UNIVERSITY OF ALBERTA

FILTRATION PROPERTIES OF GEOTEXTILES FOR HEAVY OIL WELLS

BY

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Abstract

The use of geotextile filters for heavy oil wells, in unconsolidated fine uniform sand and silty sand reservoirs, is a new concept in the oil industry. Laboratory research and field testing is required for this innovative application. This thesis discusses research procedures and test results for choosing a geotextile fabric for controlling sand flow in ambient temperature heavy oil or oil sand production wells. A gradient ratio apparatus, a modified gradient ratio apparatus and a large scale high confining stress filtration apparatus were designed, fabricated and used in the filtration testing program. The gradient ratio apparatus and the modified gradient ratio apparatus were used to determine the sand-geotextile system permeability and clogging behaviour with water as permeant. The high confining stress filtration apparatus was used to determine the effect of a high confining stress on the system permeability and clogging and blinding behaviour with heavy oil and water as permeants.

The gradient ratio and the modified gradient ratio apparatus are similar to the apparatus recommended by ASTM. The main differences in the apparatuses are the methods for defining the gradient ratio, the height of the sand specimens and the inclusion of a surface sand filter layer. The high confining stress filtration apparatus can accommodate a sand specimen up to 200 mm in height. It is equipped with seven piezometer ports for measuring hydraulic heads. As a result, the boundary between the undisturbed and filter zones can be well defined by the head changes calculated from the pore pressure measurements. The equipment can produce a maximum differential pressure across the specimen of 400 kPa, so it can accommodate high viscosity oil as the permeant. A confining stress of 1300 kPa can be achieved, simulating a horizontal effective stress from a loose sand on a well casing equivalent to a depth of 1000 m below the ground surface.

After a series of preliminary filtration tests by the gradient ratio apparatus, three commercial, nonwoven geotextile filter materials were selected and tested with the modified gradient ratio apparatus and with the high confining stress filtration apparatus. A uniform medium to fine sand from the McMurray heavy oil formation of the Athabasca Oil Sands in Alberta was used in the tests.

The results of the testing program were analyzed and the results indicate that all three geotextile fabrics had good permeability and soil retention properties. Minor blinding and clogging of the geotextile fabrics occurred but there was no indication in the test results that sand piping through the geotextiles took place. The high confining stress filtration tests give a lower geotextile absolute permeability than the modified gradient ratio tests indicating that the presence of sand compacted on top of the geotextile fabrics decreases their permeability. It is concluded that Giroud's geotextile filter design criteria for steady state conditions are valid and can be used for the McMurray Formation sands, but the design criteria for unsteady state flow conditions require more investigation.

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I would like to dedicate this thesis

to

my mother, Cheung Fong Mak

and

my wife, Eva

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CHAPTER 1: INTRODUCTION

1.1 Statement of the Problem

Sand production is a persistent problem in production wells which are located in unconsolidated oil sand and heavy oil sand formations. Sand production results in accelerated equipment wear and damage, flow line erosion, mechanical disturbance of the formation, and casing damage; all add significantly to operation costs. In extreme circumstances, sand production has forced the shut down of individual wells. Removal of the sand plugging the well is an expensive and time consuming "workover" procedure.

Current conventional methods of controlling sand production, through the use of mechanical filters, such as screens, slotted liners or gravel and sand packs have only limited success. Problems of plugging and corrosion of these filter devices are still common. Use of geotextile filters, designed with specific pore sizes and permeability characteristics, are a new and innovative approach to controlling the flow of sand in heavy oil or oil sands production wells.

1.2 Objectives of Thesis

The objectives of this thesis are (1) to examine the validity of current geotextile filter design criteria for use in the design of geotextile filters for heavy oil sand production wells, (2) to describe the process and the experimental procedures used to identify a geotextile fabric, which has favorable filtration performance, for use as a well filter to reduce sand flow in ambient temperature heavy oil or oil sands production well.

1.3 Scope of Thesis

This thesis is prepared as the result of experiments performed under a research program which was funded by the Petroleum Aid to Education Fund, an Esso University Research Grant, and the Alberta Oil Sands Technology and Research Authority (AOSTRA). In the general research program physical, mechanical, environmental and filtration properties of selected geotextile fabrics were considered. This thesis discusses the filtration properties. Environmental, physical and mechanical properties of the geotextile fabrics were investigated by Penner, and have been reported in her thesis (Penner, 1990).

The focus of this thesis is on filtration properties, such as, geotextile opening size, porosity, permittivity, clogging potential and sand-geotextile interaction. Other factors which will affect the filtration properties of the geotextiles, such as wettability and transmissivity, are not discussed in detail. Results on the wettability and transmissivity of the geotextile fabrics have been reported (Scott et al, 1988, 1990).

1.4 Organization of the Thesis

Chapter 1 discusses the objective of the research, the scope and the organization of the thesis. Chapter 2 provides an introduction to Canadian heavy oil and oil sand formations, outlines the causes of sand production, describes the current techniques used for sand control in heavy oil or oil sand production wells and describes how geotextile fabrics can be used to control sanding in production wells. Current geotextile design criteria and laboratory testing techniques are reviewed. The characteristics of the sand and fluids in the reservoirs and the characteristics of the sand and fluids used in the laboratory research program are discussed in Chapter 3. An outline and discussion of various factors and criteria considered in the initial selection of geotextile fabrics is given in Chapter 4. Chapter 5 gives a brief summary of the testing program and discusses the philosophy behind the program. The purposes of each laboratory experiment adopted in the research program and their relevant testing procedures, reliability of each testing technique and reliability of the experimental results are discussed in Chapter 6. Analysis of test results and the discussion on the filtration performance of the soil-geotextile system and the significance of the test results are discussed in Chapter 7. Lastly, the conclusions on the filtration performance of the geotextiles, the limitations of the experimental results, and the recommendations for future laboratory and insitu field tests are given in Chapter 8.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The heavy oil and bitumen resources of Alberta are distributed along an arc, beginning at Peace River, in the northwest, curving to meet the Saskatchewan border at Lloydminster and continuing south along the provincial boundary to the U.S. border (Figure 1). The total reserves in these deposits is estimated at 400 billion m^3, with the largest deposits being those of the carbonates (~125 billion m^3) and the Athabasca bituminous sands (~151 billion m^3). The bitumen deposits are in the north, saturating beds of sand in the Cold Lake, Athabasca, Wabasca and Peace River regions, covering an area of 50,000 square km (Agar, Morgenstern and Scott, 1983). About one-third of the country's supply of oil comes from heavy oil deposits and from the oil sands deposits located in the province of Alberta (Hyndman and Luhning, 1991).

2.2 Sand Production in Heavy Oil Production Wells

One of the major persistent problems in the recovery of the heavy oil from these reservoir formations is sand production. The cleaning of the well, the repairing of the equipment and the lost of revenues related to sand production and restricted production rates cost the industry millions of dollars every year. During the recovery of the heavy oil from the formation, sand particles from the formation flow into the well along with the heavy oil. The sand flow problem is greatest in production wells which are located in unconsolidated oil sand and heavy oil sand formations; the sand flow problem is often aggravated by thermally enhanced oil recovery procedures. Sand flow from unconsolidated formations has caused a variety of potentially serious and costly geotechnical and environmental problems. When the quantity of flowing sand is significantly large, sand bridges are formed in the casing , in tubing and in flowlines. As a result, the efficiency of oil production from the wells is drastically decreased . To remedy the situation production of the well is shut down and the sand plugging the well is removed in an expensive and time consuming "workover" procedure. Sand flow also results in abrasion of downhole and surface equipment which eventually causes breakdown of the equipment. Sand flow also results in the removal of the surrounding formation in the well and eventually causes failure of casing or liners (Suman, 1974) and compaction and subsidence of the ground (Allen 1973). Also, when sand is produced sand handling plants are required on the surface for subsequent handling and disposal of polluted formation materials (Garcia 1974). All of these problems cause geotechnical and environmental concerns and drastically decreased profitability of the well.

2.2.1 Mechanics of Sand Production

Sand production occurs when the formation stresses exceed the strength of the formation. The formation strength is derived mainly from natural materials that cement the sand grains. The sand grains are also held together by cohesive forces resulting from immobile formation water and the interlocking structures of the sand grains (Dusseault & Morgenstern, 1979). The stress on the formation sand grains is caused by many factors such as tectonic actions, overburden pressure, pore pressure, stress changes from drilling, and drag forces on the producing fluids.

Preliminary results from a number of studies (Tippie et al, 1973; Bratli et al, 1981, 1983; Selby et al, 1988) have shown that sand behavior is dependent upon grain shape, grain size, sand packing, grain cohesion, grain crushing and grain reorientation, the fluid flow and the in situ stress regime. Islam and George (1991) further suggest that sand production in completely unconsolidated sands is related to water production and begins immediately with fluid production. The causes are: increased total fluid production needed to maintain oil production increase the drag forces across the sand; the forces that make sand grains cohere are disturbed as the water phase becomes mobile; two phase flow and mobility of the wetting phase cause drag forces to increase; and the natural cementing material is dissolved or softened.

Field observations and records indicate that sand production is also related to the well completion techniques. Well completion is a term used to describe both the techniques and the materials used to install and prepare a well for production. Essentially, the term covers all downhole operations between the actual drilling of the borehole to the operation of the well. The most effective well completion will maximize well productivity and minimize sand production.

Typical heavy oil well completion with filters are illustrated in Figures 2 and 3. In the first type of completion (Figure 2), a steel casing is cemented into the wellbore and perforations are drilled from the inside of the well, through the casing and the cement seal into the oil formation. The filter is suspended inside the perforated casing. Generally filters are wrapped around a second, inner casing. As the oil and soil flow into the well through the perforations, some perforations become plugged, causing an increase in the velocity of flow into the other perforations. The abrasive soil particles erode the perforations, making the openings larger and even more sand is carried into the well. In the second type of completion (Figure 3), the casing stops at the tip of the oil formation and the filter is suspended from the casing, inside the open drilled wellbore. The filter, placed inside the drilled wellbore at the end of the casing, is exposed to the formation. In this case, the formation sand can collapse directly against the entire surface of the filter, filling the space between the filter and the well wall. The sand plugs and erodes slotted liners and wire wrapped screens in a manner similar to that described for perforated casings (Kerr. et al, 1988).

2.2.2 Sand Control Strategies and Techniques

2.2.2.1 Sand Control Strategies

Two distinct strategies have been suggested for sand control: total exclusion and partial exclusion of sand from the production system. Each strategy has its own merits and drawbacks.

Total exclusion, achieved through sand retention in the near-well region and in the filtration equipment, will protect the production system from erosion and reduce the risk of the near-well formation collapse. However, total exclusion could result in progressive plugging of the filter and deterioration of the oil productivity.

In the partial exclusion strategy, artificial lifting devices are required to eliminate the sand accumulated in the production system and erosion reduces the life of production equipment. However, it appears that a certain amount of sand production is beneficial to increasing the oil recovery, especially in the heavy and extra-heavy oil reservoirs where permeability and production increases are associated with moderate sand production.

Any strategy employed for the control of sand can fail to perform properly when significant quantities of previously dissoluted silica and clay are precipitated in the near-well region, plugging the completed zone. The process is often associated with the occurrence of high-velocity areas and severe erosion.

2.2.2.2 Sand Control Techniques

Sand control methods may be classified as mechanical, chemical, and mechanical/chemical. Mechanical methods prevent sand production with liners, screens, or gravel packs. Chemical control methods involve injecting consolidating materials into the formation to cement the sand grains. The suitability and the success of the sand control techniques depend on formation characteristics and the well completion methods.

Sanding control through the use of slotted liners, screens or gravel and sand packs have only limited success. Many sand control techniques were successful in reducing sand production but limited well productivity (Lea & Middleton,1986). Problems of plugging and corrosion of standard perforated casings are common (Lyness, Devenny & Dabrowski,1987). Scott and Parker (1987) detail conditions in thermally stimulated wells: temperatures varies from 15 to 350° C, pH varies from 5 to 12, fluid flow conditions are complicated by fluids with different viscosities, of entrained and dissolved solids, and high oxidation-sulphidation potentials. These aggressive downhole conditions completely disintegrate the conventional sand pack and a number of alloy shots filter media. As a result, plugging of some slots eventually leads to a high degree of erosion in others. These observations have been confirmed by Marjerrison and Sayre (1988). Difficulties in preventing sand flow in uniform sand formations by screens or slotted liners are reported (Cosberly, 1937; Clark & Turner, 1983).

A new sand control system called flexible sand barrier, has recently been developed by Dickinson, Knoll and Nordlund (1989). The flexible sand barrier is a flexible, jointed permeable tube constructed of a helically wound metal strip. This sand control system has been tested in the laboratory with promising results, but the validity of this sand control system in the field is still uncertained. Livesey and Toma (1983), Toma, Livesay and Heidrick (1986), Heidrick et. al (1987), Toma et. al. (1989), Scott and Parker (1987) discuss sanding problems in heavy oil formations and propose the use of a pre-packaged, pre-compressed steel wool filter, Meshrite®. Meshrite® has been tested in the field. However, Meshrite® has only partially been successful because plugging of the perforations on the perforated casing causes an increase in the velocity of flow into other perforations. The abrasive soil particles erode the perforations making the openings larger and even more soil is carried into the well (Toma, Korpany and King,1990,1991). To date there is still not a good mechanical method available to control sanding problems.

Sand control by consolidating formation sand by chemical methods requires precise application and careful fluid handling. It is the most sophisticated work undertaken in well completion. Suman (1975) discusses the successful application of this method in conventional oil production wells. However, reports on the use of chemical methods in thermal recovery wells have not been found.

In the last decade, woven and nonwoven geotextiles have been developed for filters in underground drainage systems and water wells. Geotextile water well filters have proven to be highly efficient for these applications (Thomas, 1982; Kennedy, Lloyd and Howley, 1988). Nonwoven geotextile fabrics have gained prominence as filters and have a considerable advantage over slotted liners, screens and gravel packs. The main advantage of the nonwoven geotextile fabrics are: the structure of the geotextile can be varied for specific fluid flow velocities; the geotextile filter pore size and distribution can be chosen for specific sand sizes and gradation; and the fibers can be chosen based on their hydrophoblic (repel water) or oleophobic (repel oil) characteristics to produce better filter flow characteristics.

These filter design innovations, combined with heat and chemical resistant polymeric materials, can resist the environments in highly corrosive ambient temperature and thermally stimulated wells to solve. Their use offers the possibility of solving the sanding problems that conventional filter systems do not adequately solve.

2.3 Requirements of a Well Filter

For a filter material to effectively perform as a well filter, the filter material must fulfill several required mechanisms:

a. It must allow fluids to flow sufficiently freely within the filter so that excessive pressure drops across the filter do not occur. Excessive pressure drops are followed by a build up of high pore fluid pressures adjacent to the well and high hydraulic gradients in the filter.
b. The filter material must prevent soil particles from being washed or piped through the filter with the exception of a small amount of the finer particles found adjacent to the filter. These can be carried away in the flowing fluid up the well.
c. It must not blind or clog by soil particles.

The first and the third mechanisms require a filter with a high permeability and high porosity and therefore large openings, while the second mechanism requires a filter with small openings. The well filter must meet these contradictory requirements.

2.4 Mechanisms of Geotextile Filtration

Geotextile filtration ability is reviewed in detail by Bell and Hicks (1980) and summarized more recently by Foruie and Bentley (1991). For a geotextile to perform effectively as a filter in a geotextile drainage system it must allow fluids to flow sufficiently freely within the filter so that excessive pressure drops across the filter do not occur. Geotextile filters typically have larger openings and higher hydraulic conductivities than adjacent soils. Therefore, in the soil near the sand-geotextile interface a relatively high hydraulic gradient develops. This gradient may cause seepage forces which are of sufficient magnitude to induce transport of small soil particles up to, into, or through the geotextile. For this reason the filter fabric must prevent soil particles from being washed or piped through the filter with the exception of small amounts of finer particles lying adjacent to the filter. These can be carried up the well in the flowing fluid. The geotextile is also required to prevent migration of fine grained soil without blinding and the passage of fine grained soil through the fabric without clogging. Figure 4 illustrates the process of blinding and clogging.

Blinding is defined as the accumulation of soil particles, also known as a filter cake, at or near the sand-geotextile interface. If the filter cake has significantly lower hydraulic conductivity than the soil backfill, the flow into the drainage system may be impeded to the degree that the drainage system cannot perform its intended function. In this case, the permeability of the cake may be less than that of the surrounding soils.

Clogging is defined as the accumulation of the soil particles in the geotextile filter. In geotextiles which have low porosity or discrete openings, accumulation of soil particles in the geotextile filter may result in a large flow impedance which could result in inadequate drainage system flow capacity. In completed clogging, the fabric permeability is reduced to less than that of the soil.

A certain amount of loss of soil grains through the filter during its early life should be allowed to take place. This type of soil movement due to the flowing fluids will not cause filtration problems with the geotextile but will promote the development of equilibrium conditions and ensure uniform long term performance of the filter zone.

The development of a filter zone in the soil is shown in the three sketches in Figure 5. Immediately after installation of the filter in an open hole, before flow into the well takes place, the formation soil grain size distribution adjacent to the filter is in its natural state, as shown in Figure 5a. During the initial stages of flow into the well, Figure 5b, the finer soil particles adjacent to the filter pass through the geotextile leaving the large particles which form a bridging network over the geotextile openings. This mechanism can take place because of the large surface area of the geotextile available for filtration, the large porosity within the filter and the high in-plane permeability of the geotextile layer. After several hours or days of flow, depending on the flow velocity, a steady state or mature soil-geotextile system is established. No further soil is washed through the system and the system is considered to be in equilibrium, Figure 5c. Lawson (1982) comments that the soil filter zone is, in effect, a reverse granular filter constructed solely from the in-situ soil particles. The stable bridging network of coarser particles adjacent to the geotextile allows a natural soil filter to develop which in turn holds the undisturbed formation soil in place. As water continues to flow through the completed soil filter-geotextile system, the soil filter actively filters out any particles in the water from the undisturbed soil mass while the geotextile retains the soil filter zone in place, preventing collapse into the drainage layer. The overall filter zone, therefore, includes the geotextile, the soil particle bridging network and the soil filter. The development of such a filter zone allows the larger pores of the geotextile to govern the geotextile's filtration ability in contrast to a sand pack, in which the finer pores govern the filtration ability. While the geotextile in one directional filter application does not actually filter the water, it does act as a catalyst for the formation of a stable soil filter from the in situ parent soil (Fourie & Bentley, 1991). Thus, the choice of a correct geotextile is critical to formation of a stable and effective soil filter.

McGown (1976) suggests that the formation of a self-induced soil filter by the fabric depends on the following factors : (1) the physical and mechanical properties of the geotextile fabric (pore size and its distribution, porosity, fabric thickness, and fabric compressibility); (2) characteristics of the soil to be protected (grain size and its distribution, porosity, permeability, cohesiveness); (3) external stresses and strains imposed on the soil - geotextile system; and (4) the hydraulic conditions prevailing (laminar or turbulent flow, unidirectional or reversible flow direction, dynamic hydraulic loading).

2.5 Filter Design Criteria

2.5.1 Filter Design Criteria in Civil Engineering Applications

The development of the first criteria for graded filter design is covered in Terzaghi and Peck (1967) and a good review of filtration and drainage fundamentals is provided by Cedergren (1967). The original design criteria proposed by Terzaghi has been subsequently researched, evaluated and refined. Current filter design criteria included requirements for permeability, soil retention (prevention of piping), and uniformity between the gradation shapes of the soil and the filter. The requirements are summarized as follows:

permeability requirement:

$$D_{15\,\text{filter}} \geq 4 \text{ to } 5\ D_{15\,\text{soil}} \qquad (1)$$

soil retention (piping) requirement:

$$D_{15\,\text{filter}} \leq 5\ D_{85\,\text{soil}} \qquad (2)$$

uniformity requirement:

$$D_{50\,\text{filter}} \leq 25\ D_{50\,\text{soil}} \text{ and} \qquad (3)$$

$$D_{15\,\text{filter}} < 20\ D_{15\,\text{soil}} \qquad (4)$$

where D_{15} is the diameter of soil particles such that 15% by mass of the soil particles are smaller than that size.

