{95} to some characteristic diameter of the soil to be retained, e.g.

particle size analysis curve of the soil and the subscripts are the relevant percentage values.

If a soil has a coefficient of uniformity greater than three, there are not enough of the largest particles to form a matrix where smaller particles are interlocked. It is only at a lower level of particle size that a matrix of particles exists where smaller particles are interlocked. If the C_u of the soil is three or less, a geotextile filter that just retains the largest soil particles is adequate: it retains all the soil because all particles are entrapped in the matrix formed by the largest soil particles. If the C_u is greater than three, a geotextile that just retains the largest soil particles does not retain all the soil: the smaller particles are not entrapped within a matrix formed by the largest particles and they pass through the geotextile filter if they are dragged by the flowing water. Thus when the C_u of the soil is larger than three, the geotextile filter must be designed to retain the particles that form a matrix where the smaller particles are entrapped.

The relative density of the soil must also be taken into consideration when designing a geotextile filter. Figure 2.1a shows schematically that, in the case of a loose soil represented by a cubic arrangement of spheres, if one particle goes through the filter opening, then all other particles can follow it. In contrast, in the case of a dense soil represented by a hexagonal arrangement of spheres, the soil structure remains stable if only one particle goes through the filter opening (Figure 2.1b): the structure becomes unstable only if two particles can pass simultaneously through a filter opening (Figure 2.1c).

2.5 Design of Geotextile Filters

2.5.1 Introduction.

A geotextile filter, as any filter, must fulfil two criteria:

Retention criterion. A geotextile filter must have openings small enough to prevent migration of soil particles:

• Permeability criterion A geotextile filter must be permeable enough to not slow down the flow of water across the plane of the geotextile.

In critical applications, an additional safety margin against clogging may sometimes be incorporated by adopting an anti-clogging criterion. A geotextile filter can only prevent a significant amount of fine particles migrating, under the action of drag forces exerted by the flow, if the soil is internally stable. When checking whether a soil is internally stable, it is not sufficient to assume that it will be stable if the particle size distribution curve is continuous. Continuity of the particle size distribution curve is a necessary, but not sufficient, condition to ensure the internal stability of a cohesionless soil. For a cohesionless soil to be internally stable, particles of any given size must be entrapped in the matrix formed by particles of a larger size. As indicated by Giroud (1982), this is only possible if the particle size distribution of the soil has a coefficient of uniformity (C_u) of three or less. C_u is defined as:

$$C_u = \frac{d_{60}}{d_{10}} \qquad (1)$$

where d_{60} and d_{10} refer to the percentage by finer by mass points on the fifth designation. We thus need to plot these values on a log-normal paper. The two values will be the 212-micron size which has 60% passing and the 300-micron size which has 100% passing. To find the Apparent Opening Size (AOS) we extrapolate between these two values. The AOS was calculated to be 280 μm.

The hydrodynamic sieving technique requires a mixture of beads be sieved through the geotextile by immersion and withdrawal from water. Assume that the mixture consists of seven different sized beads which are retained on the first seven sieve sizes (from 75 to 850-micron sieves) and that there is 50 g of each size. The total mass of the mixture is thus 350 g and the coefficient of uniformity is approximately 3.5. If exactly the same distribution of beads passes through the geotextile as in the above discussion of the AOS procedure, then a total of 180 g have passed through the geotextile. To find the Filter Opening Size (FOS), we must plot the distribution of beads that have passed through the geotextile. We thus have a graph of the percentage finer by mass vs. particle size. The value corresponding to the 212-micron sieve is 83% (since, out of a total of 180 g, 150 g are finer than the 212-micron sieve, the other 30 g remained on this sieve. The calculation is thus 150/180 x 100%). For the 300-micron sieve, the value is 100% (since all the beads are smaller than this). Extrapolating between these two points to find the point where 95% is finer by mass, the FOS is found to be 228 μm

Thus there is a decrease of 19% from the AOS to the FOS. It obviously varies for each example, but it does serve as a good illustration of the difference in calculation method.

The results showed that in general, the image analysis, mercury intrusion, and dry sieving methods showed larger pore openings than the other methods. The hydrodynamic sieving, wet sieving, and bubble point methods showed smaller geotextile pore openings within a relatively narrow range, with the bubble point results generally on the lower end of this range. The hydrodynamic and wet sieving methods produced very similar results for all geotextiles.

The hydrodynamic sieving test generally gives smaller pore opening values (FOS) compared with the dry sieving AOS. This can be attributed to the use of a glass bead mixture as opposed to glass bead designations and there is also an important mathematical difference between calculating FOS and AOS. The calculation of AOS is based upon the percentage of beads, which have passed through the geotextile, of each individual designation. The calculation of this percentage value, is done separately for each designation. The value is thus calculated without using the results of any other bead size designation. The calculation of the FOS on the other hand takes account of all the beads that have passed through the geotextile. The FOS is the 95% finer by mass point of the mixture that has passed through the geotextile.

This mathematical difference is best illustrated by an example. Assume that no beads remain in the plane of the test specimen during testing. Consider the following results for a dry sieving test: all 50 g of glass beads passed through the geotextile for the first three glass bead designations (i.e. beads retained on the 75, 106 and 150-micron sieves), but only 30 g of the fourth designation passed through (beads retained on the 212-micron sieve) and 0 g of the fifth designation passed through (beads retained on the 300-micron sieve). Thus the point where 5% of the beads pass through is somewhere between fourth and

Mercury intrusion porosimetry and the bubble point test shared a common problem (Bhatia and Smith 1995). Both methods showed little difference in the results for geotextiles of various thicknesses of the same manufacturing process. Particles passing through a thicker geotextile have a longer path to travel and there is a greater possibility that the particle may become trapped. Thus thicker geotextiles made with the same manufacturing process generally have smaller opening sizes. Mercury intrusion porosimetry results were also affected by mercury (which is heavy) displacing fibres in the pore structure of the geotextile during the tests and this may lead to errors in the measured pore sizes.

The bubble point tests were furthermore found to be dependent on the method of interpretation of results. According to Vermeersch and Mlynarek (1996), the method can only be applied to geotextile products with the maximum pore size of 160 microns, although research is in progress to widen the technique to measure pore sizes up to 300 μm. This observation seems to be in contradiction of Bhatia et. al. (1994) who were able to measure opening sizes of up to 200 μm with this method. The staple fibre, mechanically-bonded geotextiles showed the least variation in their results and the heat-bonded geotextiles showed the greatest.

Wates and Wittstock (1986) concluded that image analysis provided the most reliable information on the pore size distribution of geotextiles. However, it is time consuming, involves specialized equipment and is expensive. In addition, there is no standard method for evaluating image analysis results. Results for the geotextiles tested were fairly repeatable.

of the original glass bead mixture. For dry and wet sieving, the effects of electrostatic forces cause the smaller beads to agglomerate and thus prevents them from passing through the geotextile.

Each method was found to perform better with some types of geotextiles than others. For hydrodynamic sieving, the heat-bonded geotextiles snowed the least variation in results and mechanically-bonded, continuous filament geotextiles showed the greatest. The heat-bonded geotextiles performed best with dry sieving, while the staple fibre and the continuous filament mechanically bonded had fairly high variability in the results. For wet sieving, the nonwoven continuous filament, mechanically-bonded geotextiles showed the least variation in results and the nonwoven, continuous filament, heat-bonded geotextiles showed the greatest.

Giroud (1996) states that dry sieving should only be used in very few circumstances. Dry sieving should not be used with glass beads because glass beads are electrostatically attracted by synthetic fibres. It should also not be used with needle punched nonwoven geotextiles because it gives incorrect values of filtration opening sizes (typically too large). Dry sieving with sand particles may be used with geotextiles that meet the following conditions: geotextiles which are very thin (where vibration energy does not therefore dissipate) and where fibres (or filaments) are tightly fixed and, consequently do not move during sieving. Giroud (1996) concludes that wet sieving and hydrodynamic sieving are the preferred methods and they give similar results. However, the results of wet sieving tests may depend on the operator and the resultant variation on the application of the water and thus he believes that hydrodynamic sieving is the most reliable of the sieving methods.

woven tape, woven monofilament, heat bonded and two nonwoven needle punched geotextiles. The results showed that the coefficient of variation depended greatly on the nature of the products. The values recorded were 4% and 13% for the two nonwoven needle punched geotextiles, 9% for the woven monofilter, 14% for the woven tape, and 27% for the nonwoven heat bonded geotextile. The fluctuation between values reported by different laboratories can easily be explained because the apparatuses used in the laboratories varied greatly. The types of testing particles were different, the surface area tested and the number of cycles also varied. Despite this, the values for the coefficients of variation are quite low.

Bhatia et. al (1994) and Bhatia and Smith (1995) made a number of interesting observations about the various testing methods. The three sieving techniques all have their problems. Dry sieving tests were hindered by glass beads becoming trapped within the geotextiles and by electrostatic forces which caused agglomeration of the glass beads below a diameter of 0.09 mm. Wet sieving tests were hindered by glass beads clumping together during the test, which prevented the particles from passing through the geotextile. The difficulty of passing water through low-permeability geotextiles was also a problem. The use of a glass bead mixture for both the wet and hydrodynamic sieving tests caused problems. When particles of many sizes are allowed to interact, particle blocking and bridge formation are very likely to occur. This results in fine beads, which are smaller than the pores of the geotextile, being prevented from passing through the geotextile by the coarser glass bead particles. The complete pore-size distribution curve obtained by all three methods is of little use. In the case of hydrodynamic sieving, at a certain point in the test, the glass beads passing through the geotextile are only a reflection particle shape has an influence on filtration opening size measurement, the measured filtration opening size will be more representative of actual field situations if sand/silt particles are used in the test rather than glass beads. Giroud (1996) concludes that both glass beads and sand particles can be used in sieving tests for the determination of geotextile filtration opening size.

2.4 Comparison Between Methods

A number of attempts at comparing the different methods have been made. A special working group of the ISO Committee, chaired by B. Myles, undertook inter-laboratory tests in 1990 (ISO TC 38/SC21). Five participating laboratories evaluated the FOS values of five different geotextiles using the hydrodynamic sieving technique and the results are discussed below. Comparisons have also been discussed by Wates (1980), Faure et. al. (1986), Miller et. al. (1986), Dierickx and van der Sluys (1990), and Goure and Faure (1990). Bhatia and Smith (1995) compare the results of O_{95} for dry, hydrodynamic, and wet sieving, for twenty-eight woven and nonwoven geotextiles. Bhatia, Smith and Christopher (1994), compare the O_{95} and pore size distribution for twenty-two nonwoven geotextiles using six different techniques (dry, wet, and hydrodynamic sieving, bubble po[illegible]rcury intrusion and image analysis). Fischer et. al. (1993) discuss the types of pore sizes and distributions obtained from current test methods, the similarities and differences between the methods and the uncertainties in the use of these pore sizes in geotextile filter design.

The geotextiles tested during the ISO TC 38/SC21 interlaboratory trials were a

Small variations on these basic methods have also been presented in order to measure the opening sizes under compression, i.e. under real operating conditions. Denis and Davies (1984) present a variation of the bubble point method under simulated soil loading conditions. De Wit (1985) developed a variation of the hydrodynamic sieving technique which allowed the filtration opening size to be measured while the geotextile was subjected to various stresses. To apply the stress, glass beads, that were large enough to allow free passage of the sand particles to be sieved and small enough to apply a rather uniform stress, were used.

It is interesting to note that Canada, USA and the UK use glass beads in their standard sieving tests, while most European countries use natural soil particles. Both have their merits. Rigo et al. (1990) state that in selecting particles to perform these tests, five parameters must be considered: - chemical composition, relative density, particle shape, their size distribution and the total amount of particles used for the test. The use of glass beads erases the influence of the first three parameters in the tests (Rollin et al. 1990). Since they are very regular spheres, agglomerations are impeded. Their mineralogical characteristics are similar to those of natural soils, and their relative density is comparable to sand and silica particles (between 2.4 and 2.6)(Rollin et al. 1990). These observations are confirmed in a comparative study performed on the two types of particles, namely silica and glass beads, by Rollin et al. (1990). The silica particles tended to agglomerate, which made the interpretation of the results very difficult. The use of natural soil has the added disadvantage that very strict procedures have to be applied to ensure that laboratories perform the tests with particles having identical density, chemical nature and shape. On the other hand, it may be argued that, if indeed

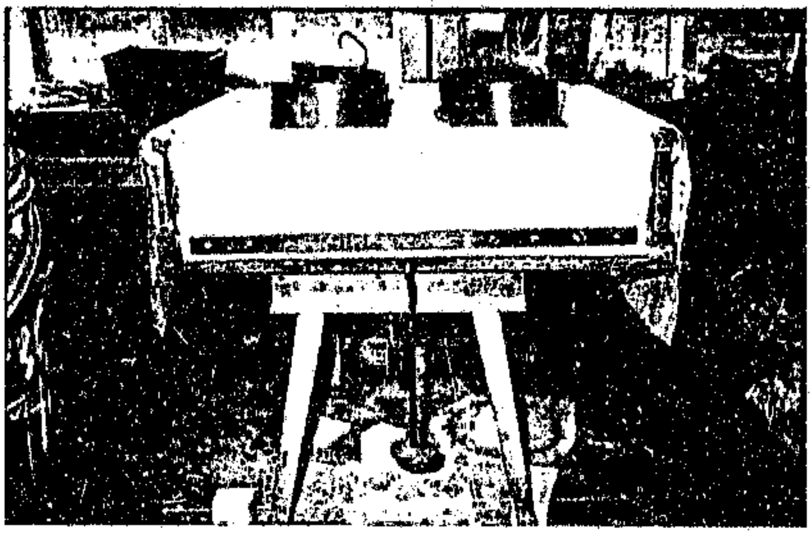

Figure 3.2 The loading frame with geotextile specimen just after tensioning (note the four cylinders from the hydrodynamic sieving mechanism on top of the geotextile).

3.3 Permeameter

The permeameter allowed for the upward flow of water. It was made from 12 mm thick mild steel and had a rubber lining on the inner surface which prevented the corrosion of the steel cell. It had an inside diameter of 250 mm and a total height of 295 mm. It consisted of two halves with a clamping ring and a rubber O-ring fitting in between. For a photo and schematic diagram, see figures 3.3 and 3.4.

The four edges of the geotextile were clamped in loading yokes. The yokes held the geotextile in position during loading and they transferred the load from the load stand to the geotextile. They had the same length as the rollers, i.e. 1.1 m, and consisted of two steel bars which had a width of 50 mm and thickness of 20 mm. Each bar had eleven evenly spaced bolt holes. A strip of rubber was glued to the inside of each of the bars to increase the grip onto the geotextile. The geotextile was held between the bars by means of sharp edged bolts (with a diameter of 8 mm) that were driven through the fabric and the yokes and then bolted. Underneath each clamp there was a central hook from which a load stand could be hung. Weights were placed onto the stand until the required tensile load was developed (see figure 3.2).

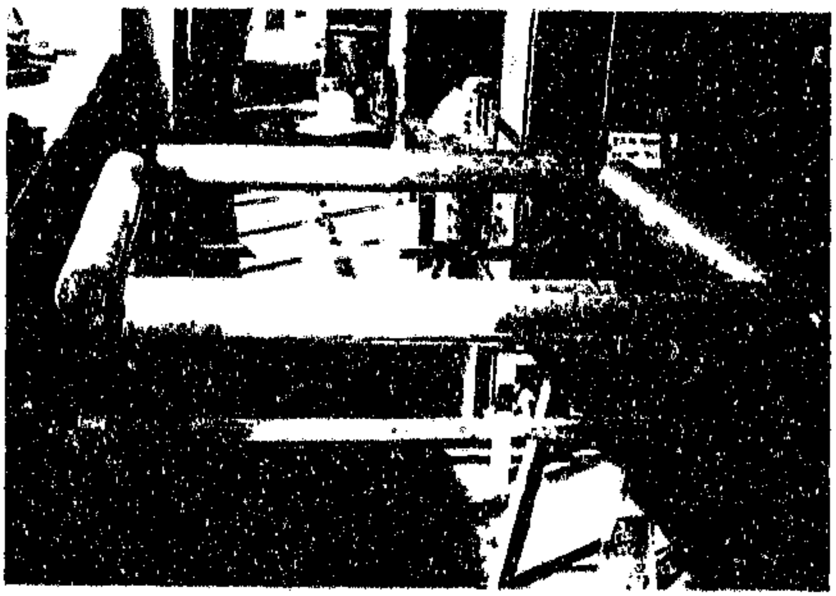

Figure 3.1 The loading frame.

3.2 Loading Frame

For all the tests, the geotextiles were first tensioned in the loading frame (see figure 3.1). The frame had to be large enough to accommodate both the permeamter and the cylinders from the hydrodynamic sieving mechanism. The four cylinders were the limiting factor because they had an external diameter of 340 mm and were all to be used together. The frame was thus designed so that it allowed an area of geotextile approximately 1.15 m by 1.15 m to work with.

The loading frame consisted of three parts. There was the frame itself which was made from hollow rectangular mild steel tubing, the four rollers that sat on top of the frame and the four loading yokes that enabled the geotextile to be clamped prior to it being placed on the rollers. The outside dimensions of the frame were 1.35x1.35x0.3 m high. It consisted of a square base with eight vertical stands on to which the rollers were placed. There were thus two stands per roller. They were positioned at the corners of the frame (two per corner) at right angles to each other and had specially cut grooves at the top that allowed the rollers to rotate but restricted any lateral movement. The mild steel tubing was 50 mm wide, 25 mm thick and has a wall thickness of 1.5 mm.

The four rollers were 1.1 m in length and 120 mm in diameter. They had extensions at each end which consisted of a steel bar, 50 mm long and 8 mm thick. The rollers were placed at right angles to each other with the extensions fitting into the grooves of the frame. Since the frame and rollers were 300 mm high, the entire loading frame was placed on two trestles. This allowed the yokes and load stands to hang from the side of the frame.

CHAPTER 3

DESCRIPTION OF EQUIPMENT

3.1 Introduction

One of the topics under investigation in the research conducted, was the effect of biaxial tensile loading on the permeability of geotextiles. The potential change in the permeability was studied with the aid of a large diameter permeameter. This permeameter was used previously (as discussed in section 2.7) and was ready for use. To study the potential change in the pore openings, one of the many available techniques for measuring the O_{95} of a geotextile, the hydrodynamic sieving technique, was used.

To tension the geotextile, a loading frame was designed that enabled tensioning either equally in two directions or unequally in two directions. The design needed to be strong enough to allow loading of up to 2.5 kN/m. The loading frame and the sieving mechanism were designed together. The frame had to be large enough to accommodate the four cylinders of the hydrodynamic sieving mechanism, while the sieving mechanism had to have detachable cylinders that were able to maintain the tension in a pretensioned geotextile.

2.8 Conclusion

The following conclusions can be drawn from the above literature survey. In certain situations, geotextiles are subjected to biaxial tensile loading. It is probable that the biaxial loading will deform the pore openings of the geotextiles. This deformation may change certain properties of the geotextile such as the permeability and the largest apparent opening size (O_{95}).

The importance of the O_{95} in the design of geotextile filters was discussed. The different methods used for determining the O_{95} were outlined and compared. It was decided to use one of these methods to study the effects of tensile loading on the O_{95} of geotextiles. Possible improvements and an expansion of a previous study on the permeability of uniaxially tensioned geotextiles were also suggested.

A fairly dramatic decrease appears to occur in both the woven and the nonwoven geotextile. The initial decrease in flowrate followed by relatively constant flow, can be ascribed to the formation of a filter zone upstream of the geotextile. It corresponds well with previous studies of long term filtration behaviour by (for example) Van der Merwe and Horak (1989).