2.5.2 Development of Geotextile Filter Design Criteria

In order to understand how geotextile filter design criteria are developed, the requirements for the geotextile fabrics, the factors which affects the performance of the geotextile fabrics and the parameters to be considered in the formulation of the filtration theory must be understood. In general, the requirements for geotextiles to be used in filtration and drainage applications are similar to those for conventional graded filters. They are:

a. the fabric must prevent piping of the adjacent soil (soil retention requirements),
b. the geotextile must be more permeable than the adjacent soil to reduce hydraulic head loss in the filter and increase drainage efficiency (permeability requirement),
c. the geotextile must remain more permeable than the adjacent soil throughout the design life of the drainage system (long term filtration requirement), and
d. the fabric must have sufficient tensile strength, puncture resistance, burst strength, and abrasion resistance to survive placement and provide adequate in service performance (long term durability requirements).

Factors which affect the performance of the geotextile fabrics and the parameters that have to be considered in the formulation of the geotextile filtration theory are summarized below Giroud (1982) and Williams and Luettich (1990) :

Soil Properties	Geotextile Properties	Boundary Conditions
Soil Type	Type	Hydraulic Gradient
Grain Size Distribution	Primary Bonding Method	Flow Velocity
Hydraulic Conductivity	Secondary Bonding Method	Direction of Flow
Soil Structure	Thickness	State of Stress
Soil Fabrics	Mass/Area	Stress History
Void Ratio	Compressibility	Type of Support Media
Plasticity Index	Porosity	Location of the Fluid
Degree of Saturation	Pore Size Distribution	Viscosity of the Fluid
Shape of Soil Mass	Permittivity or Permeability	
Shear Strength	Flexural Rigidity and Tensile strength	
Chemical Nature	Strength	
	Density of Needlepunching	

The large number of factors and variable parameters which may affect soil-geotextile interaction make the formulation and the prediction of the long term performance of geotextile filter drainage systems very difficult. Therefore, geotextile filter design criteria developed are based on the granular filter design criteria, experience, and a limited amount of laboratory data.

There is one major difference between soil and geotextile design criteria. Sand filters are designed by considering the grain size distribution of the formation sand in relation to the grain size distribution of the filter sand. In contrast, geotextile filters are designed by considering the grain size distribution of the formation sand in relation to the pore or opening size distribution of the geotextile.

2.5.3 Review of Current Geotextile Filter Design Criteria

2.5.3.1 Permeability Criterion

The permeability criteria are used to determine the minimum opening size and minimum fabric porosity. The basic requirement is that the geotextile must remain more permeable than the adjacent soil. However, in order to decrease the dynamic dragging forces on the soil particles, the permeability of the geotextile must not be too much greater than the permeability of the soil (Rollin & Lombard,1988).

Permeability criteria for geotextile filters proposed by Giroud (1982 and 1988), the U. S. Federal Highway Administration (FHWA), and the French Committee on Geotextiles and Geomembrances (CFGG) can be expressed as:

$$K_f > \lambda_p K_s \qquad (5)$$

where K_f is the hydraulic conductivity of the geotextile filter; K_s is the hydraulic conductivity of the soil and λ_p is a dimensionless permeability coefficient which is a function of the hydraulic gradient, thickness of the geotextile, the type of drainage system, and the factor of safety. A summary of the dimensionless permeability coefficient, λ_p, for each of the permeability criteria is presented in Table 1.

The FHWA permeability criterion is basically developed for applications in highway engineering. It is not appropriate in the case of high gradients encountered in other branches of geotechnical engineering (Giroud, 1988). Giroud modified his 1982 permeability criterion in 1988 because the original criterion allows the same pore pressure build up for granular and geotextile filters. This is less conservative than the criterion proposed in 1988 and is not conservative in the case of large gradients.

2.5.3.2 Soil Retention (Piping) Criterion

When a higher flow of fluid is required to flow through a geotextile, the void spaces in the fabric must be made larger. There is, however, a limit to the size of the openings when the upstream soil particles start to pass through the fabric voids along with the flowing fluid "piping" may occurs. Piping is defined as the transport of soil particles through the geotextile filter. Piping is a natural phenomenon which almost always occurs when flow is first initiated across an interface between a soil and a geotextile. In may cases, piping stops after a short period of time and an equilibrium condition is achieved between the soil and the geotextile. If piping continues and is uncontrolled, more soil particles are carried through the geotextile, leaving large voids in the soil. The piping process can be prevented by making the geotextile voids small enough to retain the soil on the upstream side of the fabric. It is the coarser soil fraction that must be initially retained; this is the targeted soil size in the design process. According to the process described earlier, these eventually block the finer sized particles.

There are number of approaches to accomplishing soil retention (or prevent soil piping), all of which use the soil particle size characteristics and compare them to the O_{95} size of the fabric. The U.S. Army Corps of Engineers (1977) recommended that:

$$O_{95} \leq d_{85\ soil} \qquad (6)$$

where: The O_{95} of the fabric indicate the approximate largest particle that would effectively pass through the geotextile; d_{85} is the diameter of soil particles such that 85% by weight of the soil particles are smaller than that size

AASHTO-AGC-ARTBA (1983) recommended the following :

a. Soil ≤ 50% passing the No. 200 sieve

AOS of the fabric ≥ No. 30 sieve (i.e., $O_{95} < 0.59$ mm) (7)

b. Soil > 50% passing the No. 200 sieve

AOS of the fabric ≥ No. 50 sieve (i.e., $O_{95} < 0.297$ mm) (8)

Carrol (1983) recommended a even more restrictive criterion:

$$O_{95} < (2 \text{ or } 3)\, d_{85} \qquad (9)$$

However, all of the above criteria do not include the importance influence of soil density.

Giroud (1982), FHWA (1985), and CFGG (1986) propose a retention criteria for cohesionless soils with relationships developed for both the relative density and the uniformity of the soil. The retention criteria for geotextile filters in drainage systems can be expressed by the following equation:

$$O_{95} < \lambda_R d_{85} \qquad (10)$$

where O_{95} is the Apparent Opening Size of the geotextile; d_{85} is the diameter of soil particles such that 85% by weight of the soil particles are smaller than this size, and λ_R is a dimensionless coefficient for retention. The dimensionless retention coefficient, λ_R, for each of the methods are summarized in Table 2.

It is important to realize that each of the above criteria were developed for specific conditions and one criterion does not necessarily meet all the conditions encountered in the field.

2.5.3.3 Clogging (Porosity) Criterion

As discused in Section 2.4, clogging is defined as the accumulation of soil particles in the geotextile filter and blinding is defined as the accumulation of soil particles at or near the sand-geotextile interface. Clogging is caused by particles penetrating the fabric and blocking off pores whereas blinding is caused by the caking on the upstream side of the fabric. Other situations that have caused clogging and blinding problems of geotextiles are high alkalinity groundwater which can cause salt deposition and mineral precipitation (Koerner, 1990); bacterial growth (Rollin & Lombard, 1988); gap graded cohesionless soil and silt under high hydraulic gradients, and dynamic loads causing hydraulic cycling of pore water back and forth across the geotextile (Koerner et al.1988).

A simple solution for avoiding clogging would be to allow any fine particles in suspension to pass through the fabric with the bridge network providing retention. Christopher and Holtz (1985) proposed the following requirements

$$O_{15\ \text{filter}} > 2\text{-}3\ D_{15\ \text{soil}} \qquad (11)$$

Giroud (1987) suggests that clogging and blinding of geotextile fabrics can be controlled by the open area or the porosity of the geotextile fabric. For nonwoven geotextiles, a minimum porosity, n_{min} , to prevent clogging and blinding from occluding is 30% and for woven geotextiles, a minimum open area , A_{min}, should be not less than 5%. These values should be determined under compressive stresses similar to those encountered in the field.

$$A_{min} \geq 5\% \quad \text{(woven geotextile)} \qquad (12)$$

$$n_{min} \geq 30\% \quad \text{(nonwoven geotextile)} \qquad (13)$$

Koerner (1990) further recommends that if complete clogging of the geotextile fabric is likely to occur, non-woven fabric should be used and that the minimum porosity of the fabric under compressive stress similar to that encountered in the field should be not less than 40%.

2.5.3.4 Wettability Criterion

"Wettability" is a term used to describe the relative attraction of one fluid for a solid in the presence of other immiscible fluids. It is the main factor responsible for the microscopic fluid distribution in porous media and it determines to a great extent the amount of residual oil saturation and the ability of a particular phase to flow in the reservoir (Honarpour, Koederitz & Harvey, 1986). When fibers are water-wet there is a tendency for water to occupy the small pores and to contact the majority of the fiber surface. Similarly, in an oil-wet system the fibers are preferentially in contact with oil. The occurrence of either a water-wet or oil-wet system will affect the filtration properties of the geotextile filters. A suitable geotextile filter should not allow oil nor water to be attracted to the fibers and coat or swell them (Scott, et al, 1988; Kerr, et al, 1988).

2.6 Testing on Hydraulic Properties of Geotextiles

2.6.1 Introduction

The actual field performance of a geotextile is highly dependent upon the soil and hydraulic characteristics in the field. Current design methods are typically based on conventional granular filter design criteria and do not account for the following factors: (1) changes in the soil properties at the sand-geotextile filter interface; (2) the effects of soil structure and soil fabric; compressibility, porosity, pore size distribution and flexural rigidity of the geotextile; (3) the flow velocity , the state of stress, the stress history, and the type of drainage support in the soil (Williams & Luettich, 1990). This oversimplication in approach may be suitable for minor, non-critical geotechnical works. However, for major and critical geotechnical works this oversimplication may have a significant impact. A laboratory soil-geotextile model is therefore need to assess the impact of parameters which are not properly accounted for in the design process. The ability of laboratory simulations of soil-geotextile interactions to predict field performance of the drainage system depends primarily on how closely field conditions are modeled by the laboratory boundary conditions.

2.6.2 Opening Size of Geotextiles

The geotextiles used in filtration are usually made of synthetic fibers or filaments bonded together by a mechanical, chemical, or thermal process. They are classified as knitted, woven, and nonwoven products. The woven and knitted geotextiles are usually thin products with very well-defined holes or pores, such that the determination of their opening and pore size is relatively easy. The random placement and arrangement of the fiber web in nonwoven geotextile fabrics causes the openings or pores between the fibers to vary in size. The nonwoven structures are so complex that pores with constant diameter and of a length equal to the thickness of the fabric cannot be found. Nonwoven products are used extensively in filtration. Geotextile filter design criteria are developed based on opening size, therefore, the opening size of the geotextile must be defined and measured accurately.

The techniques to determine the opening size of geotextiles can be classified as direct, theoretical and indirect methods (Rollin,1986, 1988). The direct methods are optical and image analyses on sections of fabrics. The theoretical methods are using analytical and geometric probability approaches to calculate the mean distance between fibers and the size of the pores. However, both methods do not account for blinding and clogging that may occur in the field and the results are therefore of little practical interest. The indirect methods such as dry and wet sieving give more information about the retention characteristic of the geotextiles and therefore have been used extensively in the geotextile industry.

2.6.2.1 Apparent Opening Size

The American Society for Testing and Materials (ASTM) had developed and established a standard test method for determining apparent opening size (AOS) of a geotextile. The test method is currently published under the designation of D4751-87 "Determining Apparent Opening Size of a Geotextile". The apparent opening size of a geotextile (O_{95}) is defined as an indication of the approximate largest particle that would effectively pass through the geotextile. The test is conducted by dry sieving known quantities of glass beads of specified diameter through a geotextile specimen in a controlled testing environment. It is important to note that AOS values do not accurately defined the pore sizes or pore structure of a geotextile. The AOS test only provides a method for determining the relative size of "straight through" openings in a fabric (Carroll, 1983). Two geotextile fabrics may have a similar AOS value but dramatically different pore structures, porosities, and permeabilities.

Rollin (1986) reported that using the same testing procedure no reproducible data could be obtained when comparing results from one laboratory to another with identical thick, nonwoven fabrics. He concluded that the difference in the results was due to different sieving apparatus using different sieving energy, the relative position of the sieves holding the geotextiles in the shakers, and from variation in the electrostatic effects of the smaller particles. Another limitation of vibrating sieving methods is the great difficultly in measuring a filtration opening size smaller than 106 μm and the impossibility of measurement under 75 μm. Despite these deficiencies, Christopher & Holtz (1985) commented that the AOS test does provide a useful index value for predicting the soil retention ability of a geotextile .

2.6.2.2 Filtration Opening Size

A hydrodynamic sieving method (Rollin, 1988) developed in Europe has been proposed by the Canadian General Standards Board (CGSB) as a standard test for the determination of filtration opening size (FOS) of geotextiles (temporary designation is CGSB 148.1-method-10.2). This method is recommended for non-woven fabrics with pore size smaller than 75 μm. The test is carried out by spreading a well graded soil on the fabric, in a sieve frame, and sieved under alternating flows of water. The immersion and emersion actions are obtained from a vertical movement of the sieve frames or from a carousel wheel on which the sieve frames are attached. The alternating flow of water forces the particles to percolate through the fabric and settle in a water pan where they can be collected to obtain their grain size curve. The filtration opening size of the geotextile is defined as the diameter of the particles of which 85% were retained by the fabric. Rollin reported that this method has good reproducibility between laboratories using different apparatus and soils. However, this method is not standardized or commonly in use because of the difficultly in the selection of a standard soil for testing and the high initial and operation costs associated with the test method.

2.6.3 Porosity Test

Porosity of a geotextile fabric is very sensitive to change in fabric thickness due to external compressive load. Porosity of a geotextile is defined as the ratio of volume of void to the total volume of the geotextile. Porosity relates to the ability of fluid to flow through the fabric but is rarely measured directly. Instead, it is calculated from other properties of the fabric (Williams & Abouzakhm, 1989).

$$n = 1 - \frac{m}{G_s \rho_w t} \qquad (14)$$

where:
- n = the porosity;
- m = mass per unit area of the geotextile;
- ρ_w = mass density of water;
- G_s = specific gravity of the polymer, and
- t = fabric thickness.

The thickness of the geotextile fabric can be determined by the test method Canadian General Standards Board, Can/CGSB-148.1 No.3-M85. A Frazier Compressometer is usually used at a temperature of 20° C and a relative humidity of 65%.

2.6.4 Permittivity Test

Hydraulic conductivity values of the fabric and the soil can be calculated by using Darcy's Law regarding laminar flow in porous media. The Darcy equation for geotextiles can be written as (Bell & Hicks, 1980):

$$q = k.\frac{dh}{L}.A.\frac{\rho g}{\mu} \qquad (15)$$

where:
- k = hydraulic conductivity;
- q = flow rate;
- A = area of fabric normal to flow direction;
- L = length of specimen in flow direction (fabric thickness);
- dh = change in head over length, L;
- μ = viscosity of test fluid;
- ρ = density of test fluid; and
- g = acceleration due to gravity .

Experimental studies indicate that for water flow normal to the plane of the geotextile, a thin geotextile and a thick geotextile can have similar hydraulic conductivities (k) but have different flow rates through each fabric. Since different fabrics have different thicknesses, use of Darcy's hydraulic conductivity is not an appropriate property for comparing fabrics (Calhoun, 1971). Therefore, for fabric comparison and analytical evaluation it is more appropriate to define hydraulic flow characteristics of geotextile fabrics in terms of volumetric flow rate per unit area under a given hydraulic head. This is defined as the geotextile permittivity, Ψ (Giroud & Perfetti, 1977).

$$\Psi = \frac{k}{T_g} \qquad (16)$$

where T_g is the fabric thickness.

ASTM has developed and established a standard test method for determining the hydraulic conductivity and the permittivity of a geotextile fabric. The method is published under the designation of D4491-89 "Water Permeability of Geotextiles by Permittivity". Either constant head or falling head techniques can be used. One disadvantage of this method is that the geotextile test specimen is under zero normal stress. Therefore, the effect of compressive stress on the permeability and permittivity cannot be assessed.

2.6.5 Transmissivity (In-Plane Permeability) Test

The ability for fluid flow in the plane of the geotextile is measured in terms of transmissivity. Numerous test methods have been developed for experimental measurement of transmissivity. The majority of these methods can be categorized as either parallel or radial flow tests.

Parallel flow test devices (Andrei, et al., 1982; Guru, et al., 1982; Durst, et al., 1982) use either square or rectangular geotextile specimens fitted between two pressure plates and have water, at constant head, enter one end and exit at the opposite end. Ionescu and Kellner (1982) use a cylindrical geotextile section and load it radially to mobilize normal stresses. Flow is in a parallel direction in the plane of the geotextile. These apparatus provide a longitudinal flow path so that the stream lines of flow through the geotextile are generally parallel. Parallel stream lines assemble flow through a laboratory soil permeameter and similarly Darcy's law is used to calculate the transmissivity.

$$q = k.i.A \qquad (17)$$

$$q = k.\frac{dh}{L}.W.t \qquad (18)$$

$$kt = q = \frac{q.L}{dh.W} = \frac{q}{i.W} \qquad (19)$$

removed dots

where: θ = transmissivity;

k = hydraulic conductivity in the plane of the fabric;
t = thickness of the fabric;
i = hydraulic gradient;
q = flow rate;
L = length of the fabric;
dh = head loss; and
W = width of the fabric.

Radial test devices (McGrown, et al., 1982; Gerry and Raymond, 1983; Raumann, 1982; Bove, 1982; Koerner, et al., 1984; Montgomery, et al., 1988; and Scott, 1991) allow flow to enter the geotextile at the central portion of the geotextile and exit through the outer edge. The stream lines of flow therefore radiate from the center of a circular disk of geotextile outward in all directions. These are constant head devices where the transmissivity is calculated on the basis of the well equation for various data sets of flow rate versus head loss from upstream to downstream edges of the geotextile. Darcy's equation for calculating transmissivity can be expressed as: (Koerner, 1990)

$$q = k\frac{dh}{dr}2\pi rt$$

$$kt = q = \frac{q \ln\left(\frac{r_2}{r_1}\right)}{2\pi\, dh} \qquad (20)$$

where: r_2 = the outer radius of the fabric specimen, and
r_1 = inner radius of the fabric specimen.

Transmissivity of the geotextile fabric is very sensitive to normal compressive load. The transmissivity of the geotextile fabric decreases exponentially as the load increases. However, the decrease in transmissivity of most fabrics reaches constant values after approximately 24 kPa, beyond which the fiber structure is sufficiently tight and dense to hold the load and still convey liquid (Koerner, 1990).

ASTM has also developed and established a standard test method for determining the transmissivity of a geotextile and geotextile related products under parallel flow conditions. The method is currently published under the designation of D4716-87 "Constant Head Hydraulic Transmissivity (In-Plane Flow) of Geotextiles and Geotextile Related Products".

2.6.6 Soil Retention and Clogging Tests

The soil retention requirements of a geotextile can be specified in terms of AOS values. These criteria are fully adequate in a majority of drainage applications where the filter clogging potential is very low or in noncritical drainage application. When the potential for filter clogging is significant or the drainage application should be classified as critical, the clogging resistance of filter fabrics should be evaluated to assure adequate long term filter performance. Soil type and hydraulic gradient used in a soil-geotextile permeability test have significant impact on the test results. Therefore, clogging behavior of a geotextile should be evaluated in a test using the same soil and hydraulic gradients that simulate expected field conditions.