This topic thus obviously required further investigation. A few possible improvements were also considered. Firstly, there is the problem of biological clogging. The effects of this were discussed by Chin et. al (1994). The growth of micro organisms on a geotextile severely reduced its permeability and was the main cause for surface clogging. After inserting a disinfectant into the water supply, they recorded a distinct increase in the permeability after a short time lag. Secondly, the geotextile was tensioned in only one direction. As a result of the specimen being relatively narrow (1,0 m wide), severe necking occurred. For the woven geotextile, there was a 10% reduction in the width, and a 20% reduction was recorded for the non woven geotextile. It is easy to imagine that such a change in a specimen's dimensions would change the shape of the opening sizes dramatically and thus reduce the permeability. This situation is also unlikely to occur in-situ. For geotextiles used as reinforcing layers beneath fills constructed on soft soils, there is likely to be straining in the direction perpendicular to the axis of the embankment, while parallel to the axis there would be very little strain, but an induced stress due to the resisting of necking. Thus the situation of a geotextile being stressed in one direction only is unlikely to happen.

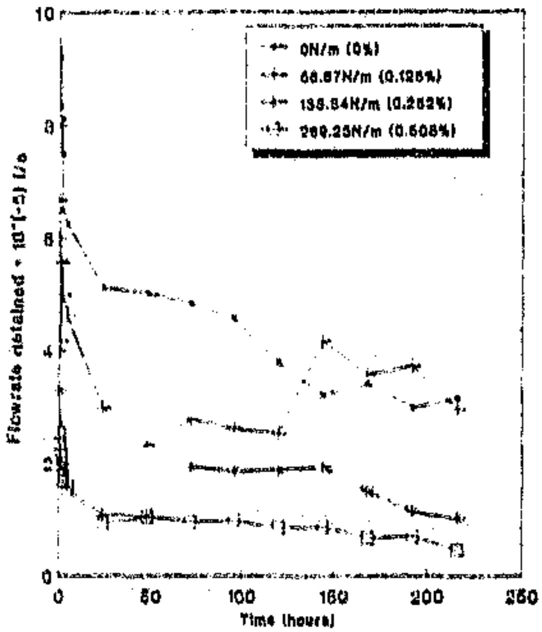

Figure 2.2 Flowrate versus time for the woven slit-film geotextile (after Kuchena, 1994)

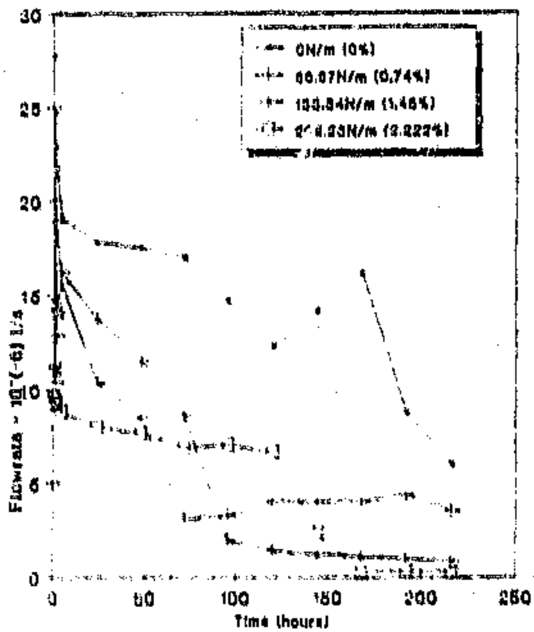

Figure 2.3 Flowrate versus time for the nonwoven needle punched geotextile

monitoring results reported by Schimelfenyg et al. (1990), who instrumented a geotextile reinforced containment dike constructed on soft soil deposits. They reported differential strains of up to 3%. Further examples of geotextiles that can be subjected to in-plane tensile strain are their use as filters or drains in leachate collection layers below landfills or mine tailings' dumps, where differential settlements are possible.

2.7 A Previous Study of The Effects of Tensile Loading on Geotextiles

Kuchena(1994) studied the effects of a uniaxially tensioned geotextile on the permeability of geotextiles. The work carried out for this dissertation is partly a continuation of Kuchena's work with a few refinements. Three types of geotextile were tested. Two woven slit film geotextiles and one nonwoven needle punched geotextile. A piece of geotextile with dimensions of 1 m wide and 1.4 m long was tensioned in a specially constructed loading frame. This frame allowed the geotextiles to be tensioned in one direction only.

The geotextiles were clamped in a specially constructed permeameter and subjected to an upward water flow. For a more detailed description of the permeameter, see the description of apparatus (chapter 3). The decrease in permeability is illustrated by figures 2.2 & 2.3. The loads and percentage of tensile strength are given in the legend.

rise in the gradient ratio, whereas internal erosion is detected by a continuous fall in the gradient ratio.

2.6 Tensile Straining of Geotextiles

Although the effect of a compressive force perpendicular to the plane of the geotextile has long been recognised (Giroud 1983), the importance of tensile strains in the plane of the geotextile appears to have been ignored. Giroud (1980) and Gourc and Faure (1990) have alluded to the problem, but little experimental work on the effect of tensile strains appears to have been carried out.

The effect of an in-plane tensile load is likely to be to reduce the geotextile openings, thus accelerating clogging or blinding problems. This would be particularly true if tensile strains occurred within the plane of the geotextile, and more strain occurred in one orthogonal direction than the other. An example of this is the use of geotextiles as reinforcing layers beneath fills constructed on soft soils where proper filtration is essential in allowing drainage and dissipation of pore pressure in soft soils. In this type of application, as discussed by Rowe and Mylleville (1990), the geotextile strain in the direction perpendicular to the axis of the embankment may be as much as 10%. In the direction of the embankment axis little or no differential settlement of the embankment occurs, and the straining of the geotextile will be solely as a result of the geotextile resisting the induced necking that would result from the strain. It is unlikely that these two orthogonal strains will be equal, and differential in-plane strain is thus likely. This is supported by the should be designed to accommodate these particles. If the particles displaced by water do not pass through the filter, they interact with the filter, i.e. they interact in three different ways:

-Soil particles may form a thin layer (often called cake) at the surface of the filter. This mechanism is sometimes referred to as "blinding" of the filter.

-Individual soil particles may obstruct geotextile filter openings. This is possible in the case of filters with individual openings such as woven geotextiles. This mechanism is sometimes referred to as "blocking" of the filter.

-Soil particles may become entrapped within the filter. This is possible in the case of thick filters, such as needle punched nonwoven geotextiles. This mechanism is sometimes referred to as "clogging" of the filter. However, the term "clogging" is also used to encompass the three mechanisms described above.

In general, a geotextile filter will fail due to clogging because the geotextile was not placed in good contact with the soil. No simple design criterion exists to determine potential clogging. Laboratory tests that determine the geotextile-soil compatibility (such as the gradient ratio test) are the easiest way to explore this potential problem (Shi et. al. 1994). The gradient ratio test involves placing the geotextile and the soil sample in a special form of constant head permeameter, called a Calhoun permeameter, and monitoring the head loss as the water flows through the soil and the geotextile. The gradient ratio is defined as the ratio of head loss across the geotextile and the adjacent 25 mm of soil to the head loss in the next 50 mm of the soil. This ratio should stabilize with time as a natural soil filter becomes established within the soil adjacent to the geotextile. Clogging is detected by a continuous the geotextile (units of s^{-1}). The permittivity must be larger than ten times the coefficient of permeability of the soil (units of m/s). This relationship can be used for all types of geotextiles because permittivity is easy to measure for all geotextiles. The coefficient of permeability should only be used with geotextiles whose thickness is sufficient to allow the accurate measurement of the coefficient.

2.5.4 Geotextile filter clogging

A geotextile filter can successfully retain a soil if the following conditions are met:

-The soil has a continuous particle size distribution and it is in a dense state, which ensures maximum interlocking of the soil particles.

-The geotextile filter openings are properly selected, as discussed above.

-The soil is in close contact with the geotextile filter, so there is no open space between the soil and the geotextile where particles could move or accumulate.

Even when the above conditions are met, some soil particles move when water flows towards the filter: those few small particles that are at the surface of the soil, next to the filter, and therefore, are not entrapped in the soil structure. More soil particles are displaced by the flow of water when the above conditions are not met.

Soil particles that are displaced by water flow may pass through the geotextile filter and migrate into the drain, e.g. geotextiles used in fin drains, trench drains, highway shoulder drains etc. If this is expected to happen, the drain

$$k_{filter} > 10\, k_{soil} \tag{3}$$

Then, for a geotextile filter it should be:

$$k_{geotextile} > 0.1\, k_{soil} \tag{4}$$

Such a low value for the geotextile permeability however, does not allow for any long-term clogging or blocking of the geotextile. Tests conducted by Heerten (1982) on thick mechanically bonded nonwoven geotextiles recovered after about 10 years of service, indicated that clogging of the geotextile while in use, reduced the permeability to between 60% and 5% of the original value. Most authorities therefore recommend that the coefficient of permeability of the geotextile should not be less than that of the soil (John 1987). Thus, the most widely used permeability criterion is:

$$k_{geotextile} \geq k_{soil} \tag{5}$$

A theoretical relationship between void distribution (opening size and porosity) and the permeability of geotextiles has also been established (Giroud 1982). A similar relationship was already known for soils. Comparing these two relationships led to a chart being created that gives the minimum value for the openings O_{50} of the geotextile as a function of the density of the soil, the porosity of the geotextile and the ratio between the coefficients of permeability of the geotextiles and the soil: this must not be smaller than one. A value of ten is recommended for this ratio.

The permeability criterion can also be expressed in terms of the permittivity of

4.4.3 Particle size distribution of the sand

The particle size distribution of the river sand was determined in accordance with BS 1377. The results are presented graphically in Figure 4.1. Note that the finest size particles are retained on the 75-micron sieve. Any other particles finer than this were washed out. The initial test in the permeameter showed that there was a possibility that the finer particles could be clogging the needle punched geotextile. Since the effect of tensile straining on the geotextile was to be monitored, the sand was made as permeable as possible by washing out particles finer than 75 μm and so potential clogging was also eliminated.

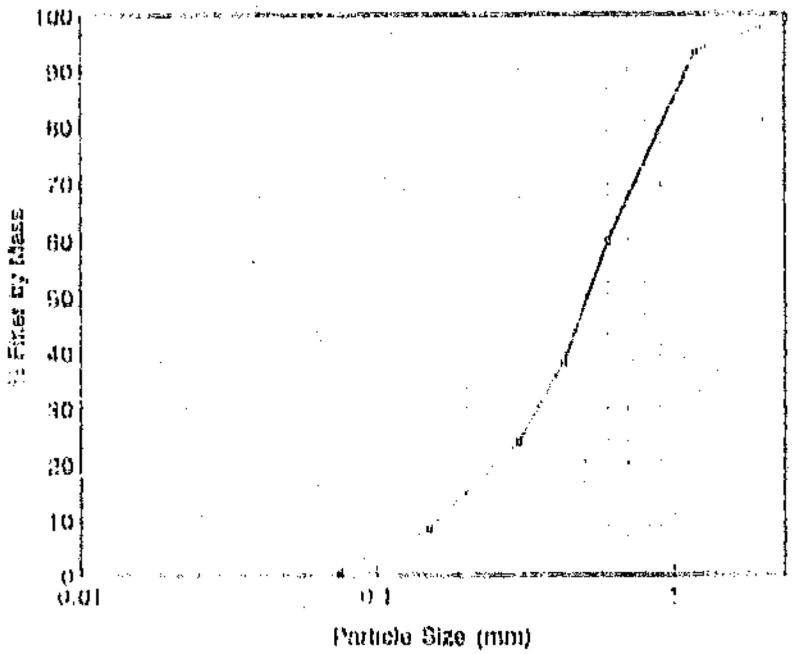

Figure 4.1 Particle Size Distribution Curve of the sand used in the permeameter.

which is much smaller than the value given in table 4.1 of 3x10[illegible] m/s. Thus it is likely that the permeability is much higher for the woven geotextile and thus the permeability criterion would be satisfied. Initial tests using the woven geotextile in the permeameter, showed that the flowrate was determined by the soil and not the geotextile which indicates that the permeability criterion was satisfied.

4.4.2 Retention criterion

Since the permeability criterion had been satisfied, the retention criterion needed to be investigated. The d_{95} of the sand was 1.0 mm. The FOS of the geotextiles was not given in the manufacturers' specifications but they were measured using the hydrodynamic sieving technique. The values calculated were 0.737 mm for the woven geotextile and 0.153 mm for the nonwoven needle punched geotextile.

There are many different methods for the design of geotextile filters as previously discussed. When designing according to the criterion of Giroud (1982) and thus using table 2.1, the following equation needs to be satisfied:

$$O_{95} < \frac{13.5}{C_u'} d_{50} \qquad (6)$$

Where C_u' is the linear coefficient of uniformity of the soil and is equal to the d_{60}'/d_{10}'. For the sand considered the d_{60}' = 0.6 mm and the d_{10}' = 0.14 mm. Thus, C_u' = 4.3. The value of the d_{50} is 0.5 mm and using equation 6, the O_{95} < 1050 μm. Thus, both geotextiles fulfill the retention criterion.

geotextile to be observed. When designing geotextile filters, a retention criterion and a permeability criterion need to be satisfied. A river sand was initially chosen because out of the three soil types that were considered, it had the highest permeability. Its permeability was measured under constant head conditions and found to be $k = 1.09 \times 10^{-4}$ m/s.

4.4.1 Permeability criterion

The permeability of a geotextile filter should be sufficient to ensure that there is no unacceptable increase in the hydrodynamic pressure. Since we know the permeability of the geotextile, and using one of the permeability criteria, we can calculate the minimum required permeability of the soil. From section 2.5.3, the permeability criterion recommended by most authorities is given by the following equation:

$$k_{geotextile} > k_{soil} \tag{5}$$

From table 4.1, the nonwoven needle punched geotextile has a permeability of $k_{geotextile} = 3 \times 10^{-3}$ m/s. Since the sand has a permeability of $k_{soil} = 1.09 \times 10^{-4}$ m/s, the permeability criterion was easily satisfied. For the woven geotextile, no permeability was given in the manufacturers specifications. An estimat can be made from the value given for the water percolation. The units of ℓ/m²/s can easily be converted to m/s. Thus we have an approximate $k_{geotextile} = 0.9 \times 10^{-3}$ m/s, for the woven geotextile. Although this value is smaller than the permeabilty measured for the soil, it can be seen that if the same conver:ion is carried out for the nonwoven geotextile, we have a $k_{geotextile} = 0.2 \times 10^{-1}$m/s

Table 4.1 Details of the geotextiles tested.

Type of geotextile	Woven Slit-film	Needle-Punched
Composition	Polypropylene Tape	Polyester
Thickness (mm)	0.91	2.3
Mass per unit area (g/m^2)	210	270
Tensile Strengths[1] (kN/m)	Warp: 45 Weft: 24	Multi: 21 Single: 14
Elongation (% Min/Max)	Warp: 20/35 Weft: 10/20	Multi: 27/30 Single:50/70
Permeability[2] (k) (10^{-3} m/s)	Not given	3
Water percolation[3] ($\ell/m^2/s$)	90	200

Notes: (1) The needle punched nonwoven geotextile does not have a visible warp and weft direction. The values are thus for one-directional tension and multidirectional tension.

(2) The permeability is measured under a 2 kPa normal stress

(3) The water percolation of the woven geotextile is measured for a head of 100 mm. The value for the nonwoven needle punched geotextile was measured for a head of 400 mm.

4.4 Choosing the Soil

The governing criterion when selecting the type of soil, was one with high permeability. This would allow the influence of the tensile stress on the taken at intervals of approximately 24 hours.

Four tests were carried out on the nonwoven needle punched geotextile. For three of the tests, the geotextile was tensioned biaxially. There were two tests that had different loads in the two directions, and one was loaded equally. The loading was as follows:

1. Untensioned
2. 365 N/m and 365 N/m
3. 365 N/m and 187 N/m
4. 365 N/m and 544 N/m

Note that this loading is in comparison with a tensile strength of 21 kN/m.

For the woven geotextile, there were also four tests carried out. The loading was as follows:-

1. Untensioned
2. 544 N/m and 544 N/m
3. 544 N/m and 365 N/m
4. 365 N/m and 187 N/m

This compares with a multidirectional tensile strength of 50kN/m.

4.3 Details of Geotextiles Used

The manufacturer's specifications of the geotextiles are given in table 4.1.

CHAPTER 4

TESTS PERFORMED USING THE PERMEAMETER

4.1 Introduction

To study the effects of biaxial tensile loading on the permeability of a geotextile, a large diameter permeameter was used as discussed in the previous chapter. The geotextiles were pretensioned in a specially constructed loading frame. They were tensioned up to a maximum of only 3% of their tensile strer. The loading varied from being equal in all four directions to being equal in only two directions. The geotextiles were clamped in the permeameter and placed into close contact with fine grained river sand. The permeameter was subjected to an upward water flow from a constant head tank. The flowrates were monitored and plotted on a graph of flowrate versus time.

4.2 Description of The Testing Program

Two types of geotextiles were investigated, a woven slit-film and a nonwoven needle punched geotextile. A total of eight tests were carried out. Each test lasted for a period of 500 hours and after the initial 48 hours, readings were

100 mm during the immersion cycle and lifted completely out of the water during the emersion cycle. The speed of the piston could be adjusted, and the duration of the immersion and the emersion cycles could be set using the timer. A counter kept track of the number of cycles.

The water pans had to be large enough to hold the cylinders, and the displaced water that occurred when the cylinders were first inserted into the pans. The pans were thus 530 by 430 and 240 mm deep. When in operation, the pans were filled to a height of 150 mm.

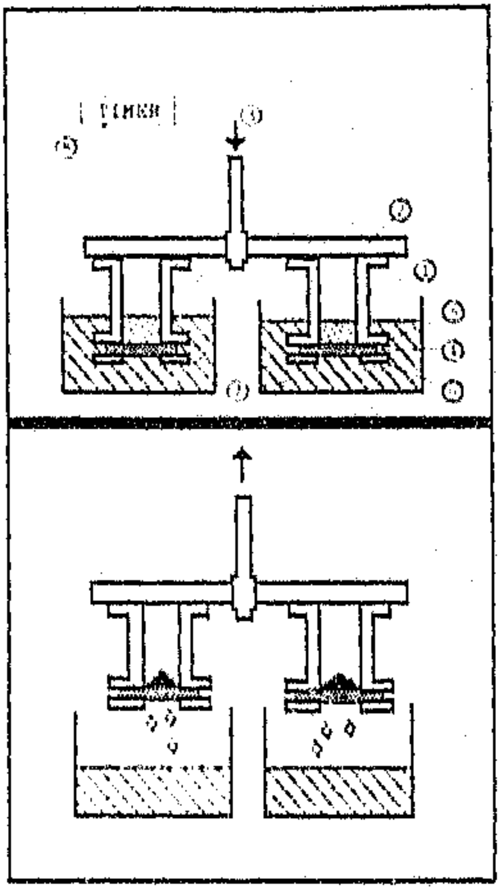

Figure 3.6 Schematic of immersion and withdrawal of the specimen (Mlynarek et. al. 1994)

The frame connected the cylinders to the pneumatic device. This allowed the cylinders to be inserted and withdrawn from the water pans. The design of the frame was such that the cylinders were held in a vertical position with the flanges parallel to the surface of the water.

The pneumatic ram had a stroke of 150 mm and was capable of working with compressed air of up to 800 kPa. It had an air filter and oil could be added to the compressed air for lubrication of the ram. When the water pans were filled and placed underneath the cylinders, the cylinders were filled up to a height of the frame by means of four 6 mm diameter bolts. They were thus easily detachable, so that they could be placed on top of the geotextile that was being tensioned in the loading frame. This was done prior to the geotextile being bolted to the cylinder.