Numerous methods exist for evaluating the filtration potential of a geotextile. The most realistic method of evaluating the filtration potential for a specific application is through direct modelling of the application in the laboratory. The first laboratory evaluation of the clogging phenomenon of a geotextile was developed in 1959 by Soil Testing Services, Inc. (Christopher & Holtz, 1985). The method was then refined by Calhoun in 1972 and was adopted as an evaluation standard by the U. S. Army Corps of Engineers. Calhoun used a permeameter device to determine the degree of fabric clogging that might be experienced by fabric in contact with a gap graded soil. Hydraulic gradient data from the soil-geotextile permeameters were analyzed to determine the clogging potential of a fabric. The analysis made use of a ratio of the hydraulic gradient across the fabric plus an adjacent 25 mm of soil to the hydraulic gradient for the entire system, as was defined as the "clogging ratio". A clogging ratio greater than one signifies fabric clogging (Calhoun, 1972). Additional research by the U.S. Army Corps of Engineers suggested that gradient ratio values greater than 3 indicate non-acceptable fabrics for the type of soil under test. Haliburton and Wood (1982) assessed the Corps' results using a hydraulic gradient approach similar to Calhoun's. They evaluated clogging performance of the fabric based on a "gradient ratio" value which is the hydraulic gradient through fabric plus the adjacent 25 mm of soil divided by the hydraulic gradient through the adjacent 50 mm of soil. The soil used was gap graded to provide the maximum potential of soil piping and filter clogging. In addition, the tests were run for 24 hours under high hydraulic gradients to cause the maximum potential for soil piping. Haliburton and Wood's results revealed dramatic performance differences between the fabrics tested versus silt content in the gap-graded soil. The gradient ratio values were found to increase slowly with increasing soil silt content until a gradient ratio value of approximately 3 was obtained, and then increase rapidly with further small increase in soil silt content (Figure 6).

The methods used by Calhoun (1972), Haliburton and Wood (1982) and the U.S. Army Corps of Engineers may not be accurate as the time for the filtration testing is limited to 24 hours for each hydraulic gradient. Koerner and Ko (1982) suggest that a similar soil fabric permeability test should be run and that the permeability versus time results be used to indicate system clogging. Long term flow tests rather than 24 hours short term gradient ratio tests, are recommended the preferred way to evaluate the clogging performance of a particular sand-geotextile system. They concluded that the behavior of long term flow tests through soil-geotextile systems show that the initial range is governed by the soil and the final range is governed by soil-geotextile interaction.

ASTM has recently standardized a gradient ratio test. The test method designation is D5101-90 "Measuring the Sand-geotextile System Clogging Potential by the Gradient Ratio".

2.7 Permeability of Geotextiles

2.7.1 Permittivity and Transmissivity

Permeability of a geotextile must be greater than of the protected soil so that water can pass freely from the soil through the fabric without buildup of hydrostatic pressure. High fabric permeability also infers that partial clogging will not reduce fabric permeability below that of the protected soil. Permeability values for fabric and soil are necessary to assess compatibility between the two. Soil permeability is typically determined by measuring the flow rate of fluid through a soil sample of specified height and cross sectional area. Soil permeability is then expressed in terms of a coefficient calculated using Darcy's law regarding laminar flow through porous media (Equation 15). If the test fluid is water, the equation is simplified to

$$q = kAi \qquad (21)$$

where "i" is the hydraulic gradient through the soil sample.

The geotextile industry has applied the same principles of flow through porous media to characterize the permeability of fabrics. Using test apparatus modeled after soil permeameters with both falling and constant head testing techniques, a fabric's permeability coefficient can be determined according to Darcy's law. These fabric permeability coefficients are then compared to that of the soil to assure compatibility. It is important to note that although the porosities of nonwoven geotextiles may be as high as 90%, it has been found that flow of water through the geotextile is still laminar and therefore meets the basic assumptions of Darcy's Law (Koerner, 1990).

In filtration applications for heavy oil wells several factors affect permeability which are not present in normal geotextile filter conditions. The fluid that flows through the filter in an oil well is multiphase consisting of oil and water or oil, water and gas. In order to compare the flow of heavy oil with water, when large variations in viscosity and density exist, the absolute permeability of the geotextile and the relative permeability of the geotextile in different permeants must be considered. For this reason, absolute permeability was used rather than hydraulic conductivity to define the permeability of the geotextile and the permeability of the soil.

The absolute permeability (K) is usually measured in the laboratory using water or oil as the fluid. Gas is occasionally employed, taking into account gas compressibility and the slip phenomenon. The absolute permeability is calculated using Darcy's equation:

$$K = 10^{12} \cdot \frac{q}{tA} \cdot \frac{L}{dh} \cdot \frac{\eta}{\rho g} \quad \text{in } \mu m^2 \qquad (22)$$

where:

K	=	absolute permeability, μm^2;
q	=	quantity of flow, m^3;
t	=	time of flow, s ;
A	=	area normal to flow direction, m^2 ;
L	=	length of specimen in flow direction , m ;
dh	=	change in head over length, L, m ;
η	=	viscosity of fluid, Pa.s ;
ρ	=	density of fluid , kg/m^3 and
g	=	acceleration due to gravity, m/s^2 .

Most geotextile fibers are hydrophobic and oleophilic, therefore, the absolute permeability may vary depending on whether water or oil is being used as the permeant. When water is the permeant, the absolute permeability, (K) can be converted to the hydraulic conductivity (k) using the following conversion factor.

$$k \text{ (in cm/s)} = 10^{-3} \times K \text{ (in } \mu m^2) \qquad (23)$$

The problem with the use of the Darcy coefficient of permeability (hydraulic conductivity) for geotextiles is the dependency of the quantity of flow on fabric thickness. A review of Darcy's law shows the Darcy coefficient of permeability to be directly proportional to the length of flow path, that is, fabric thickness (T_g). As a result, the darcy coefficient of permeability does not provide a fair comparison of flow capabilities between fabrics. Such comparisons must be made using a permeability factor that is independent of fabric thickness, (T_g). This permeability factor is permittivity or transmissivity and is dependant on the direction of fluid flow.

Permittivity of a geotextile, Ψ, is defined as the volumetric flow rate of water per unit cross-sectional area per unit head under laminar flow conditions, in the normal direction through a geotextile.

$$\Psi = \frac{k}{T_g} \quad (\text{in } s^{-1}) \qquad (24)$$

Transmissivity of a geotextile, θ, is defined as the volumetric flow rate of water per unit head under laminar flow conditions, in the in-plane direction through a geotextile.

$$\theta = k.\,T_g \qquad (\text{ in } m^2/s \text{ or } cm^2/s) \qquad (23)$$

In this work, however, permittivity and transmissivity were expressed in terms of absolute permeability in order to compare the flow of water and the flow of oil through the geotextiles.

2.7.2 Effect of Confining Stress on Permittivity and Transmissivity

When a normal stress is applied on a geotextile, the external stress will cause a collapse of the internal fabric structure, consequently causing a change in thickness (compression) of the geotextile. Compressibility is very important for nonwoven needle-punched or bulky resin-bonded fabrics. This is because such fabrics are often used to convery liquid normal to the plane or within the plane of their structure. The more a fabric compresses under load, the lower its permittivity and transmissivity. Therefore, the effect of confining stress on changes in permittivity and transmissivity of geotextiles must be taken into consideration when choosing a geotextile for filtration.

Schober and Teindl (1979) show that when two needlefelt geotextiles (about 2.4 mm thick) were compressed by a normal stress of 800 kPa the two fabrics show over 70% compression and a reduction in porosity from over 80% to between 50% and 60%. The permittivities of the geotextiles decreased approximately one-half an order of magnitude when compressed. Scott et. al (1988) reevaluated testing results by Raumann (1982) and showed that all six needled nonwoven geotextiles tested showed a compressibility of around 60% to 80% and a reduction in porosity from over 90% to between 70% to 80%. The measured transmissivities decreased between one and two orders of magnitude when compressed.

CHAPTER 3: CHARACTERISTICS OF THE SAND AND FLUIDS

3.1 Reservoir Deposits and Fluids

Crude oil is made of different fractions with each fraction having a different boiling point. The lighter fractions are rich in hydrogen and have a low density because the hydrogen to carbon ratio is high. The heavier fractions are composed of hydrocarbons which have a high carbon content and are higher in density and viscosity. The percentage of these fractions varies in crude oils, causing the oils to vary in density and viscosity. Oil reserves are classified by the American Petroleum Institute (API) into four categories, light, medium, heavy and bitumen, according to their densities, measured in API degrees of gravity. The relationship between the API unit and the specific gravity of water at 60° C is given below. The relationship indicates as the density of the oil increase, API unit decrease.

$$^{\circ}API = \frac{141.5}{SG_{60}} - 131.5 \qquad (29)$$

Heavy oil, like conventional oil, is composed of saturated and unsaturated hydrocarbons arranged in chain-like or ring-type structures. Heavy oil has a gas free viscosity of 100 to 100,000 mPa.s at ambient reservoir temperature, an API of 10 to 20° and a density of 934 to 1000 kg/m^3 (Vigrass, 1977). Heavy oils are thicker, heavier and slower to pour than light and medium crudes. Heavy oil is composed mostly of gas-oil, lube oil and asphaltenes, all high density materials. Generally, heavy oil has a higher sulfur content than lighter oils.

The sands in heavy oil and oil sand deposits are unconsolidated, fine, uniform sands. The unique feature of the Alberta oil sand deposits is that the voids contain not only water but also bitumen and perhaps gas bubbles. Since the sand is hydrophillic or "water wet" the bitumen is not in direct contact with the sand grains because of a thin film of water which surround them (Figure 7). This aqueous film surrounding the sand grains has long been recognized as the single most important factor in recovery of the bitumen in the Alberta oil sands. The oil occurs in the pores between the sand grains. The bitumen content of oil sand varies from 0 to 18% by total weight with an average of 10%. The bitumen therefore may occupy from 0 to 90% of the pore space with water occupying the rest, unless gas bubbles are present. Both water and the bitumen in the voids contain dissolved gas and may be saturated with gas. The oil sand formations are quite variable in lithology because of their geological depositional environment. Seams of silt and clay and some hard layers of siltstone usually occur in the deposits (Agar, Morgenstern & Scott, 1983).

The oil in the oil sands deposits is termed bitumen and is an extremely heavy hydrocarbon. Its gas free viscosity at reservoir temperature is greater than 100,000 mPa.s and its density is more than 1,000 kg/m3 (<10° API) (McCormack, 1987). The bitumen at the in-situ temperature of about 4° C is a viscous semi-solid which is sightly heavier than water.

Bitumen cannot be used in its natural state in conventional refineries; hydrogen is added to the bitumen or carbon is removed. Most existing commercial operations reduce the carbon content. The end product is called "synthetic crude" because it has been chemically altered from the naturally occurring state. The properties of the synthetic crude are similar to those of a high grade conventional crude oil (McRory, 1982).

Water, often referred to as interstitial water, is found in oil reservoirs. The water has a high content of dissolved salts, usually higher than the salt content of seawater. An analysis report supplied by the Norcen Energy Resources Ltd. indicated that the cations present in the water were sodium (12,066.9 mg/L), calcium (609.2 mg/L), magnesium (274.8 mg/L) and dissolved iron (3.3 mg/L) with 0.3 mg/L undissolved iron. The anions present were chloride (20,208.2 mg/L) and bicarbonate (473.5 mg/L). The pH was 7.31 at 20.4 ° C (Norcen , 1989).

3.2 Test Sand and Fluids

The sand used in the testing program is a tailings sand from the McMurray heavy oil formation of the Athabasca Oil Sands in Alberta. Grain size distribution of the test sand was determined in accordance with the ASTM Standard Method No. D422-72 "Standard Method for Particle-Size Analysis of Soils". The sand used for the grain size analysis was randomly selected from the storage pit. A total of five grain size analyses were carried out and the grain size distribution results are shown in Figure 8. The McMurray Formation sand is fine and uniform with a coefficient of uniformity, Cu of 1.8, and Cu' = 1.4. Cu' was calculated according to Giroud (1988) where the coefficient of uniformity is measured on a straight line approximating the particle size distribution curve in the classical coordinates, percentage by weight versus logarithm of the particle size. The high uniformity of the McMurray Formation sand explains why the sand is difficult to filter. The undisturbed sand formation is very dense. However, depending on the type of well drilling and completion used and the stage of production, the density of the sand in the vicinity of a production well can range from loose to dense. The McMurray Formation sands tend to have in situ porosities of about 35% and in situ densities of 2.05 to 2.10 Mg/m^3 (Kry, et. al, 1989). It is not possible to reestablish the in situ porosity by recompaction alone without pressure; nor it is possible to reestablish the interlocked fabrics by recompaction (Dusseault and Morgenstern, 1979).

The sand used in the tests was prepared to the required density by tamping in accordance with the procedures recommended in the ASTM test method for measuring the soil-geotextile system clogging potential by the gradient ratio (ASTM, 1991). The dry density of sand used in the gradient ratio tests ranged from 1.69 to 1.70 Mg/m^3. The dry density of the sand used the modified gradient ratio tests varied from 1.64 to 1.65 Mg/m^3. Whereas the dry density of the sand used in the high confining stress filtration tests were from 1.66 to 1.68 Mg/m^3.

The heavy oil used in the testing program was a low sulphur content crude oil, (also known as sweet crude oil), from a Lloydminster heavy oil well. The crude oil was supplied by Norcen Energy Resources Ltd., Provost, Alberta. The sweet crude oil was a dark, brown-black colour with a strong tar odor. The characteristics of the heavy oil are summarized in Table 3. The density of the heavy oil in the Lloyminster region varies from 956 to 958 kg/m3 at 15.6°C (AOSTRA, 1984). To determine the effect of laboratory temperature on the viscosity of the heavy oil during the permeability, a Fann direct indicating viscometer was used to measure the viscosities of the heavy oil during tests. The viscosity of the heavy oil varied from 770 to 1170 kg/m^3 when the temperature varied from 24.0 to 20.8 °C. The results of the viscosity measurements are presented in Figure 9. The density of the heavy oil was also measured in the laboratory by the density bottle method. Because the temperature variation in the laboratory was less than 4°C, it was assumed that a density for the heavy oil of 975 kg/m^3, measured at a laboratory temperature of about 22°C, remained constant within the temperature range of 24.0 to 20.8 °C

Substantial amounts of water were required for the testing program, therefore, it was not practical to use intersitial water from the reservoirs nor to use reconstituted interstitial water. Deaired distilled water was used throughout the test program to assure reproducibility of results. Deaired water was prepared under a vacuum of about 100 kPa inside a deaired tank (Figure 10) until the dissolved oxygen in water was less than 6 ppm. The dissolved oxygen content in the deaired water was measured by an electrical dissolved air oxygen measurement devices. The temperature of the water entering the deaired tank was maintained at room temperature, 18° to 23°C. This was achieved by storing two tanks of distilled water (about 500 liter) at room temperature for at least 24 hours. When water was deaired, it was drained by gravity to a sealed deaired water tank for storage until it was pumped (by a submerged pump) to a header tank for filtration testing. Before water entered the test apparatus, water was forced to travel through a sand filter so as to remove impurities and air, if present. Temperature of the deaired water was maintained at a room temperature of 18°C to 23°C. A correction to 20°C was routinely applied to the permeability measurement.

CHAPTER 4: INITIAL SELECTION OF GEOTEXTILES

4.1 Introduction

In engineering design, it is important to clearly identify a problem and determine the intended usage of a finished design. In the design of a filter for heavy oil wells, a functional design capitalizes on the characteristics of the materials which become an integral part of the design. The initial selection of geotextiles was, in general, based on the geotextile filtration design procedures outlined by Williams and Luna (1987). The selection of geotextiles was based on filtration efficiency, flow capacity, chemical environmental compatibility with fluids and soil, stress/strain/strength behavior, cost, and availability. The first four criteria are performance criteria and are listed in the order of importance for this application, although filtration and flow capacity were ranked equally. The selected filter must be permeable and durable over its design life.

4.2 Filtration Properties of the Geotextile Fabrics

Geotextile filter design criteria reviewed in Section 2.5 considered the grain size distribution, coefficient of uniformity, density and permeability of the sand and the apparent opening size (AOS), the porosity and the permeability of the geotextile filters. Giroud's (1988) filter design criteria was adopted for the preliminary evaluation of the filtration properties of the geotextile fabrics. This was because his permeability criteria were developed for critical applications at high hydraulic gradient (Giroud, 1988) and his retention criterion is the most restrictive and suitable for situations where soil retention is critical (Koerner, 1986, 1990).

4.2.1 Permeability Criterion

Giroud (1988) defines the permeability criterion as:

$$K_g > i_s K_s \qquad (5)$$

where: K_g = the hydraulic conductivity of the geotextile;
i_s = the hydraulic gradient in the sand; and
K_s = the hydraulic conductivity of the sand.

The hydraulic conductivity of the geotextile was measured under compressive stresses equal to those expected in the field. For this application, a maximum confining stress in testing conditions of 1300 kPa simulated a horizontal effective stress from a loose sand on a well casing equivalent to a depth of 1000 m below the ground surface. The hydraulic gradient adjacent to a heavy oil well may be up to 0.5 in steady state conditions. In unsteady state conditions, the in situ gradient may be as high as 5.0 (Scott, Wong, & Richards, 1991), therefore, for steady state conditions, the required K_g for a filter in a heavy oil well is > 0.5 K_s. As the hydraulic conductivity of the McMurray sand is 0.008 cm/s, the hydraulic conductivity of the geotextile should be 0.004 cm/s under steady state conditions. A hydraulic gradient of 5 is required for surge flows or when lack of permeability of the filter could have serious consequences. For these conditions, the hydraulic conductivity of the geotextile should be at least 0.035 cm/s. However, fluid flow into heavy oil wells is generally under steady state conditions, surge flows are not of long term consequence and a maximum hydraulic gradient of 2 was chosen for design. Therefore, the geotextile should have a minimum hydraulic conductivity of 0.014 cm/s under a compressive stress of 1300 kPa.

4.2.2 Retention Criterion

The retention criterion proposed by Giroud (1988) is stated as:

$$O_{95} < \lambda_R \, d_{85} \qquad (10)$$

For the McMurray Formation sand, where the coefficient of uniformity, Cu, is between 1 and 3, λ_R is calculated as $Cu^{0.8}$ for loose sands and $2Cu^{0.3}$ for dense sands (refer to Table 2). According to these criteria, the O_{95} for a geotextile filter used with the McMurray Formation sand should be as followed:

Dense sand	< 0.51 mm ;
Medium dense sand	< 0.40 mm ;
Loose sand	< 0.29 mm .

4.2.3 Clogging Criterion

Based on the clogging (porosity) criterion, the geotextile fabrics should have:

a. a gradient ratio of less than or equal to three;

b. $n \geq 30\%$ (nonwoven) (12)

$A \geq 5\%$ (woven) (13)

where n and A are a minimum porosity and minimum open area respectively for geotextile filters under compressive stresses (1300 kPa) similar to those encountered in the field.

4.2.4 Wettability Criterion

Geotextile filter fabrics should be made of fibers that are both hydrophobic (repelling water) and oleophoblic (repelling oil) which will result in a higher permeability for a given porosity.

4.3 Chemical Environmental Durability Criterion

The downhole environments in the vicinity of the heavy oil production well is aggregative. Degradation of the fibers and bonds in the geotextile fabrics can cause loss in mechanical strength, and eventually, non acceptable long term filtration performance of a geotextile fabrics (Rollin and Lombard, 1988). The compatibility of the geotextile fabrics with the aggregative conditions in the heavy oil wells have to be assessed. Chemical resistance to the various components in heavy oil, interstitial water as well as to the additives used to enhance recovery is necessary. Fibers must resist swelling and degradation in the presence of oil and water, so that pore properties of the filter are not changed. Mechanical properties such as tensile strength and abrasion resistance must be sufficiently high that fibers do not rupture under high pressure flow and are not eroded by abrasive sand particles. Factors such as the stability of fiber dimensions will ensure that filtration characteristics do not change with time. If pore properties and fiber modulus are to remain constant during filtration, it is important that the flowing oil, water and additives do not cause swelling of the fibers (Kerr et al, 1988).

In summary, to meet the chemical environmental durability criterion, the filter must be chemically compatible with the fluids produced in a heavy oil well so that there is no significant change in pore size or reduction of permeability due to interaction between the fabric polymers and the fluids in the reservoir.

4.4 Stress/Strain/Strength Criterion

The mechanical properties required in a geotextile used in an oil well filter application are high bursting strength, high tensile strength, low initial strain and high abrasion resistance.

4.4.1 Bursting Strength

Bursting strength is the stress needed to rupture a fabric by applying a pressure at right angles to the fabric (Cohen, 1982). The force is applied radially rather than in one direction as with tensile strength and is measured by the burst test (ASTM test method D3786-80a). High bursting strength is a property necessary for fabrics that are to be stressed equally in every direction. This kind of stress is imposed on a geotextile well filter in areas located over perforations in casings. It is important that the fabric structure not be stretched or ruptured during steaming or production when there may be large differences in pressures or high flow rates. The bursting strength for a nonwoven geotextile shall not be less than 4.8 MPa and the bursting strength for a woven fabric shall not be less than 10.4 MPa (Scott et al, 1988).

4.4.2 Tensile Strength and Initial Modulus

Tensile strength and initial modulus are a function of polymer type and fabric structure. A fabric with high tensile strength and high initial modulus is required for a well filter. Woven fabrics tend to have high tensile strengths and high initial moduli. The structure of a woven fabric limits yarn mobility and this, combined with high tenacity fibers, yields a fabric with a high initial modulus. A suitable woven fabric should have a high tensile strength of 55 MPa or 104 kN/m (force per unit width) at failure and a failure strain of 15 to 20%. In nonwoven fabrics, tensile strength is usually a function of mass and thickness. The suitable nonwoven fabric should have a tensile strength, at failure, of 5.7 MPa or 22.8 kN/m. The limiting factor in the use of nonwoven fabrics is the high strain at failure (50 to 180%) and low initial modulus (Scott et al, 1988).

4.4.3 Abrasion Resistance

A filter fabric must also exhibit high abrasion resistance to prevent damage during installation and erosion from produced sands.

4.5 Polymer Type

For successful filtration of heavy oil and bitumen, the fibers of a geotextile fabric should be made with a polymer which is chemical resistant to the various components in the heavy oil reservoirs. Fibers must resist swelling and degradation in the reservoir fluids and it must be hydrophobic and oleophobic with high tensile strength, high modulus and abrasion resistance.

4.6 Polymer Structure

4.6 Polymer Structure

In order that the permeability and the piping criteria will be satisfied and to avoid concentration of flow into the filter, the fabric structure should possess a range of pore or opening sizes, and a large number of openings per surface unit area or a large surface porosity.

4.7 Cost and Availability

Cost is a major consideration in engineering design, however, the considerations of cost were omitted in the initial geotextile fabrics selection. Emphasis had been put on the availability of the geotextile fabrics. This was especially important when there was a time restriction in the research program. Therefore, to satisfy the availability requirement, the selected geotextile fabrics had to be readily available on the market.

4.8 Summary and Conclusion

A total of twenty seven manufacturers in Canada, USA and Europe were contacted for product information. Only eight produced geotextiles which fulfilled the permeability and retention criteria for a filter in this application. The properties of these geotextiles were ranked according to the categories of the selection process, based on information supplied by each manufacturer. Seven nonwoven, needlefelted geotextile products were finally selected and ordered for testing in filtration-permeability and durability laboratory experiments (McClung, 1988). These geotextile fabrics are:

- Bidim B5 manufactured by Rhone Poulenc;
- Exxon P0820 manufactured by Layfield ;
- Bidimrock TTNT 200/500 manufactured by Rhone Poulenc;
- Trevira 1135 manufactured by Hoechst Celanese;
- Polyfelt TS700 manufactured by Polyfelt;
- Armtec 7605S manufactured by Texel; and
- Quline Q200 manufactured by Wellman Quline.

Nonwoven geotextile fabrics are considered more suitable than woven geotextile fabrics because nonwoven geotextile fabrics have a random arrangement of fiber webs which causes the openings or pores between the fibers to vary in size. As a result a range of sand grain sizes can be chosen because geotextile fabrics made with these polymers general have good chemical resistance to the fluids in the oil reservoir. These types of fabrics are readily available on the market. Properties of each selected geotextile fabric are summarized in Table 4.

CHAPTER 5 TESTING PHILOSOPHY AND TESTING PROGRAM

A systematic testing program was established to investigate the filtration properties of the seven selected geotextile fabrics. The testing program is summarized in Table 5. The testing program, in general, was divided into six stages:

Stage 1: AOS of the seven geotextiles

The seven nonwoven geotextile fabrics were selected based on the product information provided by each manufacturer. As the manufacturer's methods and the procedures for the determination of the geotextile opening size are not always clearly defined, the validity of the data provided and the suitability of the fabrics selected had to be confirmed. The opening size of the selected geotextiles were defined by AOS rather than by FOS because the AOS testing method was standardized by the ASTM and the equipment was readily available.

Stage 2: Sand-geotextile filtration characteristics of the seven geotextiles using the gradient ratio apparatus

The schedule of the research program and the availability of the testing equipment prohibited full scale filtration investigation on all seven selected geotextile fabrics. There was time for full scale testing of only three geotextile fabrics. Therefore, preliminary sand-geotextile interaction filtration tests were carried out in order to select three geotextile fabrics for full scale filtration, mechanical, and chemical-environmental durability tests.

An apparatus was designed and fabricated based on a drawing in the proposed ASTM standard testing method for measuring the geotextile clogging potential (ASTM,1987). In these tests the permeability and clogging behavior of the sand-geotextile system for all seven fabrics, as well as the hydraulic conductivity of the test sand, were determined under an unidirectional downward flow condition, with water flow normal to the geotextile plane. From the results of this stage of testing, three geotextile fabrics were selected for full scale filtration, mechanical and chemical-environmental durability evaluation. These three geotextile fabrics were Exxon P0820, Bidimrock TTNT 200/500, and Quline Q200.

Stage 3: Sand-geotextile filtration characteristics of the three selected geotextile fabrics using a modified ASTM gradient ratio apparatus

Two problems were identified with the gradient ratio apparatus and the testing techniques used in Stage 2. Firstly, the effect of blinding at the top of the soil sample was substantial which resulted in the actual hydraulic gradient across the sand-geotextile system being significantly less than the applied hydraulic gradient. Hence the effects of hydraulic gradient could not be evaluated. Secondly, the height of the soil in the proposed ASTM gradient ratio apparatus was only 76 mm, hence the blinded, undisturbed and filter zones identified by Scott (1980) could not be clearly differentiated. For this reason, the gradient ratio apparatus was modified by increased the height of the soil sample to 127 mm and a total of eight manometer ports were added. The three selected geotextile fabrics were tested again by using the modified gradient ratio apparatus so as to ensure the validity of the test results obtained in stage 2.

Stage 4: <u>Compressibility of the three selected geotextiles</u>

In order to study the effects of normal compressive stresses on the compressibility of the geotextile fabrics, and to ensure Giroud's clogging criterion was still satisfied by the fabrics under the in situ stress conditions, the three selected geotextile fabrics were tested in compression. The porosities of the geotextile fabrics were indirectly determined by measuring the fabric thickness at different normal compressive stresses. Porosities of single as well as multiple layers of geotextile fabrics were determined.

Stage 5: <u>Permeability of the three selected geotextile fabrics under normal compressive stresses</u>

The permittivity (cross-plane permeability) of the three selected geotextile fabrics was measured in a high confining stress permeameter without the sand sample. Geotextile specimens composed of multiple layers, approximately 10 mm total initial thickness, were tested with oil and water as the permeants. The effects of confining stresses and different hydraulic gradients on the permittivity of the geotextile fabrics were evaluated. The measured permittivity values were compared to the hydraulic conductivity of the test sand and the results were also used to evaluate the validity of Giroud's permeability criterion.

Transmissivity tests were performed by other members of the research team and the results were presented in a separate report (Scott et al, 1990). For this reason, results of the transmissivity tests will not be presented nor discussed in this thesis.

Stage 6: <u>Sand-geotextile filtration characteristics of the three selected geotextile fabrics under a high confining stress</u>

These test were carried out in order to understand the interaction of the sand-geotextile systems under high confining stress and a high hydraulic gradients. The clogging and blinding potential of the geotextile fabrics and the piping characteristics of the sand as well as the permeability of the sand-geotextile system under these conditions were studied. Tests were carried out under a confining stress of 500 kPa. Sand was compacted on the top of geotextile specimens composed of multiple layers, approximately 10 mm total initial thickness, and water was use as the permeant. Time did not permit testing with heavy oil as the permeant.

CHAPTER 6 LABORATORY TESTING

6.1 Apparent Opening Size

The purpose of this test was to determine the apparent opening size (AOS), O_{95}, of the seven selected geotextile fabrics. These data were used to confirm the validity of the initial geotextile fabric selection process and to confirm Giroud's retention criterion on the suitability of the selected fabrics for soil retention purposes. The geotextile test specimens were sampled from the geotextile fabrics in accordance with the method recommended by Canadian General Standards Board, CAN/CGSB-148.1 No.1-M85. Specimens were cut from a single swatch spaced along a diagonal line on the swatch.

ASTM Test Method D4751-87 "Determining Apparent Opening Size of a Geotextile" testing procedures were followed. The test was conducted by sieving known quantities of glass beads in specified ranges of diameter size through geotextile specimens. Starting with the fraction of beads from the smallest range (0.075 to 0.090 mm), consecutive sievings were conducted until a range of beads are found where 5% or less passes through the geotextile specimen. The AOS size, O_{95}, is designated according to the bead size designation or sieve number of this size range.

The O_{95} of the fabric indicates the approximate largest particle that would effectively pass through the geotextile. In terms of the effective fabric opening size measured, the AOS represents the opening size for which 95% of the fabric pores are smaller than that diameter. The results of the AOS tests are summarized in Table 6.

The results show that with the exception of Quline, the measured AOS values are different from the AOS values reported by the manufacturers. The results indicate that all seven selected geotextile fabrics satisfy the retention criterion for dense sand. If the formation is in a medium dense state, all geotextile fabrics, except Trevira, satisfy the retention criterion. However, if the formation is loose, only three fabrics satisfy the retention criterion. These three geotextile fabrics are Bidimrock, Exxon and Quline. The other four geotextiles have an apparent opening size that is too large and they may allow piping of the sand through the fabric. It should be realized, however, that this test is conducted with no normal stress on the fabric. A normal stress would compress the fabric, reduce the size of the pores and make the fabrics less susceptible to piping.

6.2 Geotextile Fabric Thickness and Mass

The initial thickness of each geotextile fabric was measured by using a Frazier Compressometer and the test method recommended by the Canadian General Standards Board, Can/CGSB-148.1 No.3-M85 "Thickness of Geotextile". Mass of the geotextile fabrics were determined following test method Can/CGSB-148.1 No.2-M85, "Mass per Unit Area". The thickness and the mass measurements are summarized below:

Geotextile Trade Name	Thickness (mm)	Mass (g/m^2)
Bidimrock TTNT200/500	2.55	822
Quline Q200	4.25	597
Exxon P0820	3.03	322
Trevira 1135	3.51	-
Bidim B5	2.13	-
Armtec, 7605	2.11	-
Polyfelt TS700	2.51	-

To ensure geotextile fabric specimens selected for the research program were consistent, the thickness and the mass of each selected specimen were determined routinely and were compared to the results given above.

6.3 Gradient Ratio Filtration Tests

Two types of gradient ratio filtration tests were performed. The first type of testing was done by using a gradient ratio apparatus recommended in a proposed ASTM standard (ASTM,1987). It is noted that the method was standardized in 1990 (ASTM, 1991) as ASTM designation No. D5101-90. The second type of test was done by using a modified gradient ratio apparatus.

6.3.1 Gradient Ratio Filtration Test

6.3.1.1 Objectives and Test Procedure

The tests were performed with the following objectives:

a. to select three suitable geotextile fabrics for further full scale experimental studies;
b. to understand the interaction of the sand-geotextile system under different hydraulic gradient conditions;

c. to determine the permeability of the geotextile fabrics and the clogging and blinding potentials of the sand-geotextile system under unidirectional flow conditions and zero confining stress; and
d. to determine the hydraulic conductivity of the test sand.

A gradient ratio apparatus was designed and fabricated based on a proposed ASTM standard (ASTM, 1987) for measuring geotextile clogging potential. A sectional view of the gradient ratio apparatus is shown on Figure 11 and the schematic setup of the testing system is shown on Figure 12. Because of the limitation of the laboratory ceiling height, the maximum hydraulic head that could be achieved with this setup was about 2.5 m. With a sand specimen thickness of 0.076 m, this head could produce a maximum hydraulic gradient of 7.5 through the sand when the head loss through the apparatus was taken into account.

The gradient ratio apparatus was 101.6 mm in inside diameter and the maximum height of the sand specimen which could be accommodated was 76 mm. The sand, geotextile and apparatus were prepared and assembled in accordance with the requirements outlined in the proposed standard.

A single layer of geotextile fabric was used in the test. The specimen was cut from the geotextile fabric by locating the specimen at 10% of the fabric width from the edge of the swatch. The geotextile test specimen was conditioned by soaking the specimen overnight in a closed container of deaired water. Before the placement of the specimen in the apparatus, the specimen was surface dried by paper towels. The specimen was not pressed during the surface drying process.

Deaired, distilled water at room temperature with a dissolved oxygen content of less than 6 ppm was used as the permeant. The method used for the preparation of the deaired water was given in Section 3.2.3. Before the test water entered the gradient ratio apparatus, it was forced to travel through a sand filter to remove impurities and air if there was any. The filter was changed at least once a day or whenever it was dirty.

The saturation procedures detailed in the proposed standard were closely followed. The sand-geotextile system inside the gradient ratio apparatus was saturated firstly by purging the system with carbon dioxide gas for at least 10 minutes at a regulated gas flow rate of 2 liters/min. The apparatus was then filled with deaired water until the apparatus and the test system were air free. To ensure there was not any air trapped in the sand specimen, the saturation process continued overnight in a no flow condition under a hydraulic head of about 2 m of water. For safety reasons, the carbon dioxide purging operation was carried out inside an opearting fume hood.

The test was carried out in accordance with the procedures outlined in the proposed testing standard. Hydraulic gradients were obtained by varying the height of a variable constant header tank in relation to a fixed constant header tank (Figure 11). Measurements of flow rate, temperature and readings of all six manometers were taken at 0.25, 0.5, 1, 2, 4, 6, 8, 12, 24 hours for applied hydraulic gradients of 1, 2.5, 5 and 7.5. When there was a significant difference between manometers 2 and 3, 4 and 5, the system was immediately investigated for air bubbles, plugged manometer tubes or for plugged ports in the cell wall.

6.3.1.2 Detection of Sand Piping

Water passing through the sand-geotextile system was filtered by a filter paper before it was discharged to a drain. The purpose of this filtration was to determine quantitatively the quantity and size of the sand particles which piped through the geotextile fabrics. The condition of the sand sample and the colour of the permeant were also visually observed closely to determine if piping was occurring.

6.3.1.3 Analysis of Data

The hydraulic gradient applied to the sand-geotextile, i_{apply} , can be calculated using the following equation:

$$i_{apply} = \frac{dh}{L} \qquad (30)$$

where: dh = top manometer 6 reading minus bottom manometer 1 reading (cm); and
L = the height of the sand sample plus the thickness of the geotextile (cm).

The sand-geotextile system permeabilities at the test temperature and at 20° C were calculated using equations 31 and 32:

$$K_T = \frac{Q}{i\,A\,t} \qquad (31)$$

$$K_{20} = \frac{K_T \mu_T}{\mu_{20}} \qquad (32)$$

where: k_T = system permeability at test temperature, cm/s,
k_{20} = system permeability at 20°C, cm/s,
Q = quantity of flow measured, ml,
i = hydraulic gradient of the system, that is i_{apply},
A = cross-sectional area of the specimen, cm^2,

t	=	time for measured quantity of flow, second,
μ_T	=	water viscosity at temperature of the test, and
μ_{20}	=	water viscosity at 20° C

The Gradient Ratio for the sand-geotextile system, GR, was calculated using equation 33. The Gradient Ratio for the system at each hydraulic gradient was the value computed from the 24 hour data readings.

$$GR = \frac{\frac{dh_{sf}}{L_{sf}}}{\frac{dh_s}{L_s}} \qquad (33)$$

where:	dh_s	=	((5 minus 3) + (4 minus 2))/2, cm,
	dh_{sf}	=	((3 minus 1) and (2 minus 1))/2, cm,
	L_s	=	2.54 cm,
	L_{sf}	=	2.54 plus geotextile thickness, cm.

It is important to note that the definitions of dh_s and dh_{sf} are different from the definitions used in the proposed ASTM gradient ratio test standard (see Figure 13).

6.3.1.4 Test Results and Observations

The test results for the seven fabrics are presented in Figures 14 to 41. The discussion of the test results is given in Section 7.2.

Two problems were identified when using the gradient ratio apparatus. Firstly, the effect of blinding at the top of the soil sample was substantial, the effective hydraulic gradients through the remainder of the sand-geotextile system dropped to 1.5 or less, even when the applied hydraulic gradients were increased to 7.5. Secondly, the height of the soil in the gradient ratio apparatus was only 76 mm height, hence the blinded, undisturbed and filter zones (Scott,1980) could not be clearly differentiated. For these reasons, the apparatus was modified for further testing on the three selected geotextile fabrics.

It is important to noted that no piping was observed in any of the gradient ratio tests and that the weight of the filter paper before and after the tests remained unchanged. That is, no sand grains passed through any of the seven geotextiles by observation or by measurement.

The deaired water preparation and supply system performed satisfactorily. The dissolved oxygen content of the test water in the storage tank, before entering the sand filter, after passing through the sand filter and after passing through the gradient ratio apparatus was measured and was confirmed that the dissolved oxygen content remained about 6 ppm. However, isolated air bubbles were still observed in the manometer tubes which affected the manometer readings. The problem was more noticeable when the temperature in the laboratory increased. It was possible, however, to observe and remove the bubbles from the manometer tubes to overcome this experimental difficulty.

6.3.2 Modified Gradient Ratio Filtration Test

6.3.2.1 Objectives and Test Procedure

The primary objectives of this test were similar to the gradient ratio filtration test (Section 6.3.1). However, there were two additional purposes for carrying out this test, these were:

a. to develop a better gradient ratio apparatus which would overcome the problems observed in the gradient ratio apparatus used in Section 6.3.1; and
b. to confirm the validity and the repeatability of the test results obtained in the gradient ratio apparatus.

The gradient ratio apparatus used in this testing program was a modified version of the gradient ratio apparatus originally designed and fabricated for the test in Section 6.3.1. To distinguish the present apparatus from the one used in Section 6.3.1, the present apparatus is called "modified" gradient ratio apparatus".

Four major modifications were carried out. First, the middle cylinder was extended in length so that the height of the sand sample increased from 76 mm to 127 mm. Second, a total of four pairs of manometers were installed on the apparatus in the sand sample area so that the head loss through the sand specimen could be better defined. Third, the distance between the the upper surface of the geotextile specimen and a manometer in the sand was decreased to 12.7 mm to better define permeability changes in this region (Figure 42). Lastly, a support fabric and screen included in the original gradient ratio apparatus were removed because they might have contributed to the high head loss in the top section of the test sand. Instead, a layer of uniform quartz sand about 50 mm in thickness was placed on top of the test sand so as to minimize the blinding effect which usually occurred at the top of the test sand.

To obtain an effective gradient of 10 through the sand-geotextile system, the head difference between the inflow and outflow would have to be large than 2.5 m. This was not possible because the head room clearance in the laboratory for this apparatus was only about 2 m. An air pressurized constant head device was therefore designed and fabricated to overcome this limitation (Figure 43). The setup of the modified gradient ratio testing system is shown on Figure 44. The deaired water supply system was also replaced by two 225 liters (50 Imp. gallons) capacity steel tanks. The tanks were coated inside with anti-corrosion and anti-rust paint. They were used as either vacuum or as pressure tanks. They were used as vacuum tanks when attached to a vacuum pump for making deairing water. However, when they were connected to an air pressure system, they were used as pressure tanks. These tanks were originally designed for a working pressure of 250 kPa with a factor of safety of 10. However, to avoid the complicated procedures in obtaining a pressure vessel permit from local authorities, the working pressure applied to the tanks was limited to a maximum of 100 kPa.