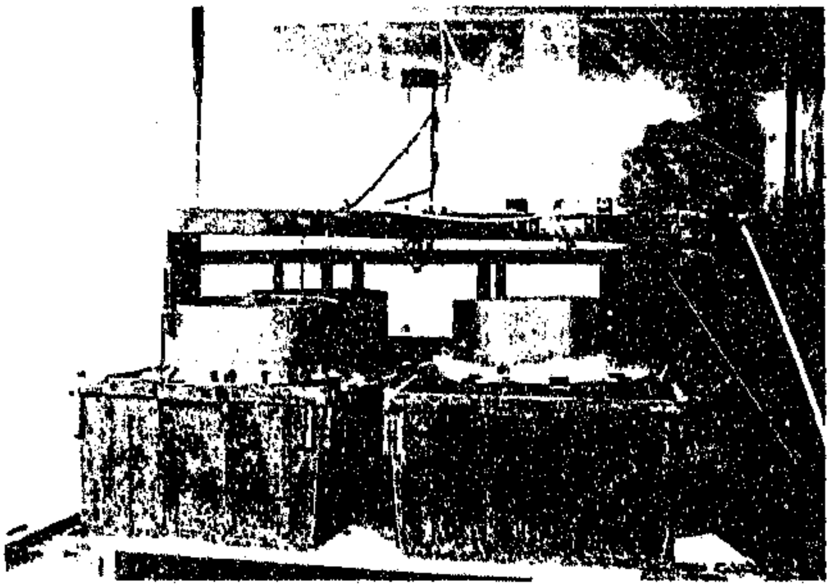

Figure 3.5 Photograph of the hydrodynamic sieving mechanism.

head loss radially through the soil sample in the cell was determined by manometers, and it was used to identify soil clogging during the course of the test. Piezometer connections were placed at heights of 20, 40, 60 and 80 mm above the base. There were three connections per level and they were placed at 120° to each other. The pipes leading from the piezometer connections to the manometer board had an outside diameter of 4 mm and inside diameter of 1.5 mm. The outlet pipe allowed the water to run into a basin which sat on a scale. In this way the flowrate and thus the permeability could be measured.

3.4 Hydrodynamic Sieving Mechanism (HSM)

The testing device had to be built and the design was based on the information supplied in the paper by Mlynarek, Lafleur, Rollin, and Lombard (1993). As shown in figures 3.4 and 3.5, the testing device consisted of four polyvinyl chloride (PVC) cylinders (donated by DPI Plastics (Pty) Ltd.) with open ends (1) fixed on a frame (2). The frame was connected to a pneumatic device (3) that permitted the cylinders to be immersed and withdrawn from the water pans (7) located underneath each basket. A geotextile specimen (4) was held in position by the two flanges (6) and (5).

The cylinders had open ends and 295 mm inside diameter, a height of 150 mm and thickness of 17 mm. Each cylinder had two flanges, made from HDPE, which have an outside diameter of 335 mm, an inside diameter of 315 mm and a thickness of 6 mm. Each flange had eight bolt holes. The first was glued to the bottom of the cylinder. The second flange was bolted onto the first after the geotextile had been placed between them. The cylinders were attached to

The bottom half of the permeameter, which contained the inlet spout, had a height of 165 mm. The sand was placed in this half of the cell and the thickness of the wall allowed the sand to be compacted to the required degree of compaction. The use of an upward water flow in the permeameter was an attempt to eliminate the inaccuracies caused by air which can become trapped during the downward flow of the water (Ryncroft and Dennis, 1982). Even when it was filled with sand, the permeameter remained mobile enough so that it could be placed below the geotextile which was being tensioned in the loading frame. The geotextile was placed into direct contact with the sand since the clamping ring was positioned over the geotextile and was then bolted onto the bottom half of the permeameter. The clamping ring had an external diameter of 515 mm and an internal diameter of 290 mm. This meant that the ring had a slightly larger internal diameter than the permeameter. It was rubber lined on both sides, to increase its grip, and it had twelve bolt holes that enabled the geotextile to be held in position. This was achieved by means of sharp ended bolts (diameter of 8 mm) which were driven through the geotextile and then bolted. The rubber O-ring sealed the gap between the two halves and it ensured that the apparatus remained water proof throughout the duration of the test. The diameter of the circular section of geotextile that remained inside the permeameter was 515 mm.

The top half of the permeameter, which had a height of 130 mm, contained the outlet pipe. It was placed on top of the O-ring and the clamping ring before it was bolted onto the bottom half. The water was supplied by a constant head tank which had as a capacity of 50 ℓ and it was designed so that the constant head was adjustable. It was connected to the permeameter with a piece of plastic piping which had an internal diameter of 5 mm. The applied head and

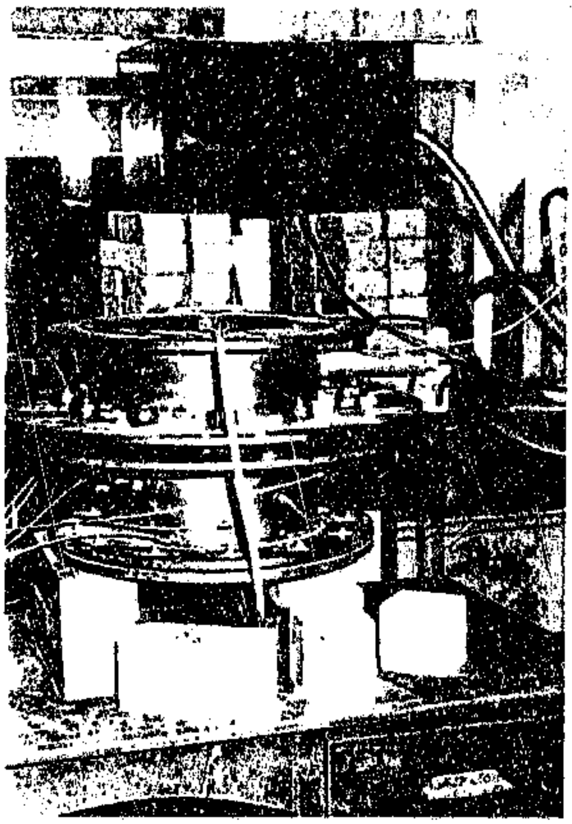

Figure 3.3 Photograph of permeameter and constant head tank

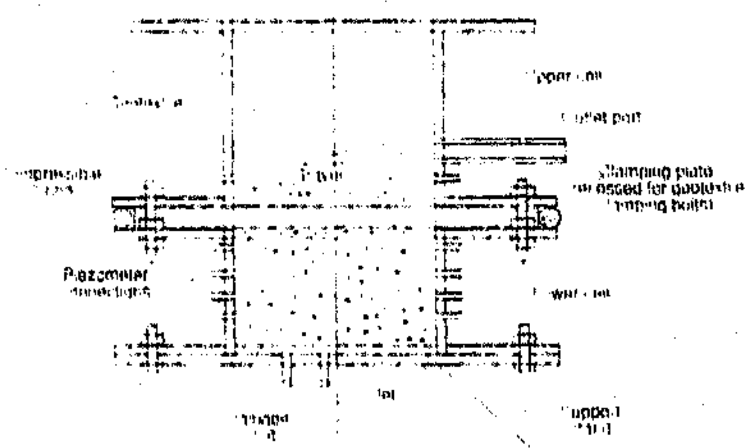

Figure 3.4 Schematic of permeameter used for testing permeability of a tensioned geotextile. (after Fourie and Kuchena, 1995).

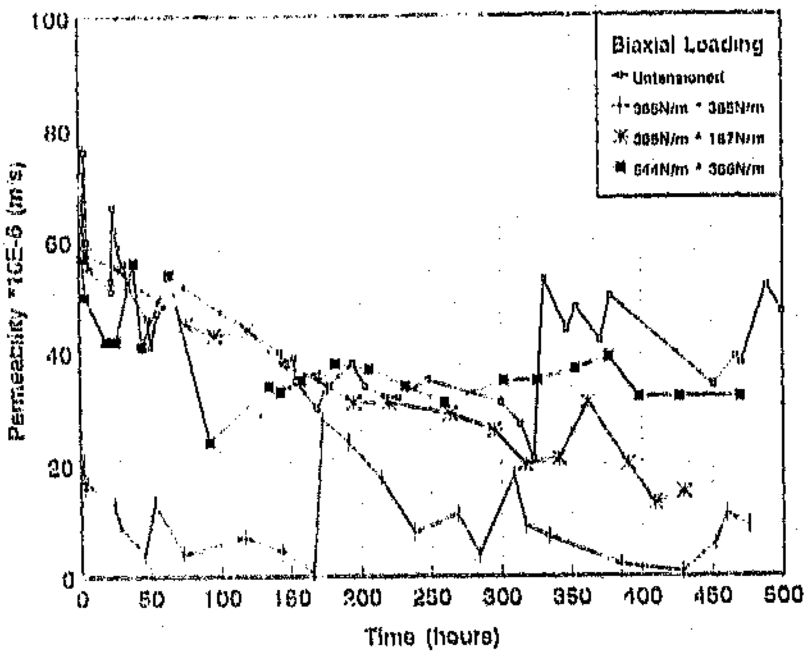

Figure 4.5 Graph of permeability vs. time for the nonwoven geotextile

The manufacturers specifications have a permeability of $3x10^{-3}$ m/s.

4.8 Discussion of Results

As can be seen from figures 4.2 to 4.5, there were no clear trends which indicated a reduction in permeability with increasing tension of the geotextile. Tests carried out with the hydrodynamic sieving mechanism did indicate a reduction in the opening sizes of the geotextile with tensioning (as described in chapter 5). This change was not reflected by the permeameter results, where a number of problems were encountered.

For the woven geotextile, the only time when the untensioned geotextile has the highest flowrate, is between 80 and 225 hours. The reason for the flowrate

4.7.3 The plot of permeability vs. time

The flowrates in figures 4.2 and 4.3 can be converted to permeabilities and it is interesting to compare these with the permeabilities that are given in the manufacturer's specifications for the geotextile (see Table 4.1).

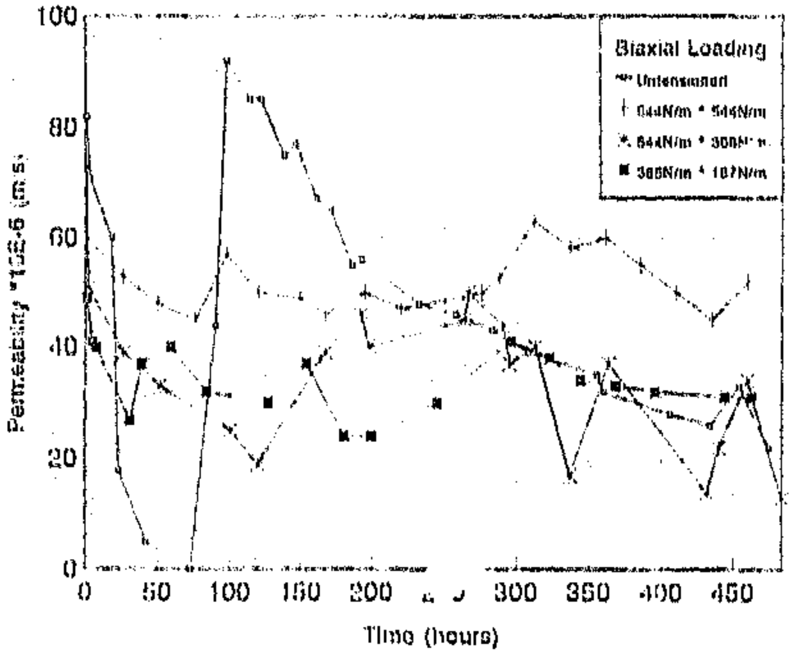

Figure 4.4 Graph of permeability vs. time for the woven geotextile

This compares with an approximate permeability of $90x10^{-6}$ m/s (see section 4.4.1 for the derivation of this approximation).

4.7.2 The plot of flowrate versus time

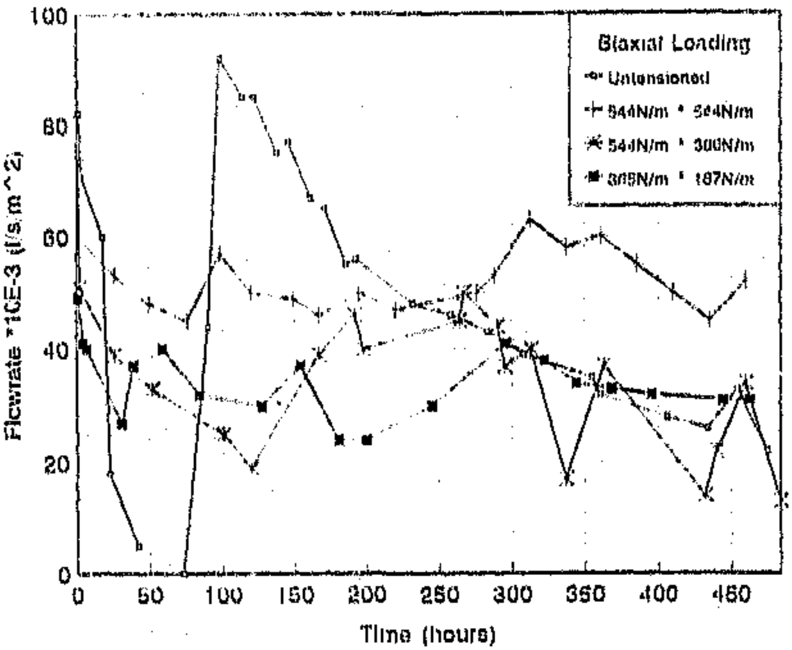

Figure 4.2 Graph of flowrate vs. time for the woven geotextile

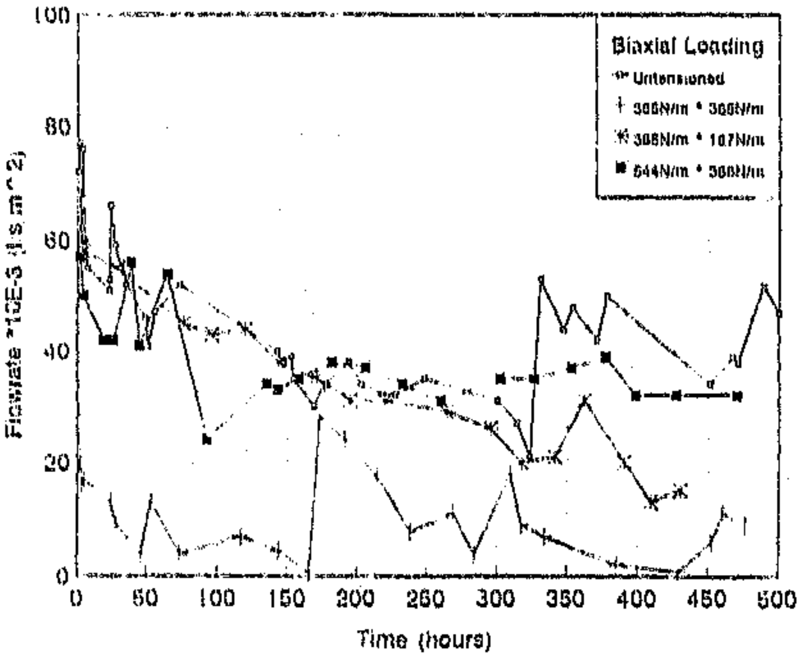

Figure 4.3 Graph of flowrate vs. time for the non woven geotextile

Table 4.2 Approximate strains of the woven slit-film geotextile

Biaxial Loading(N/m)	Approximate Strains (%)	
	Warp	Weft
544 & 544	1.6	1.3
544 & 366	1.8	1.6
366 & 187	1.2	1.8

Table 4.3 Approximate strains of the nonwoven needle punched geotextile

Biaxial Loading (N/m)	Approximate Strains (%)
366 & 544	2.4 & 3.1
366 & 366	2.4
366 & 187	3.6 & 1.5

- The final permeability was usually less than that of the soil or the geotextile and was a function of the filter zone in the soil and not the geotextile. The exact pore size of the geotextile was thus not important.
- Continuous piping occurred only where the opening sizes of the geotextile were 2 mm or larger.
- Where natural (granular) filters were tested, their performance was similar to that of geotextiles.
- The flow through a soil/geotextile system is a complex phenomenon, and can only be evaluated by long term tests.

4.7 Results of the Permeameter Tests

The results included the approximate strain measured, the flowrates and permeabilities recorded. The flowrates were measured in terms of the litres of water collected in the container connected to the outflow pipe. These values were then converted to litres per second and divided by the area of the geotextile in contact with the sand which was 0.49 m^2. The conversion of flowrate to permeability is accomplished by converting from litres to m^3 and thus the units become m/s.

4.7.1 Strain measured

The approximate strain measured for both the woven and nonwoven geotextiles are given in tables 4.2 and 4.3 below.

enable measurable flows. A hydraulic gradient of greater than 3 can result in piping erosion of the sand through the geotextile. This would result in the permeability failure of the soil-geotextile system

4.6 Mechanisms Involved in Filtration

Long term flow tests have been used by a number of researchers (Lawson 1986; Greenway et. al. 1986; Polycroft et. al 1982; Koerner et. al. 1982) to evaluate soil/geotextile compatibility in the laboratory. Although the tests were performed in different laboratories using different test apparatus and methods, certain aspects of the results were similar, thus allowing some general conclusions.

- There was an initial decrease in the permeability, followed by a relatively constant flow. This is ascribed to the formation of a filter zone upstream of the geotextile (Rankilor, 1981). At the beginning of the test, the original soil structure is intact, up to the soil/geotextile interface. The permeability is then the permeability of the soil. As the test continues, water washes the fine particles out of the zone adjacent to the geotextile, resulting in a certain amount of piping. At the same time particles build up in a zone just upstream of the first zone, thus forming a filter zone. The decrease in permeability continues until the forming of the filter zone has been completed, after which the permeability remains constant.
- The magnitude of decrease in permeability was typically a factor of 10, but varied in some cases, indicating some clogging with certain soil-geotextile combinations.

4.5.5 Taking readings

This proved to be a relatively simple task. As soon as the water started to pour out of the outlet pipe and into the bucket, a timer was started. For the initial five hours, readings were taken every hour. This was done because of the initial dramatic decrease in the flowrate. The reading on the scale was recorded and the scale was zeroed. The next reading was taken 24 hours after the first and after that a reading was taken every 24 hours.

4.4.5 Addition of disinfectant

As previously discussed, the growth of micro organisms on a geotextile severely reduces its permeability and can be the main cause for surface clogging (Chin et. al. 1994). It was thus decided to add a disinfectant to the water supply. A cup of bleach was added every second day to the constant head tank. The effect of adding the bleach was studied during the initial testing. The addition of bleach after a week of testing resulted in an increase in the flowrate. This seems to confirm the growth of micro organisms on the geotextile.

4.5.6 The Hydraulic Gradient

The hydraulic gradient was calculated as the head of water divided by the thickness of the sand layer. The head of water was 500 mm and the sand layer 200 mm. Thus, the hydraulic gradient was 2.5. This was large enough to manometer tubes and in the tubes themselves.

4.5.4 Clamping the geotextile in the permeameter

The geotextile tended to shift slightly while it was being loaded. Prior to the geotextile being clamped to the permeameter, it was thus insured that the targets remained over the centre of the permeameter. The geotextile was clamped by placing the clamping ring on top of the geotextile. This brought the sand and the geotextile into direct contact. The clamping ring and the permeameter both have bolt holes and these were aligned. The geotextile was pierced by hammering sharp ended bolts through it. The bolts were tightened and the geotextile was cut free. A tensioned disc was thus left clamped in the permeameter. The rest of the geotextile which was still connected to the loading yokes was removed.

The rubber O-ring was placed on the bottom half of the permeameter. The top half of the permeameter was then positioned over this and bolted onto the bottom half. The top half was filled with stone. This was to keep the geotextile in contact with the sand and an attempt to model an actual filter. Once the constant head tank had been filled, the pipe leading from the tank to the permeameter was connected. The outlet pipe was positioned so that the outflow of water was directed into a bucket that was placed on a scale. The permeameter was now ready for use.

content and then compacting it. This unfortunately resulted in air becoming trapped in the sand during compaction which resulted in conditions that could not consistently be repeated.

The effect of initial moisture and density of the sand samples was investigated by van der Merwe and Horak (1989). Seven different soil types were tested. They were a medium grained sand, a washed river sand, building sand, silty sand medium clay, gradings made up from the silty sand and gradings made up from the medium grained sand. The initial moisture content and density of the samples were varied as follows: samples were placed dry without compaction, at optimum moisture content (OMC) without compaction, and at OMC with compaction (87% Mod AASHTO). There was little difference between the results obtained from the compacted and uncompacted samples. It was noted visually that in the test without initial moisture, more fines washed through in the beginning of the test than was the case with the two moist samples. The permeability after 400 hours was similar for all three variations.

The compaction thus has little effect on the flowrate. So a fully saturated sand was used in an attempt to eliminate any air in the sand. The permeameter was first filled with water and the sand displaced the water when it was added. The sand was added in three layers and compacted by hand with the standard Procter hammer. This was done to agitate the sand and release any of the trapped air. After this was completed, the top of the sand was smoothed off. To avoid rusting of the permeameter and clamping ring, petroleum jelly was placed on all the surfaces that would be coming into contact with the water. The initial filling of the permeameter with water had the added advantage of showing the position of potential leaks at the connection points of the

10 and 5 kg. The specimens were loaded as uniformly as possible. The weights were added at twenty kilogram increments with each stand being loaded at virtually the same time. If the geotextile was loaded unequally, it was firstly loaded equally in all directions until the smaller of the loads was reached. The loading was then continued in one direction only until the required load was reached. When the woven slit film geotextile was loaded unequally in two directions, it was necessary to distinguish between the warp and the weft directions.

After the required load had been applied, the specimen was left overnight so that it would reach equilibrium, i.e. the strain was fully developed. Note that the weight of the yokes and the load stands were included when the required loading was calculated. The strain was measured the next day using a pair of vernier callipers. If two sets of readings remained unchanged an hour apart, the geotextile was deemed to be in equilibrium, and the next part of the experiment could proceed. A record was kept of the last strain reading and this was compared with the reading measured once the geotextile had been clamped in the permeameter and cut free. If the specimen had slipped at all, the test had to be repeated since the original strain was no longer present.

4.5.3 Setting up the permeameter

Before the sand was placed in the permeameter, the permeameter was located inside the tensile loading rig. The main difficulty with placing the soil in the permeameter, was to obtain a repeatable condition every time. Initially it was thought that this could be achieved by placing the sand at optimum moisture cut out could be monitored. Four targets were used per test. To attach them, a square grid of 100 by 100 mm was drawn onto the centre of the sample. It was important that the sides of the grid remained parallel to the line of loading. The targets were glued to the corners of the grid using non-elastic, water insoluble quick set glue. To ensure that the initial spacing was exactly 100 mm a spacer bar was used.

After the glue had hardened, the loading yokes were attached to the four edges of the geotextile. The yokes consisted of two bars and one was placed underneath the geotextile and the other placed on top of the first with the geotextile in between. The bolt holes of the two bars were in alignment and the sharp ended bolts were then driven through the geotextile. This task was easily accomplished using a 2-kg hammer. The two bars of the yoke were bolted together with the geotextile clamped between them. The other three yokes were then attached in the same manner. The geotextile with the attached loading yokes was now placed over the loading frame. Since each yoke weighed about 11 kg, this task was accomplished with the help of three other people. The permeameter was already inside the loading frame prior to the clamped geotextile being placed over the frame.

4.5.2 Loading the geotextile

After the geotextile had been placed over the loading frame, it was tensioned. The yokes were in a horizontal position and a loading stand was hung from the central hook underneath each of the yokes. The required load was achieved by placing weights on the load stands. Three different weights were used, i.e. 20,

4.5 The Testing Procedure

4.5.1 Preparation of a geotextile sample

The size of the initial geotextile specimen was dependent on the size of the loading frame. Geotextiles are sold according to their widths. Since part of the sample hangs over the side of the actual frame, the required size was 2.2 m by 2.2 m. For the woven slit-film geotextile, the sample with a specified width of 3.03 m was thus used. Cutting the samples was easily accomplished using an ordinary pair of scissors. Care must be taken when making the initial selection of a geotextile sample. An undamaged piece free of tears, scratches and obvious imperfections needs to be selected. The sample was placed on a large flat and clean surface. With the aid of a straight edge, square and marker, a square with dimensions of 1.2 by 1.2 m was marked out in the centre of the geotextile. This section has the same dimensions as the outside perimeter of the rollers when they are placed in the frame. The next step is cutting "flaps" onto which the loading yokes are attached. The flaps have to extend far enough on the side of the loading frame so that the loading yokes and the loading stand remain unhindered when the geotextile is loaded. They extend 500 mm over the actual frame and they are slightly wider than the rollers at 1.2 m. The position of the loading yokes is also marked onto the geotextile.

Once the geotextile was cut to correct size, targets were glued onto it. The purpose of these targets was twofold. The first was that it enabled measurement of the approximate strain during loading of the geotextile. The second was that any slippage of the geotextile after it has been clamped and day after the test, so a maximum of three days is needed. When the geotextiles had to be tensioned fir·t, the test still only took a maximum of a week. This test was thus quicker than those using the permeameter, and this allowed a greater number of tests to be performed. Hydrodynamic tests have the added advantage that four tests are performed at once.

There were three types of geotextiles tested. The first two geotextiles that were used were the same woven slit-film polypropylene and nonwoven needle punched polyester geotextiles that were used for the permeameter tests, and their details can be found in section 4.2. The third was a nonwoven needle punched geotextile which is made by the same manufacturer as previously. It is basically the same geotextile except for the fact that it is thicker. Its details can be found in Table 5.1.

Table 5.1 Details of the second nonwoven needle punched geotextile used.

Type of geotextile	Nonwoven Needle Punched (No.2)
Composition	Polyester
Thickness (mm)	4.4
Mass per unit area (g/m^2)	550
Multi directional Tensile Strength (kN/m)	44
Elongation under multi directional tension (%)	27/30
Normal Permeability (10^{-3} m/s)	3
Normal Throughflow ($l/sec/m^2$)	7

The bulk of the testing was carried out using the same two geotextiles that were used in the permeameter. The testing program can be divided into a results showed that the hydrodynamic sieving method is independent of the glass bead mixture when the uniformity coefficient is between 4 and 11. Mlynarek et al. (1993) concluded that the FOS values obtained from different distributions of glass beads were very similar for a range of uniformity coefficients from five to 8.5 and a maximum diameter between 300 and 800 microns.

Bhatia and Smith (1995) found that the glass beads that were smaller than 0.045mm caused two problems. The first was the difficulty in evaluating the sizes of the beads below this range by either a sieve or hydrometer analysis. The second was the initial immersion and emersion cycles of the test were very long and often required several hours to stabilize. Even geotextiles with larger pore openings (manufacturer's AOS 0.425 mm) initially took hourly cycles to fill and drain 10 cm of water. This was most likely due to the finer glass beads becoming a paste when water was added and clogging the pore openings of the geotextile during the initial stages of the test. This observation seems to contradict Mlynarek et al. (1993) who initially set the immersion and withdrawal durations at seven and 25 seconds respectively despite the fact that the smallest bead size was 10 μm. During testing, this potential problem was avoided by using beads that had a minimum size of 0.075 mm.

5.3 The Testing Program

One of the advantages of the hydrodynamic sieving test is that it is relatively short in duration. For an untensioned geotextile, the test takes a day to set up and a further day to run the test. The analysis of the results can be done the soils have the added disadvantage that very strict procedures have to be applied to insure that laboratories perform the tests with particles having identical density, chemical nature and shape.

Bhatia et al. (1994) found that despite some limitations, both wet and hydrodynamic sieving methods are better techniques than dry sieving. The main problem with the bubble point, mercury intrusion and image analysis methods was that despite the fact that they provide an entire pore-size distribution of the geotextile, they give the same result for geotextiles of different thicknesses but similar cross-sections. They thought that more work was needed to study the bubble point and image analysis techniques before the results can be used in design.

At the moment though, no test is perfect. Comparative tests between wet, dry and hydrodynamic sieving were carried out by Bhatia and Smith (1995) on twenty-eight woven and nonwoven geotextiles. They found that the hydrodynamic sieving method gave a fairly good estimation of the largest effective opening size (FOS) of the geotextile. The limitations of this method are that the results are affected by the interaction of the particles within the glass bead mixture. The complete pore size distribution curve obtained by this method is of little value, as at a certain point in the test, the glass beads passing are only a reflection of the original glass bead mixture.

The effect of the original glass bead mixture on the results was studied at the Syracuse University Laboratory. Tests were performed with two different glass bead mixtures. One glass bead mixture had a C_u of 11 and one a C_u of 4. The dipping the sample into a water container and then letting it drain. Soil particles were used as testing particles. Belise (1988) applied a pneumatically driven, vertical device for sieving. The HST procedure, modified by using glass beads instead of soil particles is recommended as a standard in Canada (CAN/CGSB-148.1-10).

As discussed previously, there are a number of methods for finding the opening sizes of geotextiles. Hydrodynamic sieving was chosen for its perceived advantages. They are the following:

1. The testing beads are wet during the sieving process as is the case in filtration applications.
2. The immersion and withdrawal process forces the particles through the geotextile.
3. The sample size is large enough to represent adequately the product, i.e. a large number of openings are involved in the test.
4. Four tests can be carried out at the same time thus saving time and giving a more accurate result.

The perceived advantages of hydrodynamic sieving should perhaps include the use of glass beads as opposed to soil particles. As discussed in the literature survey, the UK, Canada and USA use glass beads while most European countries still use soil particles. The advantages of using glass beads are:

- They are very regular spheres and thus impede formation of agglomerations.
- Their mineralogical characteristics are similar to those of natural soils.
- Their relative density is comparable to sand and soil particles.
- The consistency of their density, chemical nature and shape.

The consistency of glass beads is probably their greatest asset since natural

CHAPTER 5

TESTS PERFORMED USING THE HYDRODYNAMIC SIEVING TECHNIQUE

5.1 Introduction

In an attempt to further study the effects of biaxial tensile loading on the opening sizes of geotextiles, it was decided to use one of the previously discussed methods for determining the O_{90} of a geotextile. The hydrodynamic sieving technique was chosen and the reasons for this are discussed below. A variation on the standard testing technique was developed which enabled the testing of tensioned geotextiles in the sieving mechanism. The filter opening size was calculated for each geotextile to see if there was any variation due to the tensile loading. The test was also modified slightly in an attempt to simulate the dry sieving techniques' method of using glass bead designations instead of a mixture. The test was furthermore used to find an approximate value for the permeability of the geotextile and to monitor any change when a tensile load was applied.

5.2 Reasons for Choosing the Hydrodynamic Sieving Technique

The hydrodynamic sieving technique (HST) was developed in France by Fayoux (1977). Fayoux applied a carousel device which enabled sieving by

4.10 Conclusion

A series of tests were carried out on two different types of geotextiles. An attempt was made to monitor the effects of biaxial tensile loads on the permeability. No clear trends emerged which indicated a reduction in permeability with increasing tension in the geotextile, although there was a reduction in permeability in all the tensioned tests when compared to the untensioned test. A number of weaknesses in the test method were highlighted and possible solutions were suggested. It was decided to further i[illegible]igate the effects of biaxial tension, but to concentrate on the effects on the opening sizes of geotextiles. A further test was thus developed and it is discussed in the following chapter.

the geotextile specimen in place and subjected to a confining vertical stress similar to that of the soil specimen by means of a rod, weight and plate assembly.

-The cell was then filled with de-aired water.

-Soil, that had been brought to a fully saturated state by boiling it with water and then allowed to cool to room temperature, was pluviated from a flask. During water pluviation the particles reached a terminal velocity at a very small drop height, and the resulting deposit was in the loosest possible state.

-The reconstituted specimen was levelled using a siphon, and the mass of the specimen was established.

-The soil was then densified to the targeted density by lightly tapping the wall of the permeameter.

-A final reference measurement of the permeameter cell was made and this allowed control of the specimen thickness and hence density.

This technique would have to be modified slightly to accomodate the fact that the geotextile specimen was placed in the permeameter after the sand. The bottom half of the permeameter was filled to the top with sand and then the geotextile was placed over it and the two halves were clamped together. There was thus no way of controlling any sand and water that were not contained in the bottom part of the permeameter. A temporary extension would thus have to be in place during the addition of the sand and water. This would allow the bottom to be overfilled slightly and then densified so that the sand exactly filled the permeameter.

important. The standard permeameters have an inlet pipe located at the top. The water does not flow directly into the sand, but into an inlet chamber which has the same diameter as the permeameter. The result of this is that the water enters the soil across its entire diameter. The permeameter should thus be modified to accommodate such a chamber. This could be achieved by either increasing the depth of the permeameter or decreasing the thickness of the sand layer and thus leaving a space between the inlet pipe and the sand. Both these solutions require a support grid that allows the water to pass through, but prevents the sand entering the inlet chamber for example, a layer of gravel beneath the sand.

One of the problems encountered during testing was that the standpipes were becoming blocked with sand. Not only should the standpipes have a greater internal diameter (about 5 mm), but sand should be prevented from entering the outlet spouts. There is thus a need for a screen, placed at the holes on the inside of the permeameter that lead to the standpipes, that allows the water to pass through but not the sand.

Further care should be taken during the preparation of the sand specimen. It is necessary in any fundamental study of soil properties involving reconstituted specimens that the specimen preparation technique replicates homogenous specimens. Fanin et. al. (1994) described a water pluviation technique that created homogenous, saturated specimens of the same initial density which was well-suited to uniform sands (Vaid and Negussey 1988). The technique was for permeameters that were used in the standard gradient ratio test and it can briefly be described as follows:

-An initial reference dial measurement was taken of the permeameter cell with the pipe was connected to the tank with the aid of a hose clamp. The result was that an air lock occurred at the connection. At the beginning of each test, when the flowrates were high, it seemed as if the larger amount of water flowing through the pipe prevented the formation of an air lock. Problems arose with very low flowrates when it seemed as if the smaller amount of water flowing through the pipe allowed the formation of an air lock. In extreme circumstances the air lock caused the water flow to stop altogether. An attempt was made to seal the connection using silicone sealant. This did lead to an improvement but the problem occurred sporadically after that. This connection needs to be redesigned to ensure that it remains airtight at all times.

The pipes that were used for the manometer tubes were found to be too small. Before a test was started, the permeameter was filled with water in order to clear the manometer tubes of any blockages. The tubes unfortunately became blocked very quickly with sand when the testing started. Only a few grains were enough to affect the reading.

4.9 Suggested Improvements

There were a few differences between the standard gradient ratio permeameters and the one used in the experiments described in this chapter. With a few modifications, this permeameter could be used for a gradient ratio test. A standard permeameter typically has an internal diameter of 100 mm and it is subjected to a downward water flow. This compares with an internal diameter of 250 mm and an upward water flow. While the direction of the water flow is not critical, the way in which the water enters the sand is

A few problems were also encountered when testing. One of the weaknesses of having an upward water flow is at the soil-water interface. At the bottom of the permeameter there is a 4 mm diameter hole which has a spout screwed into it. The water pipe is connected to this spout. The water is thus flowing directly from the pipe into the much larger area of the sand. This in itself is not a problem, but the method of inserting the sand in the permeameter created one. As previously mentioned, the permeameter was first filled with water and then the sand was added. This displaced the water and the sand was then compacted slightly. The purpose of this was to eliminate any air locks in the sand.

The problem arose because the sand was so wet that it eroded around the hole where the water flowed into the permeameter. This occurred even when the water pipe was attached to the permeameter and was filled with water. Since the sand is denser than the water, it flowed into the pipe. The pipe became blocked and when it was disconnected to clear the obstruction, the sand once again eroded and flowed out. After a short while, equilibrium was reached and the sand stopped eroding. The sand didn't erode a great deal, at most 100 g, but it was not consistent. The void that was created every time could not be reproduced exactly. This had an effect on the water's ability to flow through the soil. Thus different volumes of water could flow into the permeameter, depending on the size of the void that was created, before coming into contact with the sand.

Further problems were encountered with the connection between the constant head water tank and the pipe which carried the water to the permeameter. Air was sucked into the pipe at the point of connection. This continued even after subjected to a greater deformation and this would seem to cause the reduction in permeability. Tensioning equally and non equally in two directions is a much closer approximation of what can be expected in-situ (Rowe and Mylleville 1990 and Schimelfenyg 1990.) and it is unlikely that tensioning in one direction only, while allowing necking, would occur. The growth of micro organisms could also have had an effect on Kuchena's work since no disinfectant was added to the water supply.

Thus it would appear that the test was not sensitive enough to demonstrate the change in opening sizes of the geotextile. This situation was further exacerbated by washing out the fines in the sand. A reduction in the opening sizes can result in the clogging of a geotextile. This clogging would be due to the finer particles caking in the fabric. It was originally hoped that washing out the fines would emphasize the effect of the tensioned geotextile. Since the flowrate would be increased, the flow through the geotextile would be the determining factor with regards to the flowrates. What actually happened was that the sand was determining the flowrate because its permeability was so much less than that of the geotextile. Washing out the fines didn't increase its permeability enough to affect the results. The possibility of clogging, which in itself indicates a reduction in flowrate, was eliminated. A better solution would have been to have a sand with a permeability which was much greater (thus testing the permeability criterion) or one with much finer material that would cause the geotextile to clog (thus testing the clogging criterion). Since the effect appears to be slight, a sand-geotextile system which is designed much closer to the boundary conditions of the design criteria for filters should be used when studying this problem.

dropping to zero at the 75-hour mark, was due to a blockage that occurred at the inlet pipe. After the blockage was cleared, the flowrate returned to its initial value within the next 25 hours. After 270 hours, the highest flowrate was recorded for the load of 544x544 N/m, while the untensioned and 365x187 N/m tests had very similar and fairly constant flowrates. The 544x366 N/m test on the other hand, fluctuated greatly over this period. This fluctuation is quite likely due to the airlocks that occurred at the inlet pipes.

The results for the nonwoven geotextile show very similar flowrates for the two unequally tensioned tests (365x187 and 544x366 N/m) and the untensioned test during the first 300 hours. The equal load of 365x365 N/m has the lowest flowrate for the duration of the test. The only times that the untensioned test has the highest flowrate is 70 to 120 hours, 240 to 270 hours and 325 to 500 hours. During this last period, the flowrates seem to have a fairly regular pattern with the 544x544 N/m being followed by the 365x187 N/m and 365x365 N/m. So certain vague trends are present, but nothing really substantial.