The preparation and the assembling of the modified apparatus, the sampling and the conditioning of the geotextile test specimens, the preparation of the test water, the saturation of the sand-geotextile system and the test procedures used were similar to those described for the gradient ratio filtration test in Section 6.3.1. Detection of sand passing through the geotextiles followed the same qualitative and quantitative procedures.

6.3.2.2 Analysis of Data

The hydraulic gradient applied to the sand-geotextile, i_{apply}, and the system permeability were calculated using the same equations given in Sections 6.3.1.3.

The gradient ratio for the sand-geotextile system, GR, could still be calculated using equation (33) in Sections 6.3.1.3, however, the definition for dh_s, dh_{sf}, L_s and L_{sf} are different (see Figure 45).

$$GR = \frac{\frac{dh_{sf}}{L_{sf}}}{\frac{dh_s}{L_s}} \qquad (33)$$

where: dh_s = ((9 minus 3) + (10 minus 4))/2, cm,

dh_{sf} = ((3 minus 1) and (4 minus 2))/2, cm,

L_s = 7.62 cm,

L_{sf} = 1.27 plus geotextile thickness, cm.

6.3.2.3 Test Results and Observations

The test results for the three fabrics are presented in Figures 45 to 56. The discussion of the test results are given in Section 7.3.

With the new constant head device, an hydraulic gradient of 10 across the sand-geotextile system could be easily generated. The placement of 50 mm of uniform quartz sand on top of the test sand proved to be a valuable modification. The effective hydraulic gradient through the sand-geotextile system was consistent with the applied hydraulic gradient. Head loss due to blinding in the top of the test sand was small. To ensure that any blinding at the top of the sand did not result in too low a hydraulic gradient in the sand and geotextile, the head loss between manometers 9-10 and 1-2 (Figure 44) was controlled by changing the applied head until the required hydraulic gradient was established. Two sand filters connected in series was essential in this test because rust was found in the water from the steel tank. To ensure that the water entering the gradient ratio apparatus was clean, sand filters were changed at least twice daily. The sand filters served their function to filter impurities and rust from the storage tank. To ensure that any air coming out of solution from the water, due to a change in temperature in the laboratory, was removed, a vacuum of almost 100 kPa was applied to the deaired water storage steel tank all the time until the deaired water was ready for use in testing. After this modification in the preparation of the deaired water supply system, no air bubbles were found in the modified gradient ratio apparatus. Again, piping was not observed throughout the tests and the weight of the filter paper before and after the tests was unchanged.

6.4 Compressibility of the Geotextile Fabrics

6.4.1 Objectives and Test Procedure

The objectives of this test were to study the effects of normal compressive stresses on the compressibility of the three selected geotextile fabrics and to ensure that Giroud's porosity criterion was still satisfied by the fabrics under simulated in situ stress conditions.

There is not any standard for measuring the compressibility of geotextile fabrics. A compression system consisting of a loading frame equipped with an air driven bellofram, a flat steel plate, a load cell and a LVDT was therefore developed. When air pressure was applied to the bellofram a ram compressed the geotextile fabrics which were placed underneath a rigid flat steel plate. The magnitude of the compressive load was measured by a load cell and the change in thickness of the fabric was monitored by a LVDT.

Prior to placing the geotextile fabric in the compression frame, the initial thickness of the geotextile fabrics (multiple layers) were measured by a Frazier Compressometer following the procedures given in Can/CGSB-148.1 No.3-M85 "Thickness of Geotextiles". The thickness measurements determined were used as the baseline measurements in the subsequent compressibility tests.

A 130 mm diameter geotextile specimen was placed at a marked location on the steel base of the loading frame. A 130 mm diameter flat steel plate, which generated about 2 kPa pressure due to its own weight, was placed on top of the geotextile fabric. A LVDT was then placed carefully on top of the steel plate and the LVDT reading was noted. This LVDT reading represented the initial thickness of the geotextile. A load cell was then placed on the steel plate, and the compression of the geotextile was again recorded. Air pressure was then applied slowly to the bellofram which caused the slow downward movement of the ram. When the ram was in contact with the load cell another LVDT reading was recorded. The test continued by increasing the air pressure in the bellofram in steps of about 200 kPa until a maximum of 1300 kPa was acting on the fabric. LVDT and load cell measurements were taken at every load increment, so that the relationship between stress and thickness could be determined. Tests were carried out with multiple layers of geotextile fabrics (approximately 10 mm total thickness). Each type of fabric was tested twice with different specimens to confirm repeatability of results.

Porosity of the geotextile fabrics was calculated by using equation 14 in Section 2.6.3 (Williams & Abouzakhm, 1989).

$$n = 1 - \frac{m}{G_s \rho_w t} \qquad (14)$$

where: n = the porosity;
m = mass per unit area of the geotextile (see Section 6.2);
ρ_w = density of water;
t = thickness measurements; and
G_s = specific gravity of the polymer.
G_s for polyester is 1.380
G_s for polypropylene is 0.910

6.4.2 Test Results

Four layers of Bidimrock, three layers of Exxon and two layers of Quline were tested independently. The effects of confining stress on thickness and porosity for multiple layers of selected geotextile fabrics are shown on Figures 58 and 59 respectively. The results indicate that at the maximum compressive stress of 1300 kPa, the porosities of Quline and Exxon were decreased from about 86% to about 61% and the porosity of Bidimrock was decreased from 74% to about 56%.

Even though the porosities for Exxon, Quline and Bidimrock were decreased with the increase in normal compressive stress, the final porosities for all three geotextile fabrics were still larger than 30%. Therefore, Giroud's porosity criterion for nonwoven geotextile fabrics was still satisfied by all three fabrics under a stress of 1300 kPa.

Approximately 90% of the change in fabric thickness occurred at a compressive stress of 500 kPa for all three geotextiles. It was concluded, therefore, that there was no need to compress the fabric to the maximum compressive stress of 1300 kPa during the high confining stress filtration tests. A confining stress of 500 kPa was selected for the subsequent high confining stress permeability and filtration tests.

6.5 High Confining Stress Testing

6.5.1 High Confining Stress Apparatus

In order to address the filtration requirements which exist in heavy oil wells, a large scale permeameter system was designed and fabricated. The permeameter cell (Figure 60) was 130 mm in diameter and could accommodate a sand specimen of over 200 mm in height. The cylindrical wall of the permeameter was made of high strength transparent acrylic tube (Johnson Industrial Plastic, Parts No. 030-384-024X) that had high corrosion resistance to petroleum fluids and a maximum working pressure of about 200 kPa (with a factor of safety of 4 applied to the ultimate strength of the acrylic material) at a testing temperature not higher than 50° C. Seven stainless steel piezometer ports fitted with #100 stainless steel wire mesh were provided on the cylindrical wall at vertical spacing of either 25.4 mm or 50.8 mm. The top and the bottom caps of the permeameter was made of stainless steel and were tied together by six high tensile strength steel threaded rods. Stainless steel rings of various thickness were provided so that the distance between the geotextile fabric and the bottom manometer port could be adjusted if necessary. Stainless steel porous spreader plates were provided. One plate was used in the top to transfer and to spread the load from the bellofram through the plate to the sand and the sand-geotextile system uniformly. The other plate was used at the bottom to generate reaction for the compression of the sand-geotextile system. Two precompressed heavy gauge No.10 brass screens were placed between the geotextile specimens and the underlying porous spreader plate so that fluid flow through the geotextile would be exited through the spreader plate more uniformly. Stainless steel used for the apparatus was grade 316, which is a steel with high corrosion resistance against corrosive fluids such as heavy oil.

The test system consists of a bellofram compression system, a water supply system and a data monitoring system. The bellofram compression system was used for the compression of sand, fabric or the sand-geotextile system. The load applied to the sand-geotextile system was monitored by an electrical load cell whereas the compression of the sand-geotextile system was monitored by a dial gauge or a LVDT.

The water supply system basically consists of two 225 liters capacity steel tanks and an air pressurized constant head device. The tanks were used as either vacuum or as pressure tanks (see description in Section 6.3.2.1). The air pressurized constant head device was used to control the liquid pressure applied to the permeameter cell. The working pressure applied to the tanks was limited to a maximum of 100 kPa .

Either electric transducers or mercury manometers were used as the pressure monitoring system. The selection of the system depended on the type of test and the required accuracy of the measurements.

The high confining stress apparatus can produce a maximum differential fluid head of 400 kPa *across the sand-geotextile system, can accommodate oil or water or fluid mixtures of oil, gas* and water as the permeant, can achieve a confining stress of up to 1300 kPa on the sand and geotextile, and can handle reversing flow conditions.

6.5.2 High Confining Stress Permittivity Test

6.5.2.1 Test Objectives

This test was performed on the geotextile alone. Its objectives were to study the influences of confining stress, hydraulic gradient, and time of fabric immersion in the permeant on the permeability of the geotextile fabrics with heavy oil and with water as permeants. The results of the test were used to confirm the validity of Grioud's permeability criterion used in the initial selection of the geotextile fabrics.

6.5.2.2 Water as Permeant

The setup of the test system is shown in Figure 61. The system consisted of a bellofram compression system, a deaired water supply system and a pressure monitoring system. An air pressurized constant head device was not used because the permeability of the geotextile was large and the device could not keep up with the water demand. The compression of the goetextile fabrics was generated by the bellofram compression system. The load applied to the fabric was monitored by an electrical load cell whereas the compression of the fabric was monitored by a dial gauge or a LVDT. The deaired water supply system consisted of a deaired water preparation tank, two deaired water storage tanks, and a movable constant head device.

A differential pressure transducer with a pressure range to 9 kPa (1.25 psi) was used to measured the pressure difference above and below the geotextile specimen.

The head loss across the geotextile fabric was small when compared to the head loss through the spreader plates and the wire meshes. A calibration test which was basically a permeability test without a geotextile fabric was carried out at different applied hydraulic gradients to determine the head loss through the spreader plates and the wire meshes. The head loss through the geotextile fabrics at a particular applied hydraulic gradient was determined by subtracting the differential pressure measurements (with geotextile specimens) from the pressure measurements determined in the calibration (without a geotextile) under the same applied hydraulic gradient.

6.5.2.3 Heavy Oil as Permeant

The test system consisted of a bellofram compression system, and an oil reservoir (about 700 ml in volume)(Figure 62). The higher viscosity of the heavy oil (about 10,000 mPa.s at 20° C) resulted in an extremely slow rate of flow hence the amount of oil required for each test was less than 1 liters. The temperature during testing significantly affected the viscosity of the heavy oil and the permeability of the fabric. A sealed oil container, with the same shape and same dimension as the permeameter was placed next to the permeameter in order that the variations in the temperature and in the viscosity of the heavy oil during the test could be measured. These measured viscosity values were used for the absolute permeability calculations. The viscosity of the heavy oil at various temperatures was measured with a Series 35, Fann Direct Indicating Viscometer. The heavy oil required for the test was supplied from an oil reservoir. In order to ensure the test was carried out in a constant head condition, the oil level on the upstream side of the geotextile specimen was controlled by an overflow in the permeameter cell.

The head loss through the geotextile was first monitored with an electronic differential pressure transducer, DP103-10, with an ultra low stress range to 3.5 kPa (0.5 psi). However, the transducer was proved not suitable for this test because the results were not repeatable and the zero datum kept shifting. Finally, it was decided that the head loss through the geotextile specimens could be determined by measuring the elevation difference between the upstream oil level and the downstream outlet tube level. It was calculated that, at the highest hydraulic gradient of 50, the head loss in the apparatus was approximately 0.34 mm of water. This head loss was considered small and acceptable in comparison to the accuracy required in the experiment.

6.5.2.4 Sampling and Conditioning of Geotextile Specimens

Multiple layers of each type of fabric was used in the test. A total of eight pieces of Bidimrock, nine pieces of Exxon and four pieces of Quline of 130 mm diameter were required for the permeability tests. The specimens were cut from the geotextile samples by locating specimens at 10% of the fabric width from each edge of the swatch and at the center of the swatch width.

Geotextile specimens were soaked in heavy oil or water for 48 hours prior to testing to ensure saturation. Water soaked specimens were surface dried prior to be assembled in the cell. However, surface drying was not done for the oil soaked specimens, they were placed in the permeameter with their surfaces richly coated with heavy oil.

To determine if extended exposure of the fabric to the heavy oil had any effect on the permittivity, one additional test was carried out on an Exxon geotextile specimen which was soaked in heavy oil for a period of 26 days. Exxon was chosen because polypropylene polymers were known to have interaction with heavy oil (Vittoria & Riva, 1986). Penner (1990) reported that fiber diameter for Exxon increased after this geotextile was immersed in heavy oil for 15 days.

6.5.2.5 Test Procedures

Before the permeameter was assembles, it was thoroughly cleaned and dried. All the O-ring gaskets were lubricated with silicon grease to ensure sealing. The procedures for water and heavy oil tests were different.

<u>Water as Permeant</u>

The permeameter was assembled in dry conditions. Steel rings, bottom spreader plate, wire mesh, geotextile specimens and the top spreader plate were placed, in the order named, on the bottom of the permeameter cell. The cylindrical wall of the permeameter was aligned and fitted on top of the specimen and the plates. The top cap of the permeameter cell was then assembled and the bolts in the tie rods were tightened. To ensure leakage could not happened during testing, silicon based sealant was provided between metal contact surfaces. The assembled permeameter cell was saturated firstly by purging with carbon dioxide gas, then by deaired water. Saturation procedures given in Section 6.3.1.5 were followed.

When the permeameter cell was properly assembled, it was placed in the compression system. The permittivity of the geotextile fabric was measured under six confining stresses:1.3, 100, 500, 1300, 100 and 1.3 kPa respectively.

Hydraulic gradients were obtained by varying the height of a variable constant header tank and the oultet elevation (Figure 60). Measurements of flow rate, temperature and pressure readings were taken for hydraulic gradients of 0.1, 0.25, 0.5, 1, 2.5, 5, 7.5 and 10 for each stress step. To ensure the accuracy of the measurements, a minimum quantity of flow of 10 ml was taken for each measurement and at least three sets of readings were taken for each hydraulic gradient.

Heavy Oil as Permeant

Steel rings, greased with silicon sealant, were placed at the bottom of the permeameter cell, then the cylindrical wall of the permeameter was aligned and fitted on the rings. Heavy oil was poured in the cell from the top until the rings were submerged by about 100 mm. The bottom spreader plate, the wire meshes, then the geotextile specimens and lastly the top spreader plate were placed in the cell in order. It was important to ensure that spreader plates and geotextile specimens were laid flat and air was not trapped. Air trapped during the placement of plates and specimens was difficult to remove and had to be avoided. More oil was poured into the cell until the overflow level was reached. The top cap of the permeameter cell was then put on and the bolts in the tie rods were tightened.

The upstream heavy oil level in the permeameter was fixed, therefore, hydraulic gradients were obtained by varying the elevation of the outlet (Figure 61). Measurements of flow rate, temperature and viscosity were taken for hydraulic gradients of 0.1, 0.25, 0.5, 1, 2.5, 5, 7.5, 10, 20 and 40. To ensure the accuracy of the measurement, a minimum weight of the oil collected was at least 0.1 g for each measurement and at least three sets of readings were taken for each hydraulic gradient.

The quantity of oil flow through the geotextile fabric could not be measured by volume because it took an impractical duration of time to collect a noticeable amount of oil and also the oil level inside a measuring flask could not be identified from the outside. Volume measurements were indirectly determined from the density and the mass of the oil collected. The density of the oil was determined by using a density bottle method. the mass of the oil collected was determined by weighing during the test.

6.5.2.6 Test Results

In order to compare the permeability results for water and heavy oil, the permeability of the geotextiles are expressed in term of absolute permeability. The absolute permeability was determined by using Darcy's Law for laminar flow through porous media:

$$K = 100.\frac{q}{t\,A}.\frac{L}{dh}.\frac{m}{\rho\,g} \qquad (22)$$

where:

K =	absolute permeability, m^2;
q =	quantity of flow, m^3;
t =	time of flow, s;
A =	area normal to flow direction, m^2;
L =	length of specimen in flow direction, m;
dh =	change in head over length, L, m;
μ =	viscosity of fluid, mPa.s;
ρ =	density of fluid, kg/m^3; and
g =	acceleration due to gravity, m/s^2.

Permittivity of a geotextile, Ψ, is defined as the volumetric flow rate of liquid per unit cross-sectional area per unit head under laminar flow conditions, in the normal direction through the geotextile. The permittivity is given by equation 24:

$$\Psi = \frac{k}{T_g} \quad (\text{in } s^{-1}) \qquad (24)$$

where k is the hydraulic conductivity. For comparison purposes, the absolute permeability K is used in this thesis instead of Ψ.

The absolute permeability for each geotextile fabric was plotted against different hydraulic gradients for water and for heavy oil. Results of the permittivity testing with fabrics soaked in permeant for 2 days are presented in Figures 62 to 67. The permittivity result for Exxon fabric soaked in heavy oil for 26 days is presented in Figure 68. The discussion of the test results is given in Section 7.4.

6.5.3 High Confining Stress Filtration Test

6.5.3.1 Objectives and Test Procedures

The objectives of this test were (1) to determine the interaction of the sand-geotextile system under high confining stress and high hydraulic gradient conditions, (2) to determine the clogging and blinding potential of the geotextile fabrics and the piping characteristics of the sand through the geotextile, and (3) to measure the permeability of the sand-geotextile system under the high stress and gradient conditions. It was also the purpose of this test to identify suitable geotextile fabrics for use in field testing.

A description of the high confining stress permeameter is given in Sections 6.5.1. The setup of the testing system is given on Figure 70.

In the original design, electrical pressure transducers with a stress range from 350 kPa to 1300 kPa were attached to each manometer port. It was planned to continuously monitor these transducers with a fully computerized data acquisition system. However, electrical interference in the vicinity of the laboratory (the laboratory was located next to the Alberta Micro Electronic Research Laboratories) caused continuous electronic problems with the proposed data acquisition system. After several unsuccessful modifications had been made to the datalogging devices, the objective of using a fully computerized data acquisition system was finally abandoned. A water manometer system was considered but the limitation of the ceiling height prohibited this idea. Eventually, a mercury manometer system was developed to monitor the head loss in the soil-geotextile system. The accuracy of the mercury manometer system was ± 0.5 mm of mercury (6.81 mm of water or 0.068 kPa).

Multiple layers of each type of fabric were used for this test. Four pieces of Bidimrock, three pieces of Exxon and two pieces of Quline of 130 mm in diameter were required. The specimens were cut from the geotextile sample by locating specimens at 10% of the fabric width from each edge of the swatch and at the center of the swatch width. The procedures for conditioning the geotextile specimens were described in Section 6.3.1.1. Deaired water was used as the permeant. The preparation requirements for the test water are given in Section 3.2.3.

Before the permeameter was assembled, it was thoroughly cleaned and dried. All the O-ring gaskets were lubricated with silicon grease to provide better sealing. A coating of dry silicon was sprayed on the inside of the permeameter cell to prevent sand particles adhering to the wall surface during the placement of the sand and to minimize sand arching effects during testing.

Steel rings, bottom spreader plates, wire meshes and geotextile specimens were placed, in the order named, at the bottom of the permeameter cell. Enough steel rings were provided to ensure that the surface of the compressed geotextile specimen was 25.4 mm below the center of the lowest manometer port. When the geotextile specimens were seated properly inside the cell, test sand was added in layers and tamped to the required density until the top of the sand was about 100 mm below the top of the permeameter cell. A layer of uniform coarse sand about 25.4 mm thick was loosely placed on top of the test sand, then the top spreader plate was installed. After the top spreader plate was in place, the top cap of the permeameter cell was assembled and the bolts in the tie rods were tightened. The uniform coarse sand layer was used to ensure an uniform distribution of water flowing into the test sand and to minimize sand blinding which often occurs at the top of the test sand. To ensure that any blinding at the top of the sand did not result in too low a hydraulic gradient in the sand and geotextile, the head loss between manometers 13-19 (Figure 70) was controlled by changing the applied head until the required hydraulic gradient was established

The assembled permeameter cell was then placed in the compression system and a confining stress of 500 kPa was applied. The distance between the surface of the geotextile specimen and the center of the lowest manometer port was then measured. If it was 25.4 mm ±1mm, the permeameter cell was ready for saturation. However, if the distance measured was outside the specified range, the permeameter had to be disassembled and reassembled again.