Of further concern was the fact that the results were not reflecting the results of Kuchena's work despite using the same equipment. This disparity was probably due to the differences in the technique used for tensioning the geotextile. When the geotextile was tensioned in two directions, the maximum strain recorded was 2.5% in both directions. This is opposed to the previous study where as a result of the specimen being relatively narrow (1.0 m wide) and being tensioned in one direction only, severe necking occurred. For the woven geotextile, a 10% reduction in the width occurred, and a 20% reduction was recorded for the non woven geotextile. The geotextile was thus previously

5.6 Results for The Woven Slit Film Geotextile

The results of the hydrodynamic tests can be presented in a number of ways. The complete results of the equally and non equally loaded tests are presented in Appendix A. These results are from the particle size analysis test of the beads that passed through the geotextile during the test. They give the mass of beads that were retained on each of the sieves for all four specimens. The problem with these results is that they are difficult to interpret when presented in this manner. Thus, certain aspects will be highlighted. For all the geotextiles tested, there were usually two consecutively sized beads that were critical. Beads that were smaller than these two sizes tended to all pass through the geotextile while beads that were larger tended to be retained on the geotextile. The results of these two bead sizes will be presented in a tabular form. Another interesting comparison can be made when comparing the total mass of beads that pass through the geotextile for each test. The results can also be presented graphically by determining the particle size vs. percentage finer by mass curve and from this curve the O_{95} can be calculated. A table containing these calculated values of O_{95} and their coefficient of variation are also presented.

5.6.1. The equally tensioned tests for the woven slit film geotextile

A total of five tests were carried out on the woven slit film geotextile with equal tensile loading in two directions. It was found that there were two so-called critical bead sizes in these tests. In this case, it was the beads that were the test was carried out for long enough?

5.5.3 Falling head tests

An attempt was made to measure the change in permeability of a geotextile due to tensile loading with the aid of the hydrodynamic sieving mechanism. When the mechanism is in the upward position, it can be thought of as a type of falling head permeameter. The water flows through the geotextile from a falling head. So if we can find the time that the water takes to fall a certain distance, we can use the falling head permeameter equation and thus calculate the geotextile's permeability. This is of course merely an approximation since the water will start draining before the cylinders are completely lifted out of the water. Two points were marked out on the inside of the cylinders. One was marked at a height of 1 cm above and another 11 cm above the geotextile. The base level was not taken at the geotextile for two reasons. Firstly, it is difficult to tell when the water has fully drained out and secondly the falling head equation would have a zero in the denominator. The test required four people with stopwatches to time the duration that the water level took to drop from 11 cm to 1 cm above the geotextile. The water level in the pans was such that the whole of the cylinder was filled during the immersion part of its cycle. This was done to get a better approximation for the starting time of the test.

The two tests per geotextile that were carried out in this manner were an untensioned test and tensioned test with a load of 2.06 kN/m in both directions. For each test, a total of five cycles were timed. This gave a total of twenty readings per test.

5.5.2 Method 2

Unlike the dry sieving tests that require a minimum of six designations of glass beads to be sieved, one designation at a time, the hydrodynamic sieving technique uses a mixture of beads. As discussed previously, this can lead to possible inaccuracies. It was decided to use glass bead designations instead of a mixture and then subject the beads to a set number of cycles. This method has been tried previously by Bhatia and Smith (1995). They found that it produced larger values of FOS but the results were not as consistent. Unfortunately, no details are given as to the number of cycles involved or the mass of each designation of glass beads used.

The same glass bead distribution was used in this test as previously. The smallest sized beads were added first and subjected to 100 cycles. The next largest sized beads were then added and this mixture was subjected to a further 100 cycles. This process was continued until all eight sizes had been added, the test then continued until a total of a thousand cycles were completed. Since the woven geotextile used eight designations of beads as opposed to five for the nonwoven geotextile, the test was not exactly the same for both geotextiles. The three extra designations used for the woven geotextile were subjected to fewer cycles. Despite this, it is still an interesting comparison to make. This test also investigated another query concerning the hydrodynamic sieving. The query is best illustrated with an example. Assuming we have 50 g of a certain sized bead at the start of the test. After testing, 40 g of this size have passed through the geotextile. Does this mean that 80% of all beads of this size will pass through, or will only 40g pass through if we have say 100 g of that particular size? Alternatively, will 100% of the beads pass through if weighed and placed in a bowl. The beads were thus sieved twice before testing. This was found necessary because especially the smaller sizes tended to drift from one sieve size to another.

The immersion and withdrawal durations, respectively 1[illegible] and 40-sec in a first approach, were set on the timer. The counter was set to zero and in accordance with the CAN/CGSB- 148.1-10 draft standard, the test ran for one thousand cycles. The test was started by actuating the pneumatic device. Following two, ten and twenty complete cycles, verification of the immersion and withdrawal durations was necessary. The immersion period should be such as to allow water to reach the 100 mm level above the geotextile specimen, while the withdrawal period should be such that at the end of each draining period there was no water above the geotextile speci[illegible]ms. If necessary, the setting durations were adjusted.

At the end of the test, the beads that had collected at the bottom of the pans were collected. This was achieved by pouring the water through a 38-micron sieve. The beads were then placed in a bowl that was put in an oven overnight. The beads that didn't pass through the geotextile were also collected in order to recycle them. A gradation test was undertaken to obtain the bead-size distribution for each tested specimen. This analysis was performed by using the dry sieving technique as per the ASTM reapproved 1990 test procedure of Method for Particle-Size Analysis of Soils (D 422-63). The filter opening size was determined by calculating the 95% finer by mass point of the distribution graph. The strain was checked at the end of each test to insure that the initial strain had been maintained.

attach the flange and they were pushed through the flange and holes. The cylinders were bolted to the flange from below the geotextile. This operation required two people, one to hold the cylinders in place and another to tighten the bolts. Once the cylinders were in place, the strain was measured just prior to the cylinders being cut free from the tensioning apparatus. The strain was then compared with readings taken just prior to the cylinders being bolted to the sieving mechanism. This was to check that no stress relaxation had occurred. If any relaxation occurred, the sample was not tested. This was not found to be a problem during testing.

The cylinders were then bolted onto the sieving mechanism. A spirit level was used to ensure that they remained level. The cylinders were attached, with the aid of four bolts, onto the frame that was connected to the pneumatic device. All the nuts, bolts and washers were stainless steel since the apparatus was in contact with water. Once the cylinders were all attached and level, the water pans were placed underneath them. The pans were filled while the mechanism was in the immersion part of its cycle. This was done so that the water level could be checked. The water level in each pan was such as to ensure 100 mm of water above the submerged specimens when the cylinders reached their lowest position. The air-dried glass bead mixture was then placed on the geotextile.

The glass beads used were sold in 25 kg bags (acquired from Bellambie Surface Technologies). Each bag contained beads of a certain range of sizes. The beads were thus initially sieved until at least a kilogram of each sieve size was obtained. To make up the relevant distribution of beads, smaller quantities of the required sized beads were sieved again. The required mass of beads was geotextile was the same. As before, the geotextiles were first cut into the correct shape. Prior to the loading yokes being attached, the targets were glued onto the geotextile. One set of targets was used for every cylinder and so there were four sets of targets. The geotextiles were then placed onto the loading frame. The load stands were attached to the loading yokes and the geotextile was loaded by means of adding weights onto the stands until the required tensile force was developed. The geotextile was left overnight so that they could be fully tensioned. The strain was measured, using a vernier calliper, for all four sets of targets.

The cylinders were then attached to the geotextile. The flanges were detached from the cylinders and placed on the geotextile with a set of targets in their centres. To ensure that the holes were made in the right place, a permanent marker was used to mark them through the holes in the flanges. During the initial testing, the holes were made using a quarter inch punch. The punch was placed on the required spot on the geotextile. A block of wood was put directly beneath the geotextile. The holes were then punched by using a hammer. The problem with this method is that the holes were seldom "clean" and frayed slightly around the edges. It was found that burning the holes was a much better solution. This was achieved by heating 5 mm diameter rods with the aid of a Bunsen burner. The rods were slightly smaller than the bolts that were used (6 mm), but the hole size that they made was almost exactly 6 mm. This method had the added advantage in that with the holes being melted, the edges didn't fray.

The next step was to bolt the cylinders to the flanges, thus clamping the geotextile between them. Each cylinder had eight bolts that were used to size vs. % finer by mass. The details of C_u, D_{max} and D_{min} are also given.

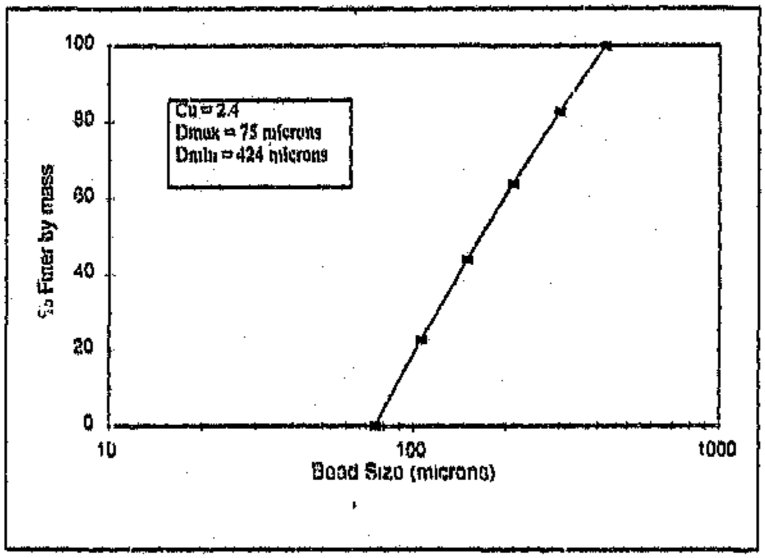

Figure 5.2 Particle size distribution curves of glass beads for the nonwoven needle punched geotextile.

Note: The coefficient of uniformity C_u is less than 4. Since the tests that were carried out were comparative tests which used the same distribution every time, it was thought that the effect of the C_u would be minimal.

5.5 The Testing Procedure

5.5.1 Equal and non equal tensile loading

The testing procedure for the equally loaded and the unequally loaded

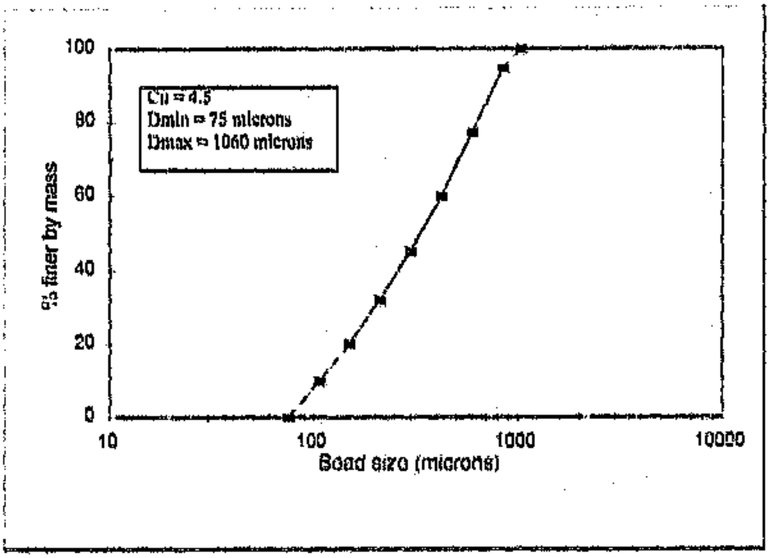

Figure 5.1 Particle size distribution curves of glass beads for the woven geotextile.

5.4.2 Nonwoven needle punched geotextile

The expected FOS of the nonwoven geotextile was smaller than that of the woven geotextile and this is reflected in the distribution of glass beads used in testing.

Table 5.3 Glass bead distribution for the nonwoven needle punched geotextile.

Bead Size (μm)	75	106	150	212	300
Mass (g)	85	80	75	70	65

This table is represented graphically in figure 5.2 below as a graph of bead

5.4.1 Woven geotextile.

Since the filter opening size for the woven geotextile was in the region of 400 microns, the maximum sized bead was chosen to be the size that was retained on the 850 microns sieve. In accordance with ASTM D 4751-87, the "in between" sieve sizes, e.g. 106, 212 and 850-micron sieves as well as the standard sieve sizes, e.g. 75, 150, 300, 425, 600-microns were used. This gives a more accurate distribution.

The details of the glass bead distribution is presented in two ways i.e. in tabular form (see table 5.2 below) and graphically (see figure 5.1 below).

Table 5.2 Glass bead distribution for woven geotextile.

Bead Size (μm)	75	106	150	212	300	425	600	850
Mass (g)	35	40	45	50	55	65	65	20

Note: The bead sizes are expressed as the sieve size that they are retained on. The actual sizes are thus in a range between the sieve sizes, for example, the bead size referred to as 75 μm in size, is in the range of 75 to 105 μm.

This distribution can be plotted on a particle size vs. percentage finer by mass curve as can be seen in figure 5.1.

study this effect by adding set amounts of progressively larger sized beads. Each set of beads was then subjected to a set number of cycles. The geotextiles were tensioned prior to the test and the loading was equal in all directions at 544 N/m.

The final test involved using the hydrodynamic mechanism as a modified falling head permeameter. Two tests were carried out. The geotextiles were firstly untensioned and then loaded equally at 2060 N/m. The test involved timing the duration that the water level took to drop over a specified distance in the cylinders.

5.4 Choosing an Initial Glass Bead Distribution

There are certain guidelines when choosing a glass bead distribution to calculate the FOS of a geotextile. The largest sized bead must be at least twice the size of the expected FOS. At the end of a test, at least 50 g of beads must have passed through the geotextile. Whenever not enough beads are collected, the test has to be performed again using another glass bead mixture with smaller sizes. The recommended mass of beads is 5.65 kg per m^2 of geotextile that is to be tested. For the cylinders, with an internal diameter of 295 mm, the required mass of beads was 375 g per cylinder. The coefficient of uniformity should be between about four and eleven. As discussed in section 4.2 research has shown that over this range the hydrodynamic sieving method is independent of the glass bead mixture. After an initial test was performed to get an estimate of the expected FOS, the following distribution was chosen for each geotextile.

number of sections. The woven and nonwoven needle punched (No.1) geotextile had the same loading in all cases. Firstly, the geotextiles were subjected to equal loads in four directions. The loading was as follows:

1. Untensioned
2. 187 N/m
3. 365 N/m
4. 544 N/m
5. 811 N/m
6. 2060 N/m

Once again the loads are relatively small in comparison to the tensile strength of the geotextiles.

The second set of tests involved unequal loading in the two directions and the loading was as follows:

1. 365 N/m and 0 N/m
2. 365 N/m and 187 N/m
3. 365 N/m and 544 N/m

The nonwoven needle punched (No.2) geotextile was used to measure the effect of the thickness of a geotextile [illegible] POS. It was used in only two tests. It was firstly loaded equally in bo[illegible] ctions. The loading was 544 N/m and 544N/m. It was also subjected to the modified hydrodynamic test which is discussed below and the loading was once again 544 N/m and 544 N/m.

One of the problems of hydrodynamic sieving is that a mixture of beads is used and thus it is possible that some smaller beads may be obstructed from passing through the geotextile by the larger beads. An attempt was made to day after the test, so a maximum of three days is needed. When the geotextiles had to be tensioned first, the test still only took a maximum of a week. This test was thus quicker than those using the permeameter, and this allowed a greater number of tests to be performed. Hydrodynamic tests have the added advantage that four tests are performed at once.

There were three types of geotextiles tested. The first two geotextiles that were used were the same woven slit-film polypropylene and nonwoven needle punched polyester geotextiles that were used for the permeameter tests, and their details can be found in section 4.2. The third was a nonwoven needle punched geotextile which is made by the same manufacturer as previously. It is basically the same geotextile except for the fact that it is thicker. Its details can be found in Table 5.1.

Table 5.1 Details of the second nonwoven needle punched geotextile used.

Type of geotextile	Nonwoven Needle Punched (No.2)
Composition	Polyester
Thickness (mm)	4.4
Mass per unit area (g/m²)	550
Multi directional Tensile Strength (kN/m)	44
Elongation under multi directional tension (%)	27/30
Normal Permeability (10^{-3} m/s)	3
Normal Throughflow (l/sec/m²)	7

The bulk of the testing was carried out using the same two geotextiles that were used in the permeameter. The testing program can be divided into a

5.7 Results for The Non Woven Needle Punched (No. 1) Geotextile

The results for this geotextile will be presented in the same manner as they were for the woven geotextile. Once again, the full results are given in Appendix A. As with the woven geotextile, there were two sizes of beads which were critical. Since the filter opening size was much smaller for this type of geotextile, the critical bead sizes were smaller as well. The initial glass bead mixture also reflected this change.

5.7.1 The equally tensioned tests

A total of five tests was carried out on the non woven needle punched-No. 1 (nwnp-1) geotextile with equal tensile loading in two directions. It was found that there were two so-called critical bead sizes in these tests: the beads that were retained on the 150-micron sieve and those retained on the 106-micron sieve. Beads that were smaller than these two sizes tended to all pass through the geotextile. Thus, the details of these two sizes are presented below. The initial mass of beads for these two sieve sizes were 75 g of beads retained on the 150-micron sieve and 80 g retained on the 106-micron sieve. The details of the approximate strains are also presented.

h_2 the final head of water

$(t_2 - t_1)$ = the time for the water level to drop from h_1 to h_2

The calculation is thus fairly simple with $a = A$, $h_1/h_2 = 11$ and $\ell = 0.91$mm.

For the woven slit film geotextile, the untensioned specimens had a mean time interval of 1.97 seconds. This gave a permeability of 11.10×10^{-4} m/s. The specimens that were equally tensioned with a force of 2060 N/m had a mean time interval of 3.42 seconds. This gave a permeability value of 6.39×10^{-4} m/s. These values of permeability are much larger than those recorded for the permeameter results. For the untensioned woven geotextile, a maximum permeability of 7.8×10^{-5} m/s was recorded. The sand thus appears to have been the controlling factor in the resultant permeability.

There was thus a drop of 42% in the permeability when the geotextile was tensioned. Whilst this is a relatively large reduction in flow capacity, it is not a sufficient reduction in itself to render the geotextile unusable. Current drainage criteria require that the permeability of a geotextile should be some percentage of that of the retained soil, with values varying between 10 and 1000 percent. (Fischer et al. 1990). A change of the order of a factor of two is thus likely to be of little significance. Unfortunately the manufacturer's specifications do not include a value for the permeability so it wasn't possible to make a comparison with the actual permeability.

Coupled with the change in the filter opening size, it can be seen that when the woven slit film geotextile was subjected to tensile loading, either equally or unequally in two directions, there was a definite change in its pore openings.

could be made. A comparison between two differently tensioned geotextiles were made. An untensioned and an equally tensioned (2060 & 2060 N/m) geotextile were tested.

For this test, the water level in the pans was such that the cylinders would be filled to the top during the immersion phase of the cycle. This was done in order to allow the water level to drop slightly before it reached the top mark. In this wav a better approximation of the start could be made. It must be emphasised that this test was just an approximate measure of the permeability. When the cylinders were lifted out of the water, the water started draining through the geotextile before the cylinders were completely out of the water. This resulted in the original head being less than it should be. Although we used the falling head equation, the movement of the sample was in contrast to the standard test where the sample remains stationary while the water flows through it. Errors also occured in the timing of the intervals. Four people with stopwatches were used to time the drop in the water level. Very small intervals were measured, sometimes less than two seconds, so inaccuracies could easily have occurred. Five cycles were timed and the mean of the twenty recorded intervals was used in the following equation:

$$k = a \frac{t}{A} \frac{\ln(h_1/h_2)}{(t_2 - t_1)} \qquad (7)$$

where k = the permeability

a = the cross sectional area of the head of water

A = the cross sectional area of the geotextile

t = the thickness of the geotextile

h_1 = original head of water

which the glass beads were added as a mixture (see Appendix A), the difference between method 1 and 2 was no greater than the variation among the four tests. This relative insensitivity of the geotextile to test method 2 was probably due to its planar structure. A bead either passed through a pore or it didn't. There was very little chance that a particular bead would be just large enough to block a particular pore.

In test method 1, it could be seen that the smaller beads of the mixture were passed through the geotextile very quickly, i.e. during the first hundred cycles. The beads that were left behind are the larger ones (300 μm and up) and these were subjected to a further 900 cycles. With method 2, the 300 micron beads were subjected to 600 cycles, the 425 micron beads to 500 cycles and the 600 μm beads to only 400 cycles. Even this variation had little effect on the resultant FOS.

5.6.4 An attempt to measure the change in permeability of a tensioned geotextile

Using the hydrodynamic sieving mechanism, an attempt was made to measure the change in permeability of a geotextile when it was tensioned. The mechanism was used in a modified falling head test. Two marks were made on the inside of each of the four cylinders. One mark was a centimetre above the geotextile when it had been clamped in position and the other was eleven centimetres above. The basis of the test was to time the drop in the water level from one mark to the next. This would then be a drop of ten centimetre and using the falling head permeameter equation, an estimate of the permeability

In order to see what effect the mixture of beads had on the results, it was decided to modify the tests slightly. The same mass and breakdown of beads were used as previously. Instead of adding them all at the beginning of the test, the beads were added one size at a time. Each size was then subjected to a hundred cycles and the next size was then added. The smallest sized beads were added first and then the next largest size was added. The geotextile was not cleaned during the test and the next bead designation was added after a hundred cycles even when there were beads remaining on the geotextile. After all the beads had been added, the test continued until a total of a thousand cycles had been completed. The beads that passed through the geotextile were collected and a particle size analysis test was carried out.

Only one test was carried out on the woven geotextile in this manner. The geotextile was tensioned and the load was 544x544 N/m. To compare the mass of beads that passed through the geotextile for the two tests, the same two sieve sizes will be considered as previously, i.e. the 425 and the 600-micron sieves. Once again, beads smaller than this all passed through the geotextile.

For the 600-micron sieve, the original test method retained a mean of 11.4 g while the second method retained a mean of 5.8 g. For the 425-micron sieve, there was also a decrease from 52.5 g with the original method, to 41.1 g for the second method. This decrease was reflected in the FOS and the total mass of beads as well. The FOS decreased from 590 to 560 μm and the total mass of beads from 277 to 271 g.

There was thus a small decrease in the mass of beads that passed through the geotextile for test method 2. If one looks at the results of the four tests in more or virtually to the same extent by equal tensioning as opposed to non equal tensioning. An equal load of 187x187 N/m had a greater effect than a load of 365x0 N/m (FOS of 600 as opposed to 620 μm). A load of 365x544 N/m had a FOS of 580 μm, while a 365x365 N/m load had a FOS of 560 μm and the 544x544 N/m had a FOS of 570 μm. The most important observation is that with all the tests, the opening sizes decreased. Initially, it was thought that diagonal stretching could open up the pores which would result in larger opening sizes, but this did not occur.

5.6.3 A different approach to hydrodynamic sieving

As discussed in chapter 2, one of the perceived weaknesses of the hydrodynamic sieving technique was the use of a glass bead mixture as opposed to using a series of glass bead designations. A mixture of beads is only used in hydrodynamic sieving. It is interesting to speculate as to reasons for using a mixture for this method. With wet and dry sieving the openings of the geotextile can be cleared after sieving each designation. When the next designation is sieved, the geotextile openings are free of any obstruction. This "cleaning" of the geotextile is possible because the geotextile is attached to the sieve with the aid of a hoop and it is thus easily detachable. This contrasts with hydrodynamic sieving where the geotextile is attached to the cylinder with a number of bolts. Four tests are run at once so it would be time consuming to remove the geotextile and clean it. When using a mixture, the beads can be added at the beginning and the test run for the set number of cycles.

of variation are given in table 5.7.

Table 5.7 The O_{95} values and coefficients of variation for the unequally tensioned woven geotextile

Biaxial Load (N/m)	O_{95} (μm)	Coefficient of Variation (%)
Zero	737	1.8
365 & 0	613	3.6
365 & 187	560	3.8
365 & 544	587	2.0

Discussion of unequally tensioned woven geotextile results

The application of unequal loads appears to have had a very similar effect on the FOS when compared with the equally loaded specimens, i.e. there was a decrease in the FOS. For the unequally tensioned geotextiles, the largest loading didn't result in the smallest filter opening size. The loading of 365x187 N/m resulted in the least amount of glass beads passing through the geotextile. Both the 425 and 600 μm sizes and subsequently the totals were the smallest for this load when compared with the other unequally tensioned tests. Despite this, unequal loading didn't produce significantly different results to the equally tensioned tests. When compared to the specimen that was loaded with 365x365 N/m which has a filter opening size of 560 μm, the test with a load of 365x187 N/m resulted in the same value for the FOS.

So it appears as if the pores of the geotextile were distorted either slightly

Graphical interpretation of results - determining the O_{95}

To determine the filter opening size of the geotextile, we needed to plot the particle size analysis curve for the beads that passed through the geotextile. These plots can be seen in figure 5.4. A mean of the four tests was used for these curves. The O_{95} was then calculated and the results can be found in table 5.7.

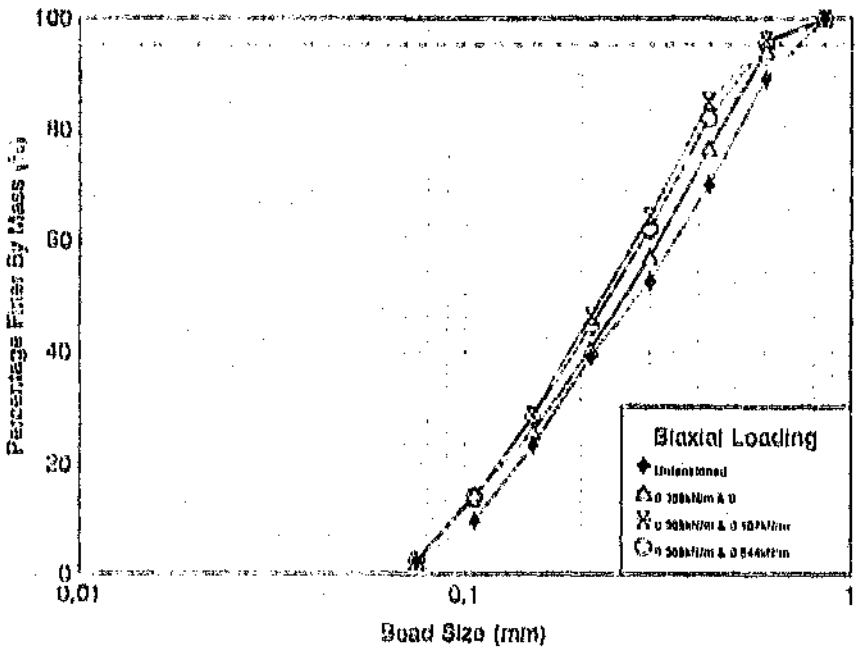

Figure 5.4 Particle Size analysis of beads that passed through the geotextile.

Note: The dashed line indicates the point where the O_{95} was calculated from.

From figure 5.4, we can calculate the O_{95}, and the results and the coefficients clogging was increased but considering that only the larger sized pores were affected, it is difficult to determine to what extent.

5.6.2 The unequally tensioned test for the woven slit-film geotextile

If we consider the individual pores of a geotextile, it seems likely that the pores can become distorted during biaxial tensile loading. This distortion may become amplified if the geotextile is subjected to unequal tensile loading. In order to investigate whether this type of loading does have a larger effect on the pores, three nonequal tensile tests were carried out on the woven geotextile. The loading was done in such a way that the warp direction was loaded with 365 N/m and the variation in loading occurred in the weft direction. The results will be presented in the same manner as those for the equally tensioned tests.

Table 5.6 Summary of results for the unequally tensioned woven geotextile

Biaxial Load (N/m)	Strain (%)		600 μm sieve (g)	425 μm sieve (g)	Total mass passing (g)
	Warp	Weft			
Zero			34.3	61	317.6
365x0	2.5	0.9	18.3	52.4	298.9
365x187	1.8	1.2	10.4	29.9	262.5
365x544	1.6	1.8	12	38	271.4

this slight increase can probably be ignored.

Table 5.4 shows a fairly steady decrease in the total mass of beads that passed through the geotextile. Note that there was an initial large decrease from the untensioned test (mean of 317.6 g) to the first loaded test of 187 N/m (mean of 294.9 g). The subsequent loadings did not have such a large effect. The change in the mass of beads that passed through the geotextile between a load of 811N/m and a load that was about two and half times greater (2060 N/m) is only 17.3 g. Thus it would appear as if there was an initial large decrease when the geotextile was first loaded and then the effect tapered off.

It is significant that only the larger sized pores were affected by the loading. The beads that were 300 μm and smaller were not affected at all by the loading. This would indicate that the pores were generally larger than a certain value. As the geotextile was tensioned, these pores became distorted and let fewer beads pass through. Although it may be speculative to consider the effect of typical working loads (say 30% of the tensile strength, or 8-15 kN/m for the woven geotextile), it was evident that the reduction in FOS at these loads would be greater than the 28% measured in this study.

So how does this affect the design procedure? A smaller filter opening size will actually improve the retention criterion. The permeability and clogging criterion would probably be most affected. Considering the fact that the permeability criterion has a built in factor of safety of ten, it seems unlikely that this change will have a large effect. The modified falling head tests (which are discussed later) using the hydrodynamic sieving mechanism attempted to monitor the subsequent change in permeability. The potential for

Table 5.5 The changes in the filter opening size of the woven geotextile due to biaxial loading.

Biaxial Load (N/m)	O_{95} (μm)	Coefficient of variation (%)
Untensioned	737	1.8
187x187	611	4.3
365x365	582	2.1
544x544	590	1.4
811x811	574	2.0
2060x2060	528	1.8

Discussion of equally tensioned tests

From the above results, it can be seen that there was a gradual decrease in the mass of beads that passed through the geotextile as the loading was increased. The filter opening size decreased from 720 μm to 520 μm which was a decrease of 28%. Considering that the maximum applied load was only about 8% of the minimum (weft direction) tensile strength, it was evident that in-plane tensile loads have an important influence on the retention and permeability characteristics of woven geotextiles. The slight increase in the filter opening size for the load of 544 kN/m was due to the fact that slightly more of the 600 μm sized beads passed through the geotextile for this test compared with the loading of 365 N/m (see Table 5.4). Since these were the largest beads to pass through the geotextile they constituted the upper part of the curves seen in figure 5.3. This part of the curve was used to calculate the filter opening size and so even a small change affected the calculation. Thus,

Graphical interpretation of results - determining the O_{95}

Using the mean values of all four specimens, the particle size distribution curve of the beads that have passed through the geotextile can be plotted. The results can be seen in figure 5.3. From these curves, the O_{95} can be calculated, as is indicated by the dashed line.

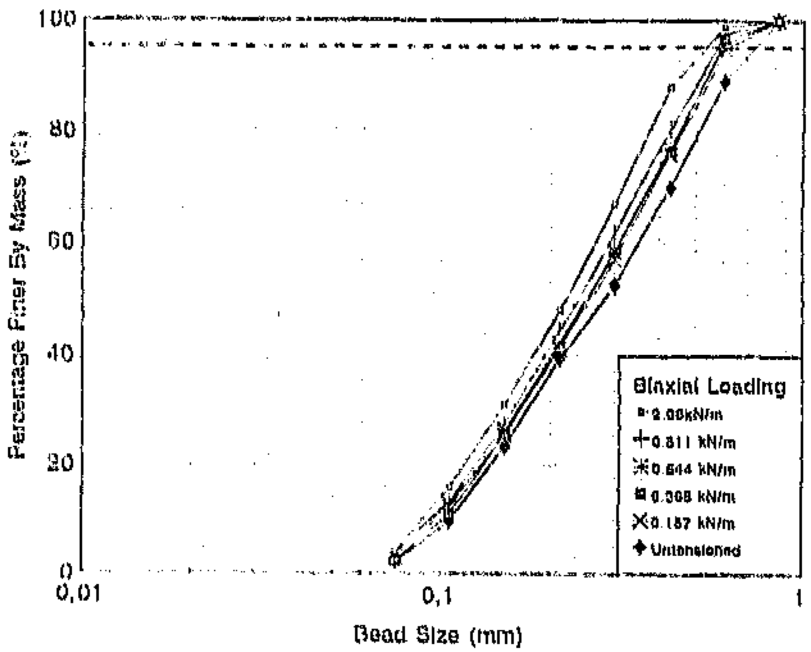

Figure 5.3 Particle Size analysis of beads that passed through the geotextile.

From the above graphs, the values for the filter opening sizes were calculated and the results are presented in table 5.5. The coefficient of variation of the results is also included.

retained on the 600-micron sieve and on the 425-micron sieve. Beads that were smaller than these two sizes, i.e. those retained on the 300, 212, 150, 106 and 75-micron sieve tended to all pass through the geotextile, while beads larger than these two sizes were all retained on the geotextile. The details of these two sizes are presented in teble 5.4 below. The details of the approximate strains and the total mass of beads that passed through the geotextile during testing are also presented. Table 5.4 gives the mean value of the four cylinders per test and the values are the results of the particle size analysis test of the beads that passed through the geotextile. Note that the initial mixture had 65 g of both the 600-micron and 425-micron sizes. For the complete results, see Appendix A.

Table 5.4 Summary of results for the equally tensioned woven geotextile.

Biaxial Load (N/m)	Strain (%)		600 μm sieve (g)	425 μm sieve (g)	Total mass passing (g)
	Warp	Weft			
Zero			34.3	61	317.6
187x187	1.6	1.4	15.3	56.2	294.9
365x365	1.6	1.5	9.5	58.5	284.7
544x544	1.6	1.3	11.4	52.5	277
811x811	2.2	1.6	7.3	46.6	272.5
2060x2060	3.6	2.3	2.7	26	255.2

The strain and the loading are small when compared with the ultimate tensile strength. The loading of 2.06 kN/m is only about 5% of the ultimate strength.

materials, i.e. HDPE and PVC for the flanges and cylinders caused a few problems when attempting to glue the two together. In hindsight it would have been better to either use the same material for the flanges and cylinders or else find another way to have them attached. For example, if the flanges and cylinders had the same internal diameter and the cylinders had a larger wall thickness, the flanges could have been screwed onto the cylinders. A solution to the problem was found as hot glue provided an adequate connection. Unfortunately, the hot glue was only effective for between five and ten tests. The flanges thus had to be stripped and reglued a couple of times.

The flanges, having a thickness of 6 mm, were too thin. The force carried by the bolts was large enough to slightly warp the flanges. Although six bolts proved to be adequate to maintain the required strain, it would be advisable to have more if any larger stresses are required for testing. The relative softness of the HDPE was a further problem. The bolts were required to be as tight as possible to maintain the stress in the geotextile. With repeated use, the washers became imbedded in the flanges and the holes became misshaped. The flanges will have to be replaced if further tests are required.

The initial sizing of the glass beads proved to be very troublesome. The beads are sold in quantities of twenty kilograms and their sizes varied over a certain range. The beads were usually sieved twice in order to establish their size. It was found that separating the beads that were finer than 75 μm was very difficult. The problem seemed to be one of the well-known faults of the dry sieving techniques. Electrostatic forces caused the finer beads to stick together and they were thus prevented from passing through the 75-micron sieve. The duration and the number of sievings seemed to have little effect on this smaller FOS. This anomaly can be explained when the mass retained on different sieves is examined. If we look at the first test, the mean of the mass retained on 106-micron sieve was 1.15 g and combining the 75-micron sieve and the pan, there was a mean of 38.5 g. For the second test, there was a mean of 1.5 g retained on the 106-micron sieve and 70.0 g retained on the 75-micron sieve and pan. The two tests had approximately the same mass of beads retained on the 106-micron sieve but the second test had 31.5 more grams of the 75-micron sieve and pan. The calculation of the FOS is based on the total mass of beads that pass through the geotextile. In this example there was practically the same mass of beads retained on the 106-micron sieve. When we plot this point on the particle size curve, we have to find the percentage finer by mass value. This involves the total mass of beads. In the first test, the 106-micron sieve corresponded to the 97% point while in the second test it was the 98% point. Therefore, despite the fact that the second test allowed more beads to pass through, we had a smaller value for the FOS.

This test also illustrated the fact that the FOS obtained was a function of the procedure used. To a certain extent, all methods of calculating the O_{95} are a function of their procedures. It is important that a test be standardized to calculate the O_{95} of geotextiles. If the hydrodynamic sieving test is chosen, all aspects of the test need to be addressed.

5.9 Problems Encountered With the Sieving Mechanism

A few problems were encountered with the design and the working of the hydrodynamic sieving mechanism. On the design side, the use of different

5.8 Results From the Non Woven Needle Punched Geotextile - No. 2

Certain methods for measuring the pore opening sizes of geotextiles, such as image processing, give the same results for geotextiles made with the same manufacturing process but with different thicknesses. As the soil particles have a much longer route to travel through a thicker geotextile, it would seem that a different opening size should be recorded for a thicker geotextile. The sensitivity of the hydrodynamic sieving process to the thickness of a geotextile was thus investigated. Two tests were carried out on a nonwoven needle punched geotextile (nwnp-2) that was made using the same manufacturing process as previously, but was thicker. The manufacturer's specifications for this geotextile can be found in table 5.1 and it can be seen that it has a thickness of 4.4 mm as opposed to 2.3 mm for the nwnp-1 geotextile.

The nwnp-2 goetextile was subjected to two tests. In both tests it was tensioned with a load of 544x544 N/m.

In the first test a mixture of beads was added at the start of the test and in the second the beads were added progressively as with test method number 2. The first test resulted in a FOS of 104 microns. The mean of the total mass of beads was 39.9 g. As the total mass of beads was less than 50 g, the test should be repeated with a different glass bead mixture. The result did confirm that a smaller FOS resulted from the thicker geotextile.

The second test had a mean total of 71.9 g, but the FOS was calculated at 100 μm. This once again illustrated the weakness in the method of calculating the FOS. Although the second test allowed more beads to pass through, we had a equation 7, with $t = 2.30$ mm, the permeability was calculated as 3.6×10^{-3} m/s. This compares with a permeability of 3.0×10^{-3} m/s which is given in the manufacturer's specifications. So this test seemed to give a fairly good approximation of permeability for the nonwoven geotextile.

For the second test, the geotextile was tensioned with a load of 2060x2060 N/m and the test repeated. The mean time of the twenty readings was 1.42 seconds. Using equation number four, this gave a permeability of 3.9×10^{-3} m/s. There was thus a slight increase in the permeability for the tensioned test. This can be attributed to a number of possible factors. During tensioning, the geotextile strained and there was a decrease in its thickness. From table 5.8, the strain recorded for this load was 3.3%. This changed the thickness to 2.23 mm (from the original thickness of 2.3 mm) and the permeability to 3.8×10^{-3} m/s. There was thus still a slight increase for the tensioned geotextile. This was most likely due to human error in timing such short time intervals and the sensitivity of the test. The actual permeability calculated according to a falling head test could well be much higher than the value calculated. The change in permeability would not be recorded, since the original value is lower than it actually is. This result is thus not significant.

When comparing this value of permeability with that from the permeameter results, it can be seen that these values are much higher. The maximum permeability recorded with the permeameter was 9.2×10^{-5} m/s. Thus the sand was once again the controlling factor.

further five hundred cycles which brought the total to a thousand cycles. The geotextile was tensioned prior to the test and the load was 544x544 N/m.