The bellofram pressure required to ensure that the geotextile experienced a confining stress of 500 kPa was determined separately in a calibration test. In the calibration, the bottom of the assembled permeameter cell was removed. A calibrated load cell was placed underneath the bottom spreader plate. Air pressure was then applied to the bellofram resulting in the compression of the sand, geotextile and load cell until the load cell measured a confining stress of 500 kPa. This bellofram pressure was recorded and was defined as the pressure required to ensure the geotextile experienced a confining stress of 500 kPa. It was found during this calibration exercise, that the sand arching effect between the sand and the wall of the permeameter was very small as the surface of the wall was coated with dry silicon.

Saturation of the permeameter cell was done by purging with carbon dioxide gas, then by saturating with deaired water. The procedures were given in Section 6.3.1.1. The testing procedure is a modification of the testing conducted in the gradient ratio test (Section 6.3). Different hydraulic gradients were obtained by regulating the air pressure acting on the constant head device. Measurements of flow rate, temperature and readings of manometers were taken at 0.25, 0.5, 1, 2, 4, 6, 8, 12, 24, 36, 48, 60 and 72 hours for applied hydraulic gradients of 0.5,1, 2.5, 5, 7.5 and 10.

6.5.3.2 Test Results

The hydraulic gradient applied to the sand-geotextile, i_{apply}, and the system permeability can be calculated using the same equations given in Section 6.3.1.3.

The gradient ratio for the sand-geotextile system, GR, can still be calculated using the same equation (33) in Section 6.3.1.3, however, the definition for dh_s, dh_{sf}, L_{sf} and L_s are different (see Figure 71).

$$GR = \frac{\frac{dh_{sf}}{L_{sf}}}{\frac{dh_s}{L_s}} \qquad (33)$$

where: dh_s = (13 minus 18), cm

dh_{sf} = (18 minus 19) , cm

L_s = 15.24 cm.

L_{sf} = 2.54 plus geotextile thickness, cm

The test results for the three fabrics are presented in Figures 72 to 83. The discussion of the test results is given in Section 7.5.

CHAPTER 7 ANALYSIS OF RESULTS AND DISCUSSION

7.1 Interpretation of Test Results

The sand-geotextile filtration test results can be analyzed with the use of a system flow rate diagram, with the use of a head loss diagram and by the use of gradient ratio values. The system flow rate diagram is a plot of system flow rate through the sand-geotextile system with time at a particular hydraulic gradient. A continuing change in the flow rate indicates that a mature soil-geotextile system (Figure 5) is still not formed. Slowing of the change in flow rate indicates that a bridge network structure is forming. When the flow rate becomes constant it indicates that a stable bridge structure at the sand-geotextile interface has been established.

The heads at each manometer during a test can be plotted to form a head loss diagram. This plot shows how the head varies from the top of the soil down through the sand sample and geotextile fabric and how it changes during the test as piping of fines from the soil and clogging of the geotextile fabric takes place. The head of water below the geotextile fabric is used as datum. The heads shown for the manometers are the heads of water above this datum, not the heads at the manometer locations. Plotting the water heads in this manner compensates for the difference in elevation of the manometer locations and shows the head loss from water flow alone.

Figure 83 is a typical plot of head loss through a soil-geotextile system (Scott, 1980). The soil-geotextile system can be divided into three zones. The top zone is the depth of soil sample in which blinding occurs as the water flowing into the sample washes fines at the surface into a concentrated layer just below the surface. This is a common action in permeability testing of soils. The blinding is an experimental problem and the head loss in this zone must be discounted in the analysis of the test results.

The undisturbed zone is that part of the soil sample which is not affected by the flow of water through the soil sample and in which all the soil grains retain their original positions, that is, no movement of soil grains occurs. The absolute permeability of the soil is not changed in this zone during the test.

The filter zone is the bottom part of the soil sample in which movement of soil grains occurs and also includes the geotextile fabric. The soil and the geotextile are considered together as it is the soil-geotextile interaction which determines whether a geotextile fabric is acceptable for use, not the permittivity of the geotextile alone. During the test the finer soil grains are washed through and out of the soil and into or through the geotextile. The soil in the filter zone therefore increases in permeability as the value of absolute permeability is increased by the removal of fines. At the same time, the absolute permeability of the geotextile decreases as fines blind the surface of the geotextile or clog the pores in the geotextile. If the fines pass through the geotextile, no blinding or clogging may occur and the permeability of the geotextile will not decrease.

It is experimentally difficult to determine the change in the filter zone alone during the test because of the complex changes in permeability in this zone and it is necessary to have a sample with sufficient height so that both the undisturbed zone and the filter zone can be defined. The permeability of the filter zone can then be compared to the permeability of the undisturbed zone to determine the changes that have taken place.

Once the undisturbed and the filter zones are identified, the hydraulic gradients in the undisturbed and filter zones can be determined from the head loss diagram. A comparison of hydraulic gradients can then be made and used as a criterion for acceptability. This comparison is made by dividing the hydraulic gradient through the filter zone by the hydraulic gradient through the undisturbed zone. This ratio is known as the gradient ratio. A gradient ratio of one indicates that the geotextile has no effect on the hydraulic flow through the sand-geotextile system and the soil is internally stable. A gradient ratio of less than one indicates that the filter zone is more permeable than the undisturbed soil or it is an indication that there is internal soil piping and movement of soil, adjacent to the geotextile, out of the system. A ratio greater than one indicates clogging or blinding of the geotextile. The gradient ratio test is an empirical test. Gradient ratio values obtained are index values and these values can be used only as an indication of the behavior of the sand-geotextile system.

The flow rate diagram, the head loss diagram and the gradient ratio values are valuable techniques for understanding the filtration performance of a sand-geotextile system. However, these techniques generally do not indicate the magnitude of the changes in permeability of the sand and the geotextile in a sand-geotextile system during a test. The suitability of a geotextile for a specific soil should be determined by analyzing what happens in the filter zone during a test. If the permeability of the filter zone increases or is unchanged then the geotextile is acceptable. If the permeability of the filter zone decreases then the geotextile may not be or is not acceptable. The permeability of the sand in the filter zone and the permeability of geotextile can be determined directly by installing manometers (for head loss measurements) within the filter zone and in the geotextile. However, this approach is experimentally difficult.

A method for the determination of the permeability of the geotextile in the sand-geotextile system is shown on Figure 84. The diagram at the top is a typical head loss diagram for a sand-geotextile system. In this example, head loss readings for four manometers are plotted. Since manometers are not provided at the interface of the sand-geotextile and in the geotextile, the head loss across the interface of the sand-geotextile and across the geotextile cannot be measured. Hence the permeability of the geotextile cannot be determined directly from the manometer measurements. A method for the determination of the head loss across the geotextile is shown in the bottom part of Figure 85. Line 1-2 is a portion of a best fit line of the head measurements in the undisturbed zone. To determine the behavior of the geotextile, this line must be extended so that it intersects the surface of the geotextile. Since the bottom of the geotextile is assumed to be the datum, the head loss at the bottom of the geotextile must be zero. There are three possible paths that line 1-2 can follow when it is extended.

Line 1-2 can extend along path 2-3-4. Line 2-3 represents the permeability of the soil between the manometer, at point 2, and the top of the geotextile. As line 2-3 indicates a larger hydraulic gradient than line 1-2, it indicates that the permeability of the sand in this zone is lower than the permeability of the sand in the undisturbed zone. The head measurements in the sand show that the head loss here is linear and the permeability of the sand is constant with depth above point 2. Therefore, there is not any movement of soil particles within the region monitored by the four manometers above point 2. It does not appear possible to develop a lower permeable zone underneath a zone which does not show any signs of soil movement. Hence, path 2-3-4 is not logical and therefore inadmissible.

Line 1-2 can extends along path 2-6-4. Line 2-6 is a path which represents that the head loss across the soil is close to zero and the permeability of this zone is very high. This may indicate that all fine material has washed out of this zone. Line 6-4 indicates that the geotextile is blinded or clogged as there is a high head loss across the geotextile. Blinding and clogging of the geotextile may be due to the migrated soil particles being trapped on the surface or in the geotextile. Path 2-6-4 is the lower limit for the permeability of the geotextile.

Line 1-2 can extend along path 2-5-4. Line 2-5 is a straight line extension of the best fit line 1-2. This extension represents that the head loss through the sand decrease continues to linearly, that is, the permeability of the sand is constant above the geotextile. Line 4-5 shows there is a head loss across the geotextile. The cause of the head loss across the geotextile may be due to blinding or clogging of the geotextile or may be the head loss of the undisturbed geotextile. Path 2-5-4 is the upper limit for the permeability of the geotextile as a path flatter than 2-5 is inadmissible.

In summary, line 2-5 in Figure 85 represents a zone with constant soil permeability. Zone A, enclosed by 2-3-5 represents a zone of low soil permeability which does not appear possible, whereas zone B enclosed by 2-5-6 represent a zone of high soil permeability which is possible. Path 2-6 and path 2-5 are the lower and upper limits respectively for determining the permeability of the geotextile.The justification in determining which path the head loss line should follow depends on the head loss measurements in the sand-geotextile system, the permeability profile in the sand and the observations during the test. Once the path of head loss in the soil is chosen, the head loss across the geotextile and the absolute permeability of the geotextile can be determined.

7.2 Gradient Ratio Test Results

Armtec is a non-woven needle-punched geotextile made of polyester and polypropylene fibers. Figure 14 shows that at a system hydraulic gradient of 1.0, the system flow rate was fairly constant over a period of 24 hours . When the system hydraulic gradients were increased to 2.5, 5.0 then to 7.5, the system flow rates increased but then decreased as the test continued. Figure 15 shows that a high head loss zone was formed in the top one third of the test sand . The effective hydraulic gradient across the sand-geotextile system was about 1.0 even though the applied system gradients were increased to 7.5. Figure 16 shows that the gradient ratio values for the sand-geotextile system under the applied hydraulic gradients of 1.0 and 2.5 were fairly constant. However, when the applied hydraulic gradient was greater than 2.5, the gradient ratio value dropped. At an applied system gradient of 7.5, the gradient ratio values dropped to about 0.4. This indicates there was movement of sand between manometers #3 and # 1. Figure 17 shows that the absolute permeability of the sand in this region increased from 5 μm^2 to 8 μm^2. This result confirms the existence of a higher permeable filter zone just above the surface of the geotextile fabric. The existence of the filter zone did not result in a high flow rate because there was a blinded zone formed in the top of the specimen which impeded the flow through the system. Piping of the sand was not detected nor observed during the test. It may due to the fact that the test sand contained a maximum of 5% of silt size particles. These silt particles might have washed out of the test sand but were trapped in the geotextile. The amount of particles trapped may have occupied only a small percentage of the openings in the geotextile, therefore, the filtration properties of the geotextile was not affected.

Bidim is a non-woven needle-punched geotextile made of polyester fibers. Figure 18 shows that as the applied system gradients increased the system flow rate decreased rapidly within the first half an hour, then continued to slow down as the test continued. This phenomenon was probably due to a rapid formation of a blinded zone at the top of the sand specimen during the test (Figure 19). The effective hydraulic gradient was 0.7 even though the hydraulic gradient applied to the sand-geotextile system was up to 7.5. Figure 20 shows that the gradient ratio values for the system were about one and Figure 21 shows that the absolute permeability of the sand in the lower two thirds of the sand was 8 μm^2 .

Polyfelt is a non-woven needle-punched geotextile made of polypropylene fibers. Figure 22 shows that at a system hydraulic gradient of 1.0, the system flow rate decreased slowly over a period of 24 hours. When the system hydraulic gradients were increased to 2.5, 5.0 then to 7.5, the system flow rates increased initially but were then decreased as the test continued. These phenomena may also be due to an increase in blinding at the top of the sand specimen during the test (Figure 23). Figure 24 shows that the gradient ratio values for the sand-geotextile system at the applied hydraulic gradients of 1.0 to 7.5 were about one throughout the test period. The absolute permeability of the sand was about 6 μm^2 (Figure 25).

Trevira is a non-woven needle-punched geotextile made of polyester fibers. Figure 26 shows that as the applied hydraulic gradient increased, the system flow rate dropped rapidly over a period of 24 hours. The test was therefore terminated without testing to a system gradient of 7.5. The formation of the blinding layer at the top of the sand specimen is shown on Figure 27. Figure 28 shows that the gradient ratio values for the sand-geotextile system at the applied hydraulic gradients of 1.0 and 2.5 were fairly constant. When the applied hydraulic gradient increased to 7.5, the gradient ratio values dropped slightly to a value of 0.5 indicating the formation of a filter zone. This observation is supported by a increase in the absolute permeability of the sand just above the top of the geotextile to 10 μm^2 (Figure 29).

Bidimrock has a malimo construction with a polypropylene scrim attached to one side of a needle-punched non-woven geotextile made of polyester fibers. Figure 30 shows that at an applied hydraulic gradient of 1.0, the system flow rate decreased slowly over a period of 24 hours. When the system hydraulic gradient was increased to 2.5, the system flow rate increased but dropped rapidly as the test continued. When the system gradients increased to 5.0 and 7.5, the system flow rates decreasing further. Again this phenomenon was due to the rapid formation of a blinding layer at the top of the sand specimen during the test (Figure 31). Figure 32 shows that the gradient ratio values for the sand-geotextile system at an applied hydraulic gradient of 1.0 was about one. However, when the applied hydraulic gradient increased to 2.5, 5.0 then 7.8, the gradient ratio values dropped to about 0.4 indicating there was movement of sand between manometers #3 and # 1. Figure 33 shows that the absolute permeability of the sand in this zone was increased from 6 μm^2 to about 20 μm^2 when the system hydraulic gradients were to higher than 2.5. This result confirms the existence of a permeable filter zone formed just above the surface of the geotextile fabric.

Exxon is a non-woven needle-punched geotextile made of polypropylene fibers. Figure 34 shows that at a hydraulic gradient of 1.0, the system flow rate was fairly constant over a period of 24 hours. When the system hydraulic gradients were increased to 2.5, 5.0 then to 7.5, the system flow rates increased initially but then decreased as the test continued. This phenomenon again was due to an increase in blinding at the top of the sand specimen during the test (Figure 35). Figure 36 shows that the gradient ratio values for the sand-geotextile system were at a value of about 0.7 at different system hydraulic gradients. Figure 37 shows that the absolute permeability of the sand just above the geotextile was slightly increased from 6 μm^2 to 8 μm^2.

Quline is a non-woven needle-punched geotextile made of polyester fibers. Figure 38 shows that at a hydraulic gradient of 1.0, the system flow rate decreased from 0.72 ml/s to about

0.5 ml/s over a period of 24 hours. When the system hydraulic gradient was increased to 2.5, the system flow rate increased but then decreased as the test continued. This Figure 38 also shows that as the applied hydraulic gradient was further increased the flow rate increased initially but then decreased as the test continued. This phenomenon was again due to an increase in blinding at the top of the sand specimen during the test (Figure 39). Figure 40 shows that the gradient ratio values for the sand-geotextile system at the applied hydraulic gradients of 1.0 to 7.5 were constant at a value of about 0.8. The absolute permeability of the sand in this zone remained constant at a value of about 6 μm^2 (Figure 41).

In all of these gradient ratio tests, the formation of a blinded zone in the top of the sand specimen caused a significant drop in the actual hydraulic gradients in the bottom two-thirds of the sand. Consequently, the effects of hydraulic gradient on the filtration properties of the sand-geotextile system could not be studied in detail. However, there is sufficient data for evaluating the filtration properties of the seven selected geotextile fabrics at an effective hydraulic gradient of 1.5 and less.

The changes of the hydraulic conductivity with time for each applied hydraulic gradient for each of the seven geotextile fabrics are plotted and are presented in Appendix A. It is important to note that the hydraulic gradient values show on these Figures are applied hydraulic gradients. The effective hydraulic gradients below the blinded zone were initially equal to the applied hydraulic gradients, but the effective hydraulic gradient decreased as the tests continued. This is because of the formation of an high head loss blinded zone. 7-1 on the figures represents the overall hydraulic conductivity of the sand-geotextile system between manometers 7 and 1. 7-5 on the figures represents the hydraulic conductivity of the blinded zone in the top one-third of the test sand. 5-3 on the figures represents the hydraulic conductivity of the sand zone between manometers 5 and 3. Whereas 3-1 represents the overall hydraulic conductivity of the sand-geotextile zone between manometers 3 and 1.

Flow rate results show that for applied hydraulic gradients of 2.5 or less, the flow rate stabilized in 24 hours. However, when the applied gradient was higher than 2.5, movement of sand particles occurred in the sand and the flow rate did not reach an equilibrium condition in the 24 hour test period. Results indicated that none of the seven selected geotextile fabrics showed signs of uncontrolled sand piping. The test analyses do not indicate any sign of clogging nor blinding of the geotextiles. The average absolute permeability of the sand used in the test was about 6 μm^2. It is concluded that all seven selected geotextile fabrics satisfied both permeability and piping criteria and satisfactorily completed the gradient ratio clogging tests without signs of serious clogging or blinding at effective hydraulic gradients up to1.5.

7.2.1 Selection of Three Geotextile Fabrics for Further Testing

One of the objectives for performing the gradient ratio tests was to identify three geotextile fabrics for full scale filtration, mechanical and environmental durability tests. Results of the gradient ratio tests showed that all seven geotextile fabrics satisfied permeability criterion and did not show signs of serious clogging or blinding effects. Therefore, from the filtration point of view, any of the seven geotextile fabrics could have been selected. In order that only the most likely three geotextile filters were selected, factors other than filtration had to be considered.

The density of the soil in the vicinity of the production wells may vary from dense to loose depending on the well completion techniques. The AOS test results showed that all seven selected geotextile fabrics satisfied the soil retention criterion for dense sand but only Bidimrock, Exxon and Quline satisfied the retention criterion for loose sand.

At high compressive stresses, a thick geotextile fabric has a better transmissivity performance than a thin geotextile fabric. Therefore, the geotextile fabrics selected for further tests should be thick. Thickness measurements indicated that Quline and Exxon were the thickest geotextiles among the seven geotextile fabrics.

In terms of the polymer type and the mechanical properties, Exxon and Quline are made of polypropylene and polyester respectively and have high puncture, burst and tear strengths. Bidimrock is a composite fabric with a scrim construction. It has the highest puncture, burst and tear strengths and the lowest elongation .

In consideration of the gradient ratio test results, the AOS results, the thickness of the geotextiles, the transmissivity, the strengths, the elongation properties, and the necessity of considering different polymers in the study; Exxon, Quline and Bidimrock were chosen for further detailed studies.

7.3 Modified Gradient Ratio Test Results

The gradient ratio cell used was modified because of the problems associated with the original gradient ratio cell (Section 6.3.1). With the use of the modified gradient ratio cell, the filtration properties of the geotextile fabrics under different hydraulic gradients could be studied.

Figure 46 shows that with Bidimrock, the system flow rate increased as the hydraulic gradients through the sand increased. At hydraulic gradients of 0.5 and 1.0, the flow rate stabilized in the 24 hour testing period. However, when the hydraulic gradients through the sand increased higher than 2.5, the flow rates started to decrease slowly but stabilized about 10 hours after the test started. When the hydraulic gradient through the sand reached 10, the flow rate increased but stabilized about 12 hours later. The head loss diagram given on Figure 47 shows that with a 50 mm high uniform quartz sand on top of the test sand, the effect of blinding in the top of the test sand was insignificant. At hydraulic gradients up to 7.5, the head loss through the highly permeable uniform quartz sand zone was almost zero. There was a sign of minor head loss through the quartz sand zone when the hydraulic gradient was 10. Figure 48 shows that the gradient ratio values increased as the system gradients increased. At a hydraulic gradient through the sand of 10, the gradient ratio increased to 1.1 indicating a slight clogging or blinding of the geotextile. Figure 49 shows that the absolute permeability of the sand was about 7 μm^2 and was almost constant throughout the whole testing period.