To compare the results from test methods 1 and 2, the same two sieve sizes are considered, the 150 and 106-micron sieves. From table 5.8, the mass of beads that passed through the geotextile and were retained on the 150-micron sieve was 1.1 g and 32.5 g for the 106-micron sieve. This compares with 10.9 g and 76.3 g for the same two sieves when using test method 2. The total mass of beads for method 1 was 125.7 g and 177.6 g for method 2. The FOS increased from 141 to 160 μm for method 2. This was an increase of 15%. In both tests, the coefficients of variation of the four replicates were small, less than 3%, and thus the difference of 15% is significant. The reason that a larger FOS was obtained with the second method is that there was less opportunity for larger beads to block pores that might permit the passage of the smaller beads. The FOS obtained is thus a function of the technique.

5.7.4 A measure of the change in permeability

Two tests were carried out on the nonwoven geotextile to measure the change in permeability using the HSM as a modified falling head permeameter. The test procedure was in accordance with section 5.6.4. The test involves the timing of the drop in water level inside the cylinders as they are lifted out of the water.

For the first test the geotextile was untensioned and a total of five cycles was timed. The mean of the resultant twenty readings was 1.55 seconds. Using of approximately 6.5% and -3.5% (i.e. a decrease in length due to necking) respectively. Since all other tests on the nonwoven specimens resulted in extension strains in both directions, it may have been expected that the test in which necking occurred would have produced the lowest FOS. That this did not occur may be due to the geotextile being unrestrained in the unloaded direction, unhindered fibre realignment occurs and there is not the same degree of "flattening" of the geotextile as occurs in biaxially loaded tests.

If only the FOS are considered, the 365x187 N/m load gave the smallest value and it would appear as if unequal loading produced the smallest opening sizes for this nonwoven geotextile. When we also consider the total mass of beads that passed through the geotextile, it can be seen that the load of 2060x2060 N/m allowed fewer beads to pass through (88.1 g) than any other test in either the equally or unequally loaded section. Coupled with the results from the other two unequally loaded tests, unequal biaxial in-plane loading did not appear to have a more detrimental effect on the opening sizes than equal loading.

5.7.3 Method 2

As with the woven geotextile, the nwnp-1 geotextile was subjected to a test where the beads were not all added at once at the start of the test. Using the same bead distribution and breakdown, the finest beads were added first and subjected to a hundred cycles. The next largest sized beads were then added and also subjected to a hundred cycles. This procedure was continued until all of the five different sized beads had been added. The test then continued for a the nwnp-1 geotextile for the unequally loaded tests

From figure 5.6, we can calculate the O_{95} of the geotextile. The results and their coefficients of variation are given in table 5.11.

Table 5.11 Calculated values of the O_{95} and coefficient of variation for the unequally tensioned non woven needle punched geotextile.

Biaxial Load (N/m)	O_{95} (μm)	Coefficient of variation (%)
Zero	157	7.6
365x0	146	1.5
365x187	137	3.0
365x544	159	4.4

Discussion of the results for the unequally loaded nwnp-1 geotextile

There is no clear trend of decreasing FOS with applied load for the nwnp-1 geotextile. The load of 365x544 N/m actually has a larger FOS than the untensioned test. This increase is very slight though and if we look at figure 5.6, the plots of these two results are virtually identical. This load thus seems to have virtually no effect on the FOS. This is surprising since it has the largest of the unequal loads, but it does also have the largest coefficient of variation of all the tensioned nwnp-1 tests. The smallest FOS and total mass of beads passing through being at a load combination of 187x365 N/m. The value of 137 μm was even lower than for the test in which 365 N/m was applied in the warp direction and zero load in the weft direction which resulted in strains

Table 5.10 Summary of results for the unequally tensioned nwnp-1 geotextile.

Biaxial Load (N/m)	Strain (%)	150 μm sieve (g)	106 μm sieve (g)	Total mass (g)
Zero		7.9	60.3	156.2
365x0	6.5 & -3.5	2.7	50.3	140.3
365x187	1.5 & 3.6	0.5	18.5	103.9
365x544	2.4 & 3.1	9.7	66.9	161.1

Graphical interpretation of the results - calculating the O_{95}

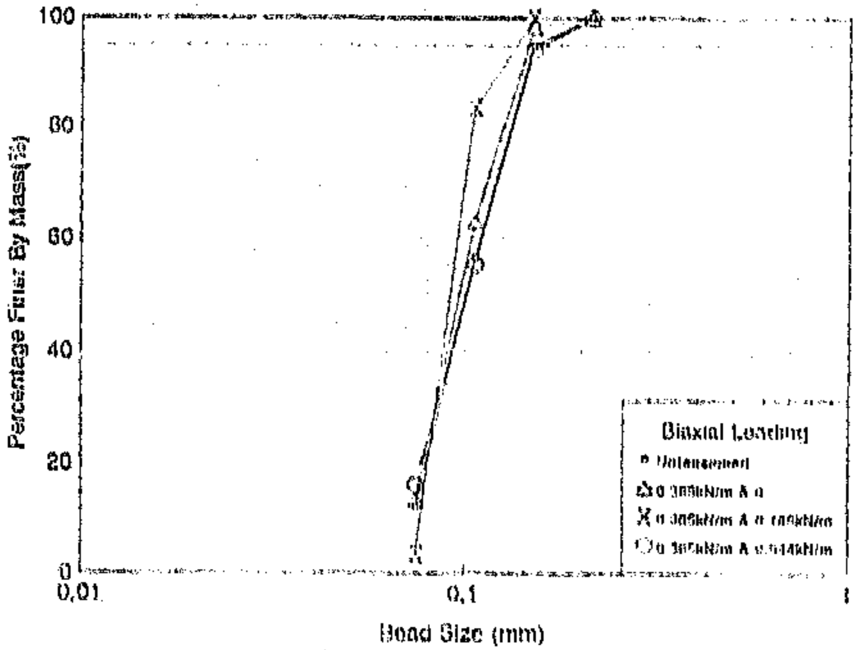

Figure 5.6 Particle size distribution curves for beads that have passed through

the 811x811 N/m test and the final test of 2060x2060 N/m. These decreases were not reflected in the FOS values. The reason for this is that the calculation of FOS was dependant on the largest sized beads that pass through the geotextile; here, the beads that were retained on the 150-micron sieve. The problem with the calculation of the values for figure 5.5 is that when considering the percentage finer amount for the 150-micron sieve, the calculation is based on the total mass of beads. As the mass retained on the 150-micron sieve decreased the total mass of beads also decreased, so similar values for the FOS can result even if there was a fairly significant decrease in the total mass of beads. The reliance of the calculation of FOS on the largest beads can be illustrated as follows. The FOS for the 811x811 N/m test (145 μm) is larger than that of the 544x544 N/m test (141 μm) despite the fact that fewer beads passed through the geotextile during testing. This result is due to the fact that slightly more of the 150 μm sized beads passed through (2.4 g as opposed to 1.1 g).

It can be seen then that the method of calculating the FOS does not always give a true reflection of what is actually happening.

5.7.2 Unequally tensioned nwnp-1 geotextile

The details of the three unequally loaded tests are presented in tables 5.10 and 5.11 and figure 5.6 below.

Table 5.9 Calculated values of the O₉₅ and coefficient of variation for the equally tensioned non woven needle punched geotextile.

Biaxial Load (N/m)	O_{95} (μm)	Coefficient of variation (%)
Zero	157	7.6
187x187	143	0.4
365x365	154	2.1
544x544	141	2.6
811x811	144	3.7
2060x2060	143	2.6

Discussion of equally tensioned nwnp-1 tests

If we look at the FOS results, it is apparent that the decrease was not as large for this type of geotextile as it was for the woven geotextile. The untensioned geotextile had a FOS of 157 μm and this decreased to a minimum of 141 μm for the 544x544 N/m loads. This was a reduction of approximately 9%. The variation of FOS with applied load can be seen to be very erratic, with most of the decrease having already occurred under the application of the smallest load (187x187 N/m).

When the total masses of beads are compared, a different picture appears to that of the FOS. There was an initial decrease (of 21 g) from the untensioned test to the smallest load (187x187 N/m). The next three tests gave very similar results but then there was a decrease of 11.3 grams between the 544x544 N/m test and the 811x811 N/m test. There was a further decrease of 26.3 g between

Graphical interpretation of the results - calculating the O_{95}

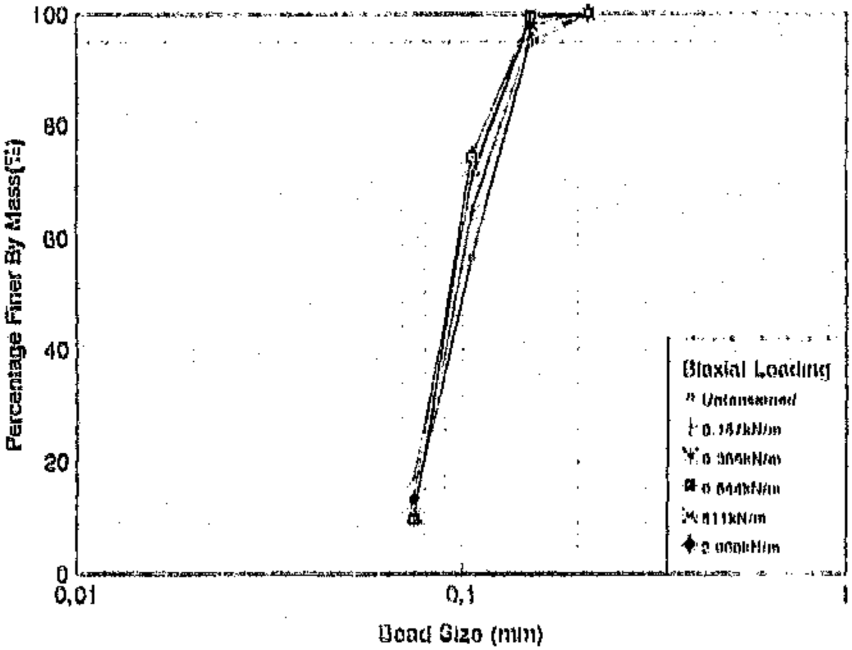

Figure 5.5 Particle Size analysis curves for the beads that have passed through the equally tensioned nwnp-1 geotextile

From figure 5.5, we can calculate the O_{95} for the geotextile. The results and their coefficients of variation are given in table 5.9.

Table 5.8 Summary of results for the equally tensioned nwnp-1 geotextile.

Biaxial Load (N/m)	Strain (%)	150 μm sieve (g)	106 μm sieve (g)	Total mass (g)
Zero		7.9	60.3	156.2
187x187	2.5	1.5	37.4	125.2
365x365	2.4	5.3	41.2	126.6
544x544	3.2	1.1	32.5	125.7
811x811	3	2.4	33.2	114.4
2060x2060	3.3	1.5	26.4	88.1

Note: For a needle punched geotextile, there is no discernable warp and weft direction and so a mean of the strain in two directions is calculated.

2.3 Mass of beads that have passed through the geotextile and are retained on the 75 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensioned	68.8	70.1	69.8	68.5	69.3
187X187	80.5	73.7	76.8		77
365X365	63.7	70.6	66.7	67.9	67.2
544X544	76.4	81.5	83.8	79.6	80.3
811X811	48.7	62.5	65.5	64	60.2
2060X2060	41.6	78.9	37.3	58.1	54
365X0	93.8	80.4	81	74.7	82.5
365X187	74.4	73.2	61.8	70.2	69.9
365X544	77.4	72.2	74.2	68.4	73.1

2.4 Mass of beads that have passed through the geotextile and are retained on the pan

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensioned	20.5	17.2	18.5	17.1	18.3
187X187	13.2	12.1	11.4		12.2
365X365	13.2	13	11.7	13.4	12.8
544X544	12.4	11.1	11.2	11.1	11.5
811X811	18.4	19.2	18	17.9	18.4
2060X2060	9.9	11.8	9.7	12.5	11
365X0	5.5	4.8	4.5	4.3	4.8
365X187	16.8	16.4	16.4	16.1	16.4
365X544	17.4	14.4	14.9	13.7	15.1

2 The Nonwoven Needle Punched (No. 1) Geotextile

2.1 Mass of beads that have passed through the geotextile and are retained on the 150 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensioned	3.7	8.4	5.5	13.8	7.9
187X187	1.2	1.9	1.4		1.5
365X365	2	3.7	3.1	12.2	5.3
544X544	0.5	1.4	1.5	1.1	1.1
811X811	0.4	1.5	2.9	4.9	2.4
2060X2060	0.8	2.4	1.6	1.2	1.5
365X0	1.4	1.7	4.4	3.4	2.7
365X187	0.2	1	0.3	0.5	0.5
365X544	8.8	11.9	9.4	8.6	9.7

2.2 Mass of beads that have passed through the geotextile and are retained on the 116 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensioned	46.3	65	70.7	59.3	60.3
187X187	41	35.9	35.3		37.4
365X365	27.5	41.8	34.1	61.5	[illegible]
544X544	18.5	40.8	26.8	43.7	[illegible]
811X811	13.5	32	49.3	38.5	33.3
2060X2060	13.3	42.8	17.8	13.1	26.4
365X0	34.5	46.9	62.1	57.5	50.25
365X187	23	23.5	10.8	16.8	18.5
365X544	76.9	74	60.8	55.7	66.9

1.9 Total mass of beads that have passed through the geotextile

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	314.9	312.3	317.6	325.7	317.6
187x187	287.4	296.6	292.8	302.8	294.9
365x365	291.5	273.1	285.5	288.5	284.7
544x544	288	286.5	256.6		277
811x811	263	283.7	261.3	282	272.5
2060x2060	252 2	258.6	255.1	255	255.2
365x0	293.8	311.2	287.9	302.6	298.9
365x187	276.7	271.5	245.1	256.5	262.5
365x544	276.6	272	259.5	277.4	271.4

1.10 Method 2 (load of 544x544 N/m)

Sieve Sizes (Microns)	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
600	5.6	7	6.3	4.2	5.8
425	49.1	43.1	41	31.3	41.1
300	55.9	55.8	55.7	55.6	55.8
212	38.5	39.4	36.4	38.5	38.2
150	42.3	41.5	43.2	42.3	42.3
106	43.1	41.1	43.3	39.4	41.7
75	39.7	40.3	39.3	41.7	40.3
Pan	5.7	7.1	7	6.6	6.6
Total	279.9	275.3	272.2	259.6	271.8

1.7 Mass of beads that have passed through the geotextile and are retained on the 75 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	15.7	26	25.2	27.4	21.5
187x187	26.5	26.2	28.1	28.2	27.3
365x365	28.9	25.7	25.9	26	26.6
544x544	24.9	25.7	25		25.2
811x811	25.2	27.3	25.8	25.3	25.9
2060x2060	33.4	32.1	31	33.8	32.6
365x0	38.5	36	38.5	37	37.5
365x187	30.3	30.4	30.3	29.8	30.2
365x544	31	30.5	29.8	31.3	30.7

1.8 Mass of beads that have passed through the geotextile and are retained on the pan

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	5.3	7.5	7.2	7.7	6.9
187x187	8.7	8.6	7.7	7.5	8.1
365x365	4.7	6.3	6.1	5.1	5.6
544x544	10.2	9.9	8.4		9.5
811x811	9.6	10.4	9.5	10.2	9.9
2060x2060	7.9	6.7	7	6.5	7
365x0	5.3	5.2	4.4	4.5	4.9
365x187	6.4	5.2	6.1	5.2	5.7
365x544	5.6	6	6.1	5.7	5.9

1.5 Mass of beads that have passed through the geotextile and are retained on the 150 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	62.3	46.6	45.6	46.7	50.3
187x187	50.9	44	45	45	46.2
365x365	43	43.4	44.5	46.7	44.4
544x544	46.5	44.5	41.1		44
811x811	43	46.1	43.2	50.3	45.7
2060x2060	43.6	43.7	43.1	43.5	43.4
365x0	43.5	43.8	44	34.1	41.4
365x187	46.8	47.1	47.3	46.5	47
365x544	45.5	44.4	44.2	45.8	45

1.6 Mass of beads that have passed through the geotextile and are retained on the 106 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	52.8	40.3	40.7	40.2	43.5
187x187	39.4	38.2	38.8	39.9	39.1
365x365	39.1	39.2	39.8	40.5	39.7
544x544	37.4	37.8	35.5		36.9
811x811	37.9	38.6	39.2	39.2	38.7
2060x2060	37.5	39.1	39.9	38.3	38.7
365x0	32.1	34.3	33.2	37	34.2
365x187	38.3	39.5	38.3	38.9	38.8
365x544	40.1	39	39	41.3	39.9

1.3 Mass of beads that have passed through the geotextile and are retained on the 300 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	53.4	53.8	55	56.9	54.8
187x187	54.3	54.8	54.7	54.1	54.5
365x365	51.4	50.4	49.7	49	50.5
544x544	52	51.7	47.9		50.5
811x811	49	53.9	47.7	50.7	52.8
2060x2060	55	55.4	54.1	54.4	54.7
365x0	57.3	58.3	57.1	58.6	57.8
365x187	54.5	54.6	52.8	54.3	54.1
365x544	54.7	54.8	52.9	53.2	53.9

1.4 Mass of beads that have passed through the geotextile and are retained on the 212 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	28 6	46.9	47.5	46.9	
187x187	42.3	49.3	49.7	48.8	47.5
365x365	48.2	50.4	49.7	47.9	49.1
544x544	45	49.2	43.7		46
811x811	48.4	48.2	49.9	44.3	47.7
2060x2060	46.7	47.3	47.7	46.9	47.2
365x0	50.1	49.7	49.7	49.8	49.8
365x187	46.5	46.3	44.6	47.4	46.2
365x544	46.2	48	44.6	46	46.2

APPENDIX A

COMPLETE RESULTS FOR THE HYDRODYNAMIC SIEVING TESTS

1 The Woven Slit-Film Geotextile

1.1 Mass of beads that have passed through the geotextile and are retained on the 600 micron sieve (mass in grams)

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	34.8	28.4	34.6	39.5	34.3
187x187	11.6	16.3	13.3	20	15.3
365x365	9.8	6.8	9.7	11.7	9.5
544x544	14	11.6	8.6		11.4
811x811	5.8	10.1	3.9	9.2	7.3
2060x2060	2.8	3.5	1.9	2.6	2.7
365x0	14	24.8	15.1	19 3	18.3
365x187	18.2	10	6.3	7.1	10.4
365x544	14	12.6	10.6	10.7	12

1.2 Mass of beads that have passed through the geotextile and are retained on the 425 micron sieve

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensione	62	61.1	60.4	60.2	61
187x187	53.7	57.8	54.6	58.5	56.2
365x365	62.8	50.1	59.5	61.7	58.5
544x544	57	56.1	44.5		52.5
811x811	43.5	49.1	40.9	52.8	46.6
2060x2060	23.7	29.2	23.5	27.6	26
365x0	52.5	57.2	45.5	54.3	52.4
365x187	36	37.4	27.5	18.6	29.9
365x544	39.5	36.7	32.3	43.3	38

There are many applications in which a geotextile may be subjected to in-plane tensile loads, eg. when used as a reinforcing layer beneath a fill, or even when used to line an excavation drainage trench that may subsequently undergo settlement as a result of overlying fill construction. If the particle retention and flowrate characteristics of the geotextile in these applications are important, it is suggested that cognisance be taken of the reduction in opening size that may occur. Tests at higher tensile loads as well as on a range of different geotextile types should still be performed.

smaller than those for the woven geotextile. This was probably due to the greater consistency in the pore opening sizes that result from the needle punching process. For the unequally tensioned tests, there was still a decrease in the FOS. This type of loading didn't appear to have a more detrimental effect on the opening sizes than equal loading. The through-flow capacity for this geotextile increased slightly when the geotextile was tensioned. The increase was less than 10%, and can be attributed to human error in timing such small time intervals.