The system flow rate diagram for Exxon (Figure 50) is similar to that of the Bidimrock. The main difference is that when the hydraulic gradient through the sand was increased to 10, the flow rate remained constant at 6.8 ml/s for about 13 hours and then dropped to 5.5 ml/s at the end of 24 hour test period. The head loss diagram (Figure 51), however, does not show any sign of head loss in the top of the test sand. Head loss across the uniform quartz sand becomes apparent only when the hydraulic gradients through the sand were higher than 5.0. Figure 52 shows that the gradient ratio value stabilized at about 0.9 even when the hydraulic gradients through the sand increased from 0.5 to 10. The absolute permeability of the sand was about 8 μm^2 and was constant through the test (Figure 53). Figure 53 also shows that the sand was loose and more permeable in the beginning of the test but the sand densified as the hydraulic gradients through the sand increased.

Figure 54 is a system flow rate diagram for Quline, it shows that the system flow rate increased as the hydraulic gradients through the sand increased. The system flow rates at each hydraulic gradient remain unchanged throughout the 24 hour test period. The head loss diagram given on Figure 55 does not show any sign of head loss in the top of the test sand. Head loss across the uniform quartz sand becomes noticeable when the hydraulic gradients through the sand were higher than 5.0. Figure 56 shows that the gradient ratio values were about 0.8 for hydraulic gradients of up to 10 and the absolute permeability of the sand was about 8 μm^2 (Figure 57) .

All three test results indicate that with the use of a 50 mm high uniform quartz sand on top of the test sand, blinding did not occur in the test sand. The test sand between manometers #9 to #3 can be considered to be an undisturbed zone. To ascertain the effect of sand on the permeability of the geotextile fabrics, the absolute permeability of each of the three fabrics at different hydraulic gradients was determined by using the technique discussed in Section 7.1. Absolute permeability diagrams for all three fabrics do not show any significant increase in permeability in the sand below manometer #3. As well, no sand piped through the geotextiles. Therefore, the head loss through the sand on top of the geotextiles was assumed to be the linear extension of the head loss line in the undisturbed zone.

The head loss through the geotextile fabrics was determined by extending the head loss lines linearly until they intersected the top of the geotextile (Figures 47, 51 and 55). After the head loss across the geotextile was determined, the absolute permeability of the geotextile was calculated by using equation 22. The calculated absolute permeabilities for all three geotextile fabrics are summarized in Table 7. It is important to point out that for most of the hydraulic gradient tests the head loss line intersected the top of the geotextile at zero head loss indicating that the absolute permeability of the geotextiles were considerably higher than the sand. However, in the preparation of Table 7, the absolute permeability of the geotextile fabrics is conservatively assumed to be equal to the absolute permeability of the sand-geotextile system.

The addition of a layer of uniform quartz sand on top of the test sand has proved to be a major improvement in the testing technique. There is no evidence to indicate the formation of a blinded zone in the top of the test sand and a system hydraulic gradient up to 10 was successfully applied. The test procedure allowed the effect of different hydraulic gradients on the sand-geotextile interaction to be studied.

Flow rate results show that when the hydraulic gradients through the sand are 7.5 or less, the flow rate stabilizes within 24 hours. However, when the applied gradient is higher than 7.5, a 24 hour test period may not be long enough to ensure that a steady flow condition exists.

The changes of the hydraulic conductivity with time for each applied hydraulic gradient for each of the three geotextile fabrics are plotted and are presented in Appendix B. The head loss between manometers 9-10 and 1-2 (Figure 44) was controlled by changing the applied head until the required hydraulic gradient was established. The hydraulic gradient applied was almost equal to the hydraulic gradient through the test sand because there was insignificant head loss in the top of the quartz and test sand. The hydraulic gradient values show on these figures are therefore actual hydraulic gradients through the test sand. 11-1 on the figures represents the overall hydraulic conductivity of the sand-geotextile system between manometers 11 and 1. 9-1 on the figures represents the hydraulic conductivity of the sand-geotextile system between manometers 9 and 1.11-9 on the figures represents the hydraulic conductivity of both the uniform quartz sand and the top one-third of the test sand. 9-7, 7-5 and 5-3 on the figures are the hydraulic conductivity of the sand zone between manometers 9 and 3. Whereas 3-1 represent the overall hydraulic conductivity of the sand-geotextile zone between manometers 3 and 1. It is interesting to observe that the hydraulic conductivities of the test sand were almost independent of the changes in the hydraulic gradient. The exception occurred at the lowest hydraulic gradient where a loose sand layer was compacted and hence changed the hydraulic conductivity. The hydraulic conductivity of the sand changed very slightly but quickly when the hydraulic gradients were changed then remained constant throughout the test.

Test results on the three selected geotextile fabrics did not show any sign of sand piping. Bidimrock test results, however, indicate signs of minor clogging and blinding of the geotextile. The average absolute permeability of the sand used in the test was about 7 μm^2 but the absolute permeability of the geotextiles used in the tests varied from 7 to 10 μm^2. It is concluded that all three selected geotextile fabrics satisfied permeability criterion for steady flow conditions. The absolute permeability of the geotextile is equal to or greater than that of the absolute permeability of the sand, therefore, the three geotextile are acceptable. Exxon and Quline completed gradient ratio clogging tests with no sign of clogging or blinding for hydraulic gradients up to 10. Although test results for Bidimrock showed signs of clogging and blinding, the gradient ratio values were still around one which indicates that this geotextile is still acceptable. There was not a strong indication in the test results that a filter zone existed above the geotextile.

7.4 High Confining Stress Permeability Test Results

The normal absolute permeability of the geotextiles was measured in the high confining stress apparatus without a sand sample. The tests were conducted with either water or oil as the permeant. Figures 63 and 64 show the normal absolute permeability for Bidimrock when water and oil are the permeants. For both permeants, there is a decrease in absolute permeability with an increase in confining stress. The absolute permeability of water through the geotextile ranges between 175 μm^2 at 1.3 kPa to 20 μm^2 at 1300 kPa; and the absolute permeability of oil through the geotextile ranges from 160 μm^2 at 1.3 kPa to 39 μm^2 at 1300 kPa. Bidimrock appears to be slightly more permeable to oil than to water. For both permeants, when the confining stress is unloaded, from 1300 kPa to 100 kPa and then to 1.3 kPa, the original permeability at those confining stress is not recovered. However, there was a greater recovery in permeability upon unloading with oil as the permeant than there was with water.

Similar results were observed with Quline (Figures 65 and 66). This geotextile, which is also polyester, also appeared to be slightly more permeable to oil than to water. The absolute permeability of water through the geotextile ranges between 213 μm2 at 1.3 kPa to 15 μm^2 at 1300 kPa; and the absolute permeability of oil through the geotextile ranges from 247 μm^2 at 1.3 kPa to 22 μm^2 at 1300 kPa.

Figures 67 and 68 show results of the absolute permeability testing for Exxon. The absolute permeability of water ranges between 290 μm^2 at 1.3 kPa to 22 μm^2 at 1300 kPa and the absolute permeability of oil ranges between 122 μm^2 at 1.3 kPa to 6 μm^2 at 1300 kPa. This geotextile, which is polypropylene, is significantly more permeable to water than to oil. Penner (1990) reported that Exxon fibers swelled after immersion in heavy oil. Specimens of Exxon were soaked for 2 days and for 26 days prior to permeability testing to determine if a longer soaking time caused the permeability of the geotextile to oil to decrease even further. The results of these tests are presented in Figures 68 and 69 and are not significantly different from the shorter soaking period test. The possible explanation of this effect is that a layer of oil is rapidly attracted and bound to the surface of these highly oleophilic fibers, thus increasing the viscous resistance to oil flow through the pores.

The absolute permeability of Bidimrock and Quline dropped approximately one order of magnitude in oil and water when the confining stress increased from 1.3 to 1300 kPa. The absolute permeability of Exxon to oil was about 2/3 to that of water at 1.3 kPa an 1/4 to that of water at 1300 kPa. The permeability of the geotextile fabrics appeared to be most affected by the change in porosity resulting from compression, rather than by any wettability effect from the different permeants.

In conclusion, all three geotextile fabrics were highly permeable to both water and oil, but there was a slight difference in absolute permeability between water and oil depending on the fiber type. The polyester fabrics were sightly more permeable to oil and the polypropylene fabric was significantly more permeable to water. The permeability criterion requires a minimum absolute permeability of 3.5 μm^2 for the geotextile under steady state flow conditions but a minimum absolute permeability of 14 μm^2 for unsteady state flow conditions. The two polyester geotextile fabrics comply with this permeability requirement but the polypropylene fabric only had an absolute permeability to oil of 6 μm^2 under a compressive stress of 1300 kPa.

7.5 High Confining Stress Filtration Test Results

The high confining stress filtration test and the modified gradient ratio test are filtration tests to study the sand-geotextile interaction under different hydraulic gradients. One difference between these two tests is that multiple layers of a geotextile fabric compressed to 500 kPa were used in the high confining stress filtration test. In the modified gradient ratio test, only one layer of geotextile fabric was used at a time and the only stress acting on the geotextile was the weight of the test sand. The second difference was on the duration of the test under each hydraulic gradient. ASTM test procedures were followed for the modified gradient ratio test, therefore, the tests were performed for 24 hours for each hydraulic gradient. In the case of the high confining stress filtration tests, the duration of the tests were controlled by whether a steady state filtration condition was reached. For this reason, each high confining stress filtration test lasted for 18 days as 3 days were used for each hydraulic gradient. It is noted that even with all these differences, the high confining stress filtration test results were found compatible with the test results obtained from the modified gradient ratio tests.

The head loss diagrams given on Figures 73, 77 and 81 show that a high head loss zone existed between the top two manometers, even though a layer of uniform quartz sand, about 20 mm thick, was placed on top of the test sand. This phenomenon may have occurred because the uniform quartz sand layer was not thick enough to dissipate the high entrance velocities from the inflowing water through the porous spreader plate. However, the existence of this head loss zone did not affect the test as the hydraulic gradients through the sand still complied with the design hydraulic gradients. This problem was overcome because the hydraulic gradients applied during the tests were controlled by the difference between manometer readings #13 and #19. The applied gradient were not based on the difference between manometer readings #12 and #19.

Figure 72 is the flow rate diagram for Bidimrock which shows the same performance as in the modified gradient ratio test where the system flow rate increased as the hydraulic gradient through the sand increased. At hydraulic gradients up to 2.5, the flow rate stabilized in about 24 hours. However, when the hydraulic gradients through the sand increased to higher than 2.5, it took at least 48 hours for the flow rate to stabilize. Figure 73 shows that the head loss of the sand between manometers #13 to #18 was slightly bilinear. This action may be due to the variation of the sand density in the sand sample. Figure 74 shows that the geotextile fabric was blinded or clogged initially because the sand was placed and compacted directly on top of the fabric. The blinded or clogged zone disappeared when the hydraulic gradient was increased to 2.5. The gradient ratio values dropped from 3.4 to about 1.0. Further increases in hydraulic gradient did not change the gradient ratio. Figure 75 shows that the average absolute permeability of the sand was about 12 μm^2 but the absolute permeability of the sand just above the top of geotextile and the geotextile was about 7 μm^2 indicating that the geotextile was either blinded or clogged (Figure 73).

Figure 76 is the flow rate diagram for Exxon which shows that the system flow rate increased as the hydraulic gradients through the sand increased. At hydraulic gradients up to 2.5, the flow rate stabilized in about 24 hours. However, when the hydraulic gradients through the sand increased to higher than 2.5, the flow rates required at least 48 hours for stabilization. The head loss of the sand between manometers #13 to #18 was linear (Figure 77). Figure 78 shows that when the hydraulic gradient through the sand increased to 2.5, the gradient ratio values increased to about 1.0 from a value of 0.3. This may be caused by the movement of sand particles to the sand zone just above the top of the geotextile or it may be caused by the clogging or blinding of the geotextile. Further increases in hydraulic gradients did not change the gradient ratio. Figure 79 shows that the average absolute permeability of the sand was about 8 μm^2 . The absolute permeability of the sand just above the top of geotextile and the geotextile started at about 50 μm^2 as the hydraulic gradient through the sand increased, it dropped to about 7 μm^2. The sand in this zone may have been initially loose and more permeable, arching may have initially reduced the confining pressure at this depth or the manometer may have misbehaved under the low hydraulic gradients.

Figure 80 is the flow rate diagram for Quline which shows the same performance, that as the hydraulic gradients through the sand increased the system flow rate increased. For hydraulic gradients up to 1.0, the flow rate stabilized in about 24 hours. However, when the hydraulic gradients through the sand increased to higher than 1.0, it took about 48 hours for the flow rate to stabilize. Figure 81 shows that the head loss of the sand between manometers #13 to #18 was again linear. Figure 82 shows that the geotextile fabric was blinded or clogged initially, but the blinded or clogged zone disappeared as the hydraulic gradient through the sand increased. A further increase in hydraulic gradient caused movement of sand but the test soon stabilized at a gradient ratio of about 1.0. Further increases in hydraulic gradient did not change the gradient ratio values. Figure 83 shows that the average absolute permeability of the sand was about 8 μm^2 but the absolute permeability of the sand just above the top of geotextile and the geotextile decreased slightly to about 7 μm^2 indicating that there might be minor blinding or clogging of the geotextile (Figure 81).

All three test results indicate that blinding occurred either in the uniform quartz sand or near the top of the test sand. The head loss diagrams show that this blinded zone was limited in depth. The head loss in the sand below manometer #13 was linear indicating that there was no movement of soil in this zone. The test sand between manometers #13 to #19, therefore, is considered as an undisturbed zone. To ascertain the effect of the sand on the the permeability of the geotextile fabrics, the absolute permeability of each of the three fabrics at different hydraulic gradients was determined by using the technique discussed in Section 7.1. Absolute permeability diagrams for all three fabrics do not show any significant increase in permeability in the sand below manometer #18. As well, no sand piped through the geotextiles. Therefore, the head loss through the sand on top of the geotextiles was assumed to be the linear extension of the head loss in the undisturbed zone.

The changes of the hydraulic conductivity with time for each applied hydraulic gradient for each of the seven geotextile fabrics are plotted and are presented in Appendix C. The same hydraulic gradient controlling method used in the modified gradient ratio test was adopted in this test, therefore, the formation of high head loss zone between manometers 12 and 13 did not affect the actual gradient through the test sand. The hydraulic gradients report on the figures are the actual hydraulic gradient through the test sand between manometers 13 and 19. 12-13 on the figures represents the hydraulic conductivity of the uniform quartz sand and in the top of the test sand between manometers 12 and 13. 13-14, 14-15, 15-16, 16-17, and 17-18 on the figures represent the hydraulic conductivity of the sand between manometers 13-14, 14-15, 15-16, 16-

17, and 17-18 respectively. Whereas 18-19 represents the overall hydraulic conductivity of the sand-geotextile zone between manometers 18 and 19.

The head loss through the geotextile fabrics was determined by linearly extending the head loss lines until they intersected the top of the geotextile (Figures 72, 76 and 80). After the head losses across the geotextiles were determined, the absolute permeability of the geotextiles were calculated by using equation 22. The calculated absolute permeabilities for all three geotextile fabrics are summarized in Table 9. It is important to point out that for some of the Exxon tests the head loss line intersected the top of the geotextile at zero head loss, indicating that the absolute permeability of the geotextile was considerably higher than the sand. However, in the preparation of Table 9, for this condition, the absolute permeability of the geotextile fabric is conservatively assumed to be equal to the absolute permeability of the sand-geotextile system.

The average absolute permeability for Quline, Bidimrock and Exxon are 6 μm^2, 6 μm^2 and 8 μm^2 respectively. The permeability criterion requires a minimum absolute permeability of 3.5 μm^2 for the geotextile under steady state flow conditions and a minimum absolute permeability of 14 μm^2 for unsteady state flow conditions. It is concluded that all three geotextile fabrics complied with the permeability criterion for steady flow conditions. However, none of these three fabrics complied with the permeability criterion for unsteady state flow conditions. As unsteady state flow conditions in oil wells are transitory and exist for only short times, the influence of these low permeabilities may not be significant for oil production. The criterion for unsteady flow requires more investigation.

7.6 Comparison of Test Results

Since the hydraulic gradients through the sand in the gradient ratio tests were less than 1.5 , it is not possible to compare these results with other tests which were tested under higher hydraulic gradients. For this reason, the gradient ratio test results will not be compared with other test results.

The results of the high confining stress filtration tests show the average absolute permeability for Quline, Bidimrock and Exxon are 6 μm^2, 6 μm^2 and 8 μm^2 respectively. These results are slightly lower than the test results obtained from the modified gradient ratio tests where the average absolute permeability for Quline, Bidimrock and Exxon are 10 μm^2, 10 μm^2, and 9 μm^2 respectively (Figure 86). The slight difference in the absolute permeabilities of the geotextile fabrics is likely due to the effect of the high confining stress on the geotextile fabrics and the method used for the compaction of the test sand, in which the sand was placed and was tamped on top of the geotextiles.

In comparing the results from the high confining stress permittivity tests and from the high confining stress filtration tests, results show that under the same conditions of 500 kPa confining stress and the same hydraulic gradients, the absolute permeability of the geotextiles in high confining stress permittivity tests were higher than the absolute permeability of the geotextile in high confining stress filtration tests (Figure 86). It is clearly shown that the presence of sand on top of the geotextile fabrics decreases the absolute permeability of the geotextile fabrics.

7.7 Limitations in the Application of the Test Results

This thesis presents a systematic and a detailed experimental program for the selection of geotextile fabrics for filtering a tailings sand from the McMurray heavy oil formation of the Athabasca Oil Sands in Alberta. The testing program and the test techniques adopted were well planned and were proven. Therefore, the same testing approach can be fully transferred or be adopted for similar filtration studies for any oil well in unconsolidated sands. The AOS tests results, the compressibility results and the high confining stress water permeability test results for the geotextile fabrics tested are not site specific. As these results are considered as basic characteristics of the geotextile fabrics, the use of these results for other purposes is acceptable. However, the results from the gradient ratio tests, the modified gradient ratio tests, the high confining stress oil permeability tests and the high confining stress filtration tests are site specific. The results and conclusions are only applicable to the sand and oil tested. Interpretations of the current test results for other oil reservoir sands may be invalid and therefore not recommended.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The sand used in the testing program is a tailings sand from the McMurray heavy oil formation of the Athabasca Oil Sands in Alberta. The McMurray Formation sand is fine and uniform with a coefficient of uniformity, Cu of 1.8. The density of sand used in the gradient ratio tests ranged from 1.69 to1.70 Mg/m^3. The density of the sand used in the modified gradient ratio tests varied from 1.64 to 1.65 Mg/m^3. Whereas the density of the sand used in the high confining stress filtration tests varied from 1.66 to 1.68 Mg/m^3.

The heavy oil used in the testing program was a low sulphur content crude oil from a Lloydminster heavy oil well. The viscosity of the heavy oil varied from 770 to 1170 kg/m^3 when the temperature varied from 24.0 to 20.8 °C. The density of the heavy oil was 975 kg/m^3 at a temperature of 22°C.

The apparent opening size (AOS) tests were conducted with no normal stress on the fabric. The test results indicate that all seven selected geotextile fabrics satisfy Giroud's retention criterion for dense sand. If the formation is in a medium dense state, all geotextile fabrics, except Trevira, satisfy the retention criterion. However, if the formation is loose, only Bidimrock, Exxon and Quline satisfy Giroud's retention criterion.