Two tests were carried out on the thicker nonwoven geotextile and the results showed a smaller FOS results from a thicker geotextile. For both of the nonwoven geotextiles a test where the bead size designations were added one at a time was performed. In both cases a larger mass of beads passed through than with the original test. This was due to the fact that the larger beads have less opportunity to block pores that might permit the passage of the smaller beads. It illustrated the fact that the FOS obtained was a function of the procedure.

A study was also made on the effect of in-plane tensile loads on the permeability of geotextiles. A large diameter, constant head, permeameter was used. The design was such that a pretensioned geotextile was tested in direct contact with a fine grained soil. Four tests were performed on each of the two geotextiles tested. Not only were a number of problems encountered during testing, but the test did not show a decrease in flowrate through the geotextile between the tensioned and untensioned specimens. The length of time of these tests and the lack of any real trends appearing, resulted in the tests being stopped.

is a relatively large reduction, it would probably not prevent the geotextile of performing adequately if we take into account the factors of safety used in design.

The effect of the initial glass bead mixture on the resultant FOS was also tested. The beads were added, one designation at a time, at regular intervals during the test as opposed to adding a mixture of beads at the start of the test. There was a slight decrease in the mass of beads that passed through the geotextile and thus the FOS also decreased. This decrease was not greater than the variation that occurred between different cylinders during testing and it can thus be ignored.

The same series of tests were also performed on a nonwoven needle punched geotextile. A second nonwoven geotextile, made using the same manufacturing process but being slightly thicker, was also used for two tests. There was a much smaller reduction in the FOS for the nonwoven geotextile for both the equally tensioned and unequally tensioned tests. For a load equal to 10% of multidirectional tensile strength, there was a maximum reduction of 9% in the FOS with most of the reduction occurring at very low tensile loads. This was attributed to the low tensile modulus of the geotextile which resulted in relatively large strains occurring at low tensile loads. The decrease in the total mass of beads passing through the test specimens was not always reflected in the FOS. In one case, a smaller total mass of beads resulted in a larger FOS. This is because the calculation of FOS is very dependant on the mass of the larger beads passing through the geotextile.

The values for the standard deviation of the nonwoven geotextile were much

CHAPTER 6

CONCLUSION

Two types of tests were carried out on a woven slit-film polypropylene geotextile and a nonwoven needle punched continuous filament polyester geotextile. In both cases, the geotextiles were first tensioned in a specially constructed loading frame. The frame was able to tension a sample of 1.6x1.6 m either equally in all directions or unequally in two directions. The effects on the permeability and the filtration opening sizes (O_{95}) were monitored.

Hydrodynamic sieving tests with glass beads were used to investigate the effect on the largest apparent opening sizes. The mechanism consisted of four large diameter cylinders, into which pretensioned geotextile specimens could be placed.

Tests carried out on the woven slit-film geotextile showed a marked reduction in the filtration opening size (FOS). A load of 8% of the minimum tensile strength of the geotextile caused a reduction of 28% in the FOS. Tests in which unequal loads were applied in the two orthogonal in-plane directions showed similar results to the equally loaded specimens. A test on the through-flow capacity of the geotextile was also carried out. The flowrate through the specimen was measured for an untensioned test and compared with that of a specimen with a load of approximately 8% of the minimum tensile strength. A 43% reduction in the flowrate for the tensioned specimen resulted. While this problem. If we refer to Appendix A sections 1.8 and 2.4, it can be seen that in some cases, up to 25% of the beads that were initially sized as 75 to 106 μm, were in fact smaller. After the beads were oven dried and subjected to a size distribution test, some of the beads would be sieved through to the pan. The beads that were used during the tests were always recycled. This was not only an attempt at saving time but also to try and improve the grading of the beads. The beads that were sieved through to the pan were always discarded. Despite this precaution, this problem continued throughout the testing.

Oeverbeschermingsconstructies, K and O (Nederlandse Vereniging Kust- en Oeverwerken) Rotterdam.

Vermeersch, O.G. and Mlynarek, J., (1986), *Determination of pore size disribution of nonwoven geotextiles by a modified capillary flow porometery technique*, Recent developments in Geotextile Filters and Prefabricated Drainage Composites, ASTM STP 1281, Eds. S. K. Bhatia and L. D. Suits, American Society for Testing Materials, Phil., Pa, pp. 14.

Wates, J.A. and Witsoek, G.H., (1986), *Selection of geofabrics for filtration applications with particular reference to gold tailings*, March 1986, pp. 83-89, Johannesburg.

Wittmann L., (1982), *Soil filtration phenomena of geotextiles*, Proceedings of the Second International Conference on Geotextiles, Las Vegas, U.S.A. Vol. 1, pp. 79-84.

Saathoff, F., and Kohlhase, S. (1986), *Research at the Franzius-Institut on geotextile filters in hydraulic engineering*, Proceedigs of the Fifth Congress Asian and Pacific Reg. Div., ADP/IAHR, Seoul, Korea.

Schimelfenyg, P., Fowler, J. and Leshchinsky, D., (1990), *Fabric reinforced containment dyke, New Bedford superfund site*, Proceedings of the Fourth International Conference on Geotextiles, Geomembranes and Related Products, Vol.1, The Hague, The Netherlands, May 1990, pp. 149-154.

Shi, Y.C., Fannin, R.J. and Vaid, Y.P., (1994), *Interpretation of gradient ratio test results*, Proceedings of the Fifth International Conference on Geotextiles, Geomembranes and Related Products, Vol., Singapore, pp. 673-676.

US Army Corps of Engineers, (1977), *Civil Works construction specification for plastic filter fabric*, CW 00215, Washington DC

Vaid Y.P. and Negussey D., (1988), *Preparation of reconstituted sand specimens*, Advanced Triaxial Testing of Soil and Rock, ASTM STP 977, R. T. Donaghe, R.C. Chaney and M.L. Silver, eds., ASTM, Philadelphia, pp. 405-417.

Van der Merwe, C.J. and Horak, E., (1989), *Evaluation of soil/geotextile compatibility*, Twelth International Conference on Soil Mechanics and Foundation Engineering.

Veldhuizen van Zanten, R., (1983), *Handboek*

Geomembranes and Related Products. Balkema. Rotterdam. pp. 295-299.

Rollin. A.L.. Masounave. J.. and Dallaire, G.. (1977). *Etudes des proprietes hydrauliques des membranes nontisses*. Proceedings of the International Conference on the Use of Fabrics in Geotechnica. Association Amicale des Ingenieurs Anciens Eleves del l'Ecole Nationale des Ponts et Chaussees. Paris. 2:295-299.

Rollin. A.L.. Masounave, J.. Dennis R.. Estaque L.. (1978). *Etude des proprietes hydrauliques des membranes synthetiques non tissees utilisees en geotechnique*. Rapport pour le Ministere des Transports du Quebec. Ecole Polytecnique de Montreal. Report No. CDT.P.288.

Rollin. A.L.. Masounave. J.. and Lafleur J.. (1982). *La perte de charge au travers des geotextiles non tisses : un nouveau modele*. Proceedings of the Second International Conference on Geotextiles. Las Vegas. U.S.A. pp. 161-166.

Rowe, R.K. and Myleville. B.L.J.. (1990). *Implications of adopting an allowable geosynthetic strain in estimating stability*. Proceedigs of the Fourth International Conference on Geotextiles. Geomembranes and Related Products. Vol.1. The Hague. The Netherlands. May 1990. pp. 131-136.

Rycroft. D. and Dennis. J.P.. (1982). *Geotextiles filtration performance and current filtration criteria*. Proceedings of the Second International Conference on Geotextiles. Las Vegas. U.S.A.

Filtration: Gas, Vol. 1, ASTM STP975, ASTM, Philadelphia, PA, pp. 97-106

Mlynarek, J., Lafleur, J., Rollin, A., and Lombard, G., (1993), *Filtration Opening Size of Geotextiles by Hydrodynamic Sieving*, Geotechnical Testing Journal, GTJODJ, Vol. 16, No. 1, March 1993, pp. 61-69.

Ogink, H.J.M., (1975), *Investigation on the hydraulic characteristics of synthetic fabrics*, Delf Hydraulics Laboratory, Publ. No. 146.

Polycroft, D. and Dennis Jones, P., (1982), *Geotextile performance and current filter criteria*, Proceedings of the Second International Conference on Geotextiles, Vol. 1, Las Vegas, pp. 67-72.

Prapaharan, S., Holtz, R. D., and Luna, J. D., (1989), *Pore size distribution of nonwoven geotextiles*, Geotech. Testing J., 12:261-268.

Rankilor, P.R., (1981), *Membranes in ground engineering*, Chichester: Wiley, 377p.

Rigo, J.M., Lhote, F., Rollin, A.L., Mlynarek, J., and Lombard, G., (1990), *Influence of geotextile Structure on Pore Size Determination*, Geosynthetics: Microstructure and Performance, ASTM STP 1076, I.D. Peggs, Ed., Philadelphia, pp. 90-101.

Rollin, A.L., Mlynarek, J., and Vidovic, A., (1990), *Filtration opening size of geotextile: The parameters influencing the pore size determination*, Proceedings of the Fourth International Conference on Geotextiles, *Bewahrung*, Mitt. Franszius-Institut, Univ. Hannover.

Heerten, G. (1982), *Dimensioning the filtration properties of geotextiles considering long-term conditions*, Proceedings of the Second International Conference on Geotextiles, Las Vegas, Vol. 1, pp. 115-120.

John, N.W.M., (1987), *Geotextiles*, Blackie and Son, London.

Koerner, R.M. and Ko, F.K., (1982), *Laboratory studies on long-term drainage capabilities of geotextiles*, Proceedings of the Second International Conference on Geotextiles, Las Vegas, Vol. 1, pp. 91-95.

Kuchena, S.M., (1994), *Geotextile filtration behaviour under biological clogging and under the influence of in-plane unidirectional tensile stresses*, MSc. Dissertation, The University of the Witwatersrand, South Africa.

Lawson, C., (1986), *Geotextile filter criteria for tropical residual soils*, Proceedings of the Third International Conference on Geotextiles, Vol. 2, Vienna, pp. 557-562.

Loudiere, D. and Fayoux, D., (1982), *Filtration and Drainage with Geotextiles - Test And Requirements*, Second International conference on Geotextiles, Las Vegas, NV, Session 3a, 1982, pp. 61-62.

Miller, B., Tyomkin, I., and Wehner, J.A., (1986), *Quantifying the porous structure of fabrics for filtration applications*. In: R.F Raber, editor, Fluid

International Conference on Geotextiles, Las Vegas, U.S.A. pp. 103-108.

Giroud, J.P., (1982). *Designing with geotextiles*. Materiaux et Constructions Vol. 14, No. 82, pp. 257-295.

Giroud, J.P., (1983). *Geotextile Drainage Layers for Soil Consolidation*. Civil Engineering for Practicing and Design Engineers, Vol. 2, Pergamon press Ltd., pp. 275-295.

Giroud, J.P., (1996). *Granular filters and Geotextile filters*. Proceedings of the International Conference on Geofilters, Montreal Canada, pp. 565-680.

Goure, J.P., (1982). *Quelques aspects du comportement des goetextiles en Mecanique des Sols*. These de Docteur es-Sciences, Universite Scientifique et Medicale de Grenoble, France.

Goure, J.P. and Faure, Y., (1990). *Soil particles, water ...and fibres - A fruitful interaction now controlled*. Proceedings of the Fourth International Conference on Geotextiles, Geomembranes and Related Products, Vol. 3, The Hague, The Netherlands, May 1990, pp. 949-971

Greenaway, D.R., Ho, K.W. AND Brand, E.W., (1986). *Filtration and degradation behaviour of some non-woven geotextiles in Hong Kong*. Proceedings of Third International Conference on Geotextiles, Vol. 2, Vienna, pp. 605-609.

Heerten, G., (1982). *Geotextilien im Wasserbau - Prufung, Anwendung,* Fischer, G.R., Christopher, B.R., and Holtz,R.D., 1990, *Filter criteria based on pore size distribution*, Proceedings of the Fourth International Conference on Geotextiles, Geomembranes and Related Products, Vol.1, The Hague, The Netherlands, May 1990, pp. 289-294.

Fischer, G.R., Holtz, R.D., and Christopher B.R., (1993), *A critical review of geotextile pore size measurement methods*, Filters in Geotechnical and Hydraulic Engineering, Eds. Brauns, Heibaum and Schuler, Balkema, Rotterdam, 1993, pp. 83-90.

Fourie, A.B. and Kuchena, S.M., (1995), The *influence of tensile stresses on the filtration characteristics of geotextiles*, Geosynthetics International, Vol2, No. 2, pp.455-471.

Gerry, B.S., and Raymond, G.P., (1983), *Equivalent opening size of geotextiles*, Geotechnical Testing Journal, 6:53-63.

Giroud, J.P., (1977), Gourc, J.P., Bally, P. And Delmas, P., (1977), *Comportement d'un textile non tisse dans un barrage en terre*, Proceedings of the International Conference on the Use of Fabrics in Geotechnics, Session 6, Paris, France, April 1977, pp. 213-218, (In French).

Giroud, J.P., (1980), *Introduction to geotextiles and their Applications*, Proceedings of the first Canadian Symposium on Geotextiles, Sept. 1980, pp. 3-31.

Giroud, J.P., (1982), *Filter Criteria for Geotextiles*, Proceedings of the Second

Dierickx, W. and van der Sluys, L., (1990), *Comparative Studies of Different Porometry Determination Methods for Geotextiles*, Geotextiles and Geomembranes, No. 9, pp. 183-198.

Fannin R.J., Vaid Y.P. and Shi Y., (1994), *A Critical Evaluation of the Gradient Ratio Test*, Geotechnical Testing Journal, GTJODJ, Vol. 17, No.1, March 1994, pp. 35-42.

Faure Y.H., Gourc, J.P., Millot, F. and Sunjoto, S., (1986), *Theoretical and Experimental Determination of the Filtration Opening Sizes of Geotextiles*, Proceedings of the Third International Conference on Geotextiles, Vienna, Austria, Vol IV, p. 1275-1280.

Faure Y.H., Gourc, J.P., and Genddrin, P., (1990), *Structural study of porometry and filtration opening sizes of geotextiles*, In: I. S. Peggs, editor, Geosynthetics: Microstructure and Performance, ASTM STP 1076, ASTM, Philadelphia, PA, pp. 102-119.

Fayoux, D., (1977), *Filtration hydrodynamique des sols par les textiles*, Proc. of the Int. Conf. on the Use of Fabrics in Geotechnics, Ass. amicale des ingeneurs anciens eleves de l'Ecole nationale des ponts et chaussees, Paris, vol. 2, pp. 329-332.

Fayoux, D., Cazzuffi, D., and Faure, Y., (1984), *The determination of the filtration characteristics of geotextiles: Comparison of the results of different laboratories*, Proceedings of the International Conference on Materials for Dams, Monte Carlo.

Blaauwm, H.G., Groot, M.T., Van der Knaap, F.C.M. and Pilarczyk, K.W., (1984), *Design of bank protection of inland navigation fairways*, Proceedings of the International Conference on Flexible Armoured Revetments Incorporating Geotextiles, London, Thomas Telford, pp. 39-65.

Calhoun, C.C., Jr., (1972), *Development of design criteria and acceptance specifications for plastic filter cloth*, Technical Report F-72-7, U.S. Army Corps of Engineers Waterways Experimental Station, Vicksburg, MI.

Carroll, R.G., (1983), *Geotextile Filter Criteria*, Transportation Research Record, 916, pp. 46-53.

Chin, Y.M., Nikraz, H.R. and Press, M., (1994), *Laboratory Filtration Performance of Nonwoven Geotextiles*, Proceedings of the Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore, Sept. 1994, pp. 635-638.

Christopher, B.R. and Holtz, R.D., (1985), *Geotextile Engineering Manual*, U.S. Federal Highway Administration, Report Fhwa-ts-86/203, pp. 1044.

De Wit, P., (1985), *Porometrie des geotextiles non tisses aiguilletes*, Memoire de 3eme annee, ENITRTS, Strasbourg, CEMAGREF Antony, France.

Dennis, C.W. and Davies, P.A., (1984), *Filter Openings Measured by a Suction Method*, Geotechnical Testing Journal, GTJODJ, Vol. 7, No. 3, Sept. 1984, pp. 153-157

REFERENCES

Andrei, S., Strunga, V., Antonescu, I. and Petricia, I., (1982), *On Hydric Properties of Geotextiles*, Proceedings of the Second International Conference on Geotextiles, Las Vegas, U.S.A, pp. 121-126.

Belisle, J., (1988), *Etude de lc mesure de l'ouverture de filtration des geotextiles non-tisses par tamisage hydrodynamique*. Master Thesis, Ecole Polytechnique de Montreal: Montreal.

Bhatia, S.K., Huang, Q. and Mlynarek, J., (1994), *Pore size characterisation of non-woven geotextile using image processing technique*. Paper under preparation.

Bhatia, S.K., Huang, Q. and Mlynarek, J., (1993), *Application of digital image processing in morphological analysis of geotextiles*, Proc. Conf. on Digital Image Processing: Techn. and Appl. in Civil Engr., ASCE, Honolulu, Hawaii, 1:95-108.

Bhatia, S.K. and Smith, J.L., (1995) *Sieving Techniques for Measuring Pore Openings - An Open Question*, Geosynthetics 1995, pp. 281-295.

Bhatia, S.K., Smith, J.L. and Christopher, B.R., (1994), *Interrelationship between Pore Openings of Geotextiles and Methods of Evaluation*, Proceedings of the Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore, Sept. 1994, pp. 705-710

3 The Nonwoven Needle Punched (No. 2) Geotextile

3.1 Mass of beads retained on the 106 micron sieve

Test Number	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
No.1	1.3	1.2	1.2	0.9	1.2
No.2	1.3	1.3	2	1.4	1.5

3.2 Mass of beads retained on the 75 micron sieve

Test Number	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
No.1	31.8	30.6	20.2	32.4	28.8
No.2	63.7	63.8	69.4	62.9	65

3.3 Mass of Beads retained on the pan

Test Number	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
No.1	9.6	9.5	9.1	10.6	9.7
No.2	4.3	4.9	5.4	5.5	5.1

3.4 Total mass of beads retained

Test Number	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
No.1	43.1	41.6	30.6	44.4	39.9
No.2	69.6	70.7	77.4	69.9	71.9

2.5 Total mass of beads that have passed through the geotextile

Biaxial Load N/m	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
Untensioned	139.7	161.2	173.3	150.7	156.2
187X187	128	123.6	124.9		125.2
365X365	106.7	129.1	115.6	155.1	126.6
544X544	108.3	135.1	122.9	136.5	125.7
811X811	81.2	115.4	135.8	125.3	114.4
2060X2060	64.8	135.9	66.4	85.4	88.1
365X0	135.3	151.4	134.5	140.1	140.3
365X187	108.4	114.1	89.3	103.6	103.9
365X544	170.7	172	155.2	146.4	161.1

2.6 Method 2 (Load of 544x544 N/m)

Sieve Sizes (Microns)	Specimen Number				Mean
	No.1	No.2	No.3	No. 4	
150	17.5	9.6	4.9	11.5	10.9
106	77.1	72.2	74.8	81.2	76.3
75	82.6	80.6	77.6	76.3	79.3
Pan	10.5	11.9	11.2	9.7	10.8
Total	188	174.7	168.7	178.8	177.6