The gradient ratio filtration tests were performed under zero compressive stress and water was used as the permeant. Test results show that the effect of blinding at the top of the soil sample was substantial, the effective hydraulic gradients through the remainder of the sand-geotextile system dropped to 1.5 or less, even when the applied hydraulic gradients were increased to 7.5. The flow rate results show that for applied hydraulic gradients of 2.5 or less, the flow rate stabilized in 24 hours. However, when the applied gradient was higher than 2.5, movement of sand particles occurred in the sand and the flow rate did not reach an equilibrium condition in the 24 hour test period. Results indicated that none of the seven selected geotextile fabrics showed signs of uncontrolled sand piping. The test analyses do not indicate any sign of clogging nor blinding of the geotextiles. The average absolute permeability of the sand used in the test was about 6 μm^2. It is concluded that all seven selected geotextile fabrics satisfied both Giroud's permeability and piping criteria and satisfactorily completed the gradient ratio clogging tests without signs of serious clogging or blinding at effective hydraulic gradients up to1.5.

Exxon, Quline and Bidimrock were chosen for detailed filtration, mechanical and environmental studies because they were the only geotextile fabrics which satisfied Giroud's retention criterion for loose to dense sand. Quline and Exxon were the thickest geotextiles among the seven geotextile fabrics and therefore have better transmissivity performance at high compressive stresses. Also all three geotextiles have high puncture, burst and tear strengths. Bidimrock also has the lowest elongation properties among all fabrics. The other reason for the selection of these three fabrics was because Exxon is made of polypropylene, Quline is made of polyester and Bidimrock is made of both polypropylene and polyester; hence the influence of polymer types can be evaluated.

The filtration performance of the sand and the sand-geotextile system could not be studied in detail in the gradient ratio tests because of the formation of the blinded zone at the top of the test sand and the height of the test samples were only 76 mm. The gradient ratio cell was therefore modified by increasing the height of the test sample to 127 mm, by the addition of 4 more manometers in the test sample, and a layer of uniform quartz sand, 50 mm thick, was placed on top of the test sand. With the use of the modified gradient ratio cell, the filtration properties of the geotextile fabrics under different hydraulic gradients could be studied.

The modified gradient ratio tests were performed under zero compressive stress and water was used as the permeant. All three test results indicate that with the use of a 50 mm high uniform quartz sand on top of the test sand, blinding did not occur in the test sand and hydraulic gradients of up to 10 were successfully applied. Flow rate results show that when the hydraulic gradients through the sand are 7.5 or less, the flow rate stabilizes within open area. However, when the applied gradient is higher than 7.5, a 24 hour test period may not be long enough to ensure that a steady flow condition exists. Test results on the three selected geotextile fabrics show an undisturbed zone existed. As well, no sand piped through the geotextiles. Bidimrock test results, however, indicate signs of minor clogging and blinding of the geotextile. The average absolute permeability of the sand used in the tests was about 7 μm^2 but the absolute permeability of the geotextiles used in the tests varied from 7 to 10 μm^2. It is concluded that all three selected geotextile fabrics satisfied Giroud's permeability criterion for steady flow conditions and therefore, the three geotextile are acceptable. Exxon and Quline completed gradient ratio clogging tests with no sign of clogging or blinding for hydraulic gradients up to 10. Although test results for Bidimrock showed signs of clogging and blinding, the gradient ratio values were still around one which indicates that this geotextile is still acceptable. There was not a strong indication in the test results that a filter zone existed above the geotextile. The modified gradient ratio test also confirmed that the results obtained from the gradient ratio tests are valid.

In the geotextile compressibility tests, four layers of Bidimrock, three layers of Exxon and two layers of Quline were tested independently. The results indicate that at a maximum compressive stress of 1300 kPa, the porosities of Quline and Exxon were decreased from about 86% to about 61% and the porosity of Bidimrock was decreased from 74% to about 56%. Even though the porosities for Exxon, Quline and Bidimrock were decreased with the increase in normal compressive stress, the final porosities for all three geotextile fabrics were still larger than 30%. Therefore, Giroud's porosity criterion for nonwoven geotextile fabrics was still satisfied by all three fabrics under a stress of 1300 kPa.

Approximately 90% of the change in fabric thickness occurred at a compressive stress of 500 kPa for all three geotextiles. A confining stress of 500 kPa was therefore selected for the subsequent high confining stress permeability and filtration tests.

The normal absolute permeability of the geotextiles was measured in the high confining stress apparatus under a compressive stress of 500 kPa without a sand sample. The tests were conducted with either water or oil as the permeant. When the confining stresses applied to the fabrics increased, there was a decrease in the absolute permeability of the fabrics. The test results show all three geotextile fabrics were highly permeable to both water and oil, but there was a slight difference in absolute permeability between water and oil depending on the fiber type. The polyester fabrics were sightly more permeable to oil and the polypropylene fabric was significantly more permeable to water. All three geotextile fabrics comply with Giroud's permeability requirement for both steady and unsteady flow conditions except Exxon only had an absolute permeability to oil of 6 μm^2 under a compressive stress of 1300 kPa.

In the high confining stress filtration test a compressive stress of 500 kPa was applied on the sand-geotextile system and water was used as the permeant. All three test results indicate that blinding occurred either in the uniform quartz sand or near the top of the test sand. The head loss diagrams show that this blinded zone was limited in depth. An undisturbed zone was detected just underneath the blinded zone.The average absolute permeability for Quline, Bidimrock and Exxon were 6 μm^2, 6 μm^2 and 8 μm^2 respectively. All three geotextile fabrics complied with Giroud's permeability criterion for steady flow conditions, however, none of these three fabrics complied with the permeability criterion for unsteady state flow conditions. As unsteady state flow conditions in oil wells are transitory and exist for only short times, the influence of these low permeabilities may not be significant for oil production in the field.

Results indicate the high confining stress filtration tests give a lower geotextile absolute permeability than the modified gradient ratio test. The slight difference in the absolute permeabilities of the geotextile fabrics is likely due to the effect of the high confining stress on the geotextile fabrics and the method used for the compaction of the test sand, in which the sand was placed and was tamped on top of the geotextiles. Comparison of high confining stress permeability and filtration tests indicates that the presence of sand on top of the geotextile fabrics decreases their absolute permeability.

The three geotextile fabrics initially were selected based on Giroud's permeability, soil retention and porosity criteria. Test results show that all three fabrics have excellent permeability and filtration performance for McMurray Formation sand. Giroud's geotextile filter design criteria are therefore applicable for the design of a geotextile filter for McMurray Formation sand. It is therefore concluded that any of these three geotextile fabrics could be used for a full scale field test.

8.2 Recommendations

The results of the permeability and filtration tests are excellent for all three geotextiles. Based on these results, future research toward the development of geotextile filters will include the following recommendations.

First, the geotextiles may have filtered the McMurray Formation sand too efficiently. They appeared to prevent any piping of the sand through the geotextile. Although no significant clogging of the geotextiles occurred in the laboratory tests, clogging may develop with time in the field if no fines can pass through the filter. Similar filtration-permeability tests should be conducted on geotextile filter materials that have larger pore size. Such filter fabrics should allow some piping of very fine particles to occur and should reduce the chance of clogging.

Second, filtration testing should be conducted to examine the difference in interaction between the polyester and polypropylene geotextiles with the heavy oil. The testing would determine if the behavior of these geotextiles is significantly different to affect the functioning of a well filter and would examine whether the effects on permeability are functions of the fiber type , the fabric structure or some combination of the two.

Third, a search should be conducted for a coarse geotextile to use as a transition material between the filter fabric and the sand. The benefits of a transition material have been suggested to us by other researchers based on recent experience with geotextiles in the field.

Fourthly, the high confining stress filtration test results indicate that none of the three geotextile fabrics complied with Giroud's permeability criteria for unsteady flow conditions. The criterion for unsteady flow therefore requires more investigation.

Based on the results of the above recommended research, a geotextile filter system could be designed and fabricated for a field trial in a heavy oil well under primary production.

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TABLE 1: Dimensionless Coefficient, λ_p, for the Permeability Criteria (adapted from Giroud 1988)

Author	λ_p	Remarks
Giroud (1982)	0.10	
Giroud (1988)	i_s	
FHWA	1	for small gradients and stable soils
FHWA	10	for large gradients and unstable soils
CFGG	$10^3\ T_g$	for ordinary drainage system and clean soil
CFGG	$10^4\ T_g$	for ordinary drainage system and low permeability soils
CFGG	$10^5\ T_g$	for drainage system where a high safety is required

where T_g = thickness of geotextile (m)

i_s = hydraulic gradient in the soil

TABLE 2 : Dimensionless Coefficients, λ_R, for Retention Criteria

(adapted from Giroud , 1988)

Giroud (1982)		1 < Cu < 3	Cu > 3
Soil Density	Loose	$Cu^{0.3}$	$9Cu^{-1.7}$
	Dense	$2Cu^{0.3}$	$18Cu^{-1.7}$

FHWA (1985)	1 < Cu < 2	2 < Cu < 4	4 < Cu < 8	Cu > 8
All soils	1.0	0.5Cu	8/Cu	1.0

CFGG (1986)	1 < Cu < 4			Cu > 4		
	i < 5	5 < i < 20	20 < i < 40	i <5	5 < i < 20	20 < i < 40
Soil loose or unconfined	0.64	0.51	0.38	0.8	0.64	0.48
Soil dense or confined	1.00	0.8	0.6	1.25	1.00	0.75

Notes: Cu = uniformity coefficient

i = hydraulic gradient

TABLE 3 - Characteristics of the Heavy Oil (adapted from Norcen, 1989)

Viscosity	770 mPa.s at 24°C
	11700 mPa at 20.8°C
Density	975 kg/m^3 at 22°C
Carbon Content	75.3%
Hydrogen Content	10.6%
Nitrogen Content	6.4%
Oxygen Content	10.2%
Sulphur Content	2.7%

TABLE 4: Properties of the Seven Selected Geotextile Fabrics
(data provided by the manufacturers)

Geotextile Fabric Properties	Exxon P0820	Polyfelt TS700	Trevira 1135	Bidim B5	Bidimrock TTNT 200/500	Quline Q200	Armtec 7605
hydraulic permeability (cm/s)	0.2	0.50	0.52	0.58	0.49	1.19	0.59
permittivity (s-1)	0.93	1.87	1.36	2.40	1.86	2.04	3.10
porosity (%)	86	88	93	93	78	92	90
mass per unit area (g/m^2)	271.2	281.4	356	220	800	678	175
thickness (mm)	2.16	2.67	3.81	2.40	2.66	5.84	1.9
AOS/EOS/O_{95} (mm)	0.212-0.15	0.09	0.212-0.125	0.20	0.120	0.125-0.09	–
transmissivity (cm^2/s)	0.043	0.134	0.20	0.069	0.042	0.69	–
puncture strength (N)	489	534	689.5	489	–	1090	–
burst strength (MPa)	2.41	2.30	3.8	2.07	–	4.65	1.1
tear strength (N)	356	–	128	440	6400	1112	–
grab strength (N)	890	1001	1550	1100	200kN/m	2224	–
elongation (%)	70	50-90	80	80	12	90	36
fabric construction	NF	NF	NF	NF	NFN	NF	NF
fabric type	PP	PP	PE	PE	PP/PE	PE	PP/PE

NF - needlefelted
NFN - needlefelted with net
PE - polyester
PP - polypropylene
PP/PE - polypropylene / polyester

TABLE 5 : Filtration Testing Program for the Selected Geotextile Fabrics

Geotextile Fabric	Exxon P0820	Polyfelt TS700	Trevira 1135	Bidim B5	Bidimrock TTNT 200/500	Quline Q200	Texel 7605
Fabric type	PP	PP	PE	PE	PP/PE	PE	PP/PE
Type of Test							
Apparent Opening Size (Fabric only)	X	X	X	X	X	X	X
Gradient Ratio Test (sand/geotextile)	X	X	X	X	X	X	X
Modified Gradient Ratio Test (sand/geotextile)	X				X	X	
Compressibility Test (geotextile only)							
- single layer	X				X	X	
- multi layers	X				X	X	
Permittivity Test (geotextile only)							
- water	X				X	X	
- heavy oil	X				X	X	
High pressure Filtration Test (sand/geotextile) - water	X				X	X	

Notes:

"X" denotes tests carried out

PE - polyester

PP - polypropylene

PP/PE - polypropylene / polyester

TABLE 6 : Apparent Opening Sizes of the Selected Geotextiles

Geotextile	Fiber Type	Manufacturer's AOS (mm)	Measured AOS (mm)	Standard Sieve Size
Trevira 1135	PE	0.210	0.412	40
Bidim B5	PE	0.200	0.300	50
Bidimrock TTNT 200/500	PP/PE	0.120	0.110	140
Quline Q200	PE	0.150	0.150	100
Exxon P0820	PP	0.212 - 0.150	0.110	140
Polyfelt TS700	PP	0.125 - 0.180	0.300	50
Armtec	PP/PE	0.750 - 1.25	0.300	50

PP = Polypropylene

PET = Polyester

TABLE 7 : Absolute Permeability of Geotextiles in the Modified Gradient Ratio Test (No Confining Stress)

Geotextile Type	Applied System Gradien	Geotextile Thickness (mm)	Head Loss across the Geotextile (mm of water)	Absolute Permeability of Geotextile (μm2)
Quline (one layer)	10	4.24	0	9
	7.5	4.24	0	10
	5.0	4.24	0	10
	2.5	4.24	0	10
	1.0	4.24	0	10
	0.5	4.24	0	10
Bidimrock (one layer)	10	2.54	10	10
	7.5	2.54	7	10
	5.0	2.54	5	10
	2.5	2.54	0	8
	1.0	2.54	0	10
	0.5	2.54	0	10
Exxon (one layer)	10	3.02	0	7
	7.5	3.02	0	7
	5.0	3.02	0	8
	2.5	3.02	0	8
	1.0	3.02	0	10
	0.5	3.02	0	11

Note: It is assumed that if the head loss across the geotextile is zero, the absolute permeability of the geotextile is equal to the average absolute permeability of the sand - geotextile zone. This zone is defined as a zone between the manometer which is just above the top of the geotextile and the manometer which is at the bottom of the geotextile.

TABLE 8 : Absolute Permeability of Geotextiles in the High Confining Stress Permittivity Test

		Water as Permeant		Oil as Permeant soaked for 2 days		Oil as Permeant soaked for 26 days	
Geotextile Type	Confining Stress (kPa)	Thickness (mm)	Absolute permeability (μm2)	Thickness (mm)	Absolute permeability (μm2)	Thickness (mm)	Absolute permeability (μm2)
Quline (2 layers)	1.3	9.26	213 - 233	9.20	247 - 306	-	-
	100	5.07	43 - 58	5.11	56 - 91	-	-
	500	3.31	23 - 26	3.42	29 - 40	-	-
	1300	2.67	15 - 17	2.82	22 - 23	-	-
	100U	3.73	23 - 25	3.35	24 - 28	-	-
	1.3U	3.85	36 - 37	4.66	39 - 50	-	-
Bidimrock (4 layers)	1.3	9.77	175 - 185	9.35	160 - 240	-	-
	100	7.52	65 - 68	7.32	73 - 101	-	-
	500	6.12	27 - 33	5.98	52 - 57	-	-
	1300	5.46	20 - 29	5.36	39 - 45	-	-
	100U	5.99	23 - 24	6.00	52 - 53	-	-
	1.3U	7.01	32	6.76	68 - 81	-	-
Exxon (3 layers)	1.3	8.05	290 - 295	8.48	122 - 238	8.48	113 - 171
	100	3.94	75	4.08	36 - 45	4.09	21 - 36
	500	2.66	33 - 39	2.72	10 - 12	2.57	7 - 13
	1300	2.24	22 - 27	2.35	6	2.10	5 - 7
	100U	2.68	28 - 31	2.82	6 - 8	2.71	5 - 7
	1.3U	3.93	65 - 67	3.95	10 - 15	3.74	12 - 17

Note: 100U denotes unloading to 100 kPa

TABLE 9 : **Absolute Permeability of Geotextiles in the High Confining Stress Filtration Test (500 kPa Confining Stress)**

Geotextile Type	Applied System Gradient	Geotextile Thickness (mm)	Head Loss across the Geotextile (mm of water)	Absolute Permeability of Geotextile (μm2)
Quline (2 layers)	10	3.27	50	5
	7.5	3.27	50	4
	5.0	3.27	22	6
	2.5	3.27	10	7
	1.0	3.27	4	8
	0.5	3.27	5	3
Bidimrock (4 layers)	10	6.66	95	6
	7.5	6.66	65	7
	5.0	6.66	58	5
	2.5	6.66	30	6
	1.0	6.66	20	4
	0.5	6.66	10	4
Exxon (3 layers)	10	3.12	63	4
	7.5	3.12	0	8
	5.0	3.12	0	9
	2.5	3.12	25	3
	1.0	3.12	0	60
	0.5	3.12	0	50

Note: It is assumed that if the head loss across the geotextile is zero, the absolute permeability of the geotextile is equal to the average absolute permeability of the sand-geotextile zone. This zone is defined as a zone between the manometer which is just above the top of the geotextile and the manometer which is at the bottom of the geotextile.

Figure 1: Distribution of Heavy Oil and Oil Sand Deposits of Alberta

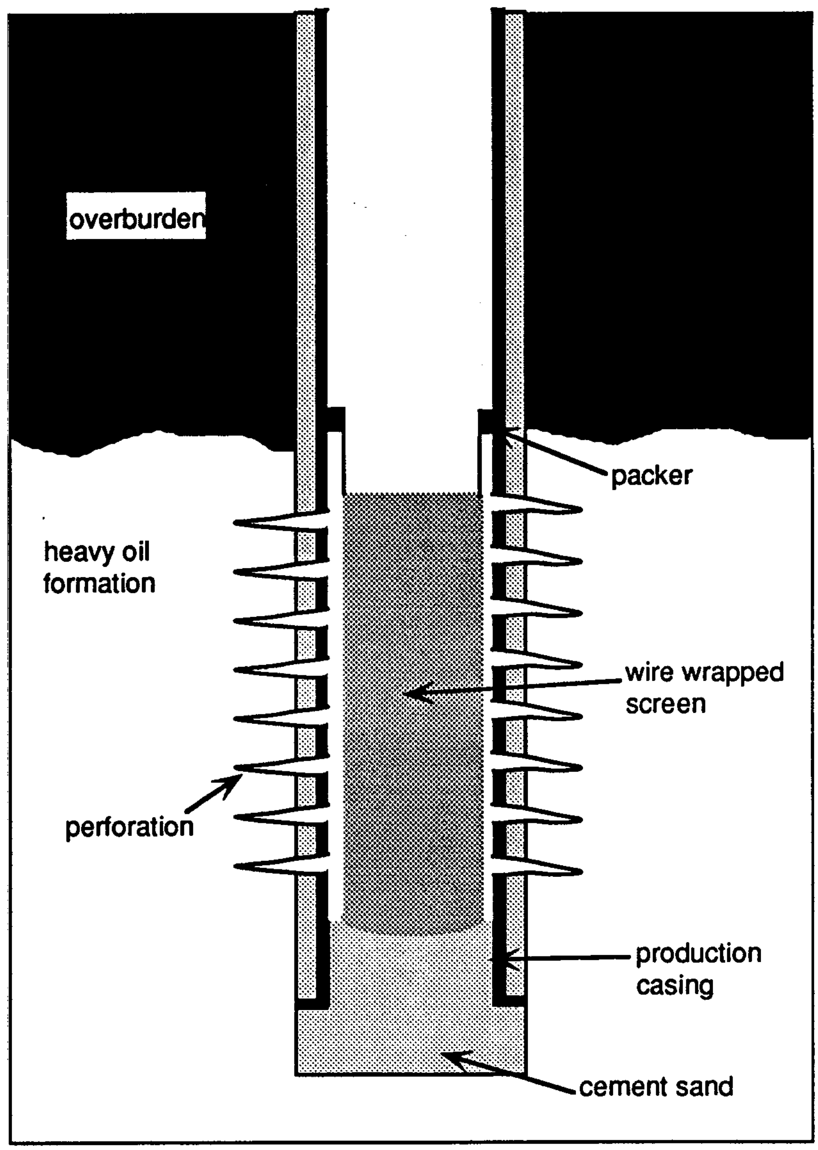

Figure 2: Perforated Casing Well Completion with Wire Wrapped Screen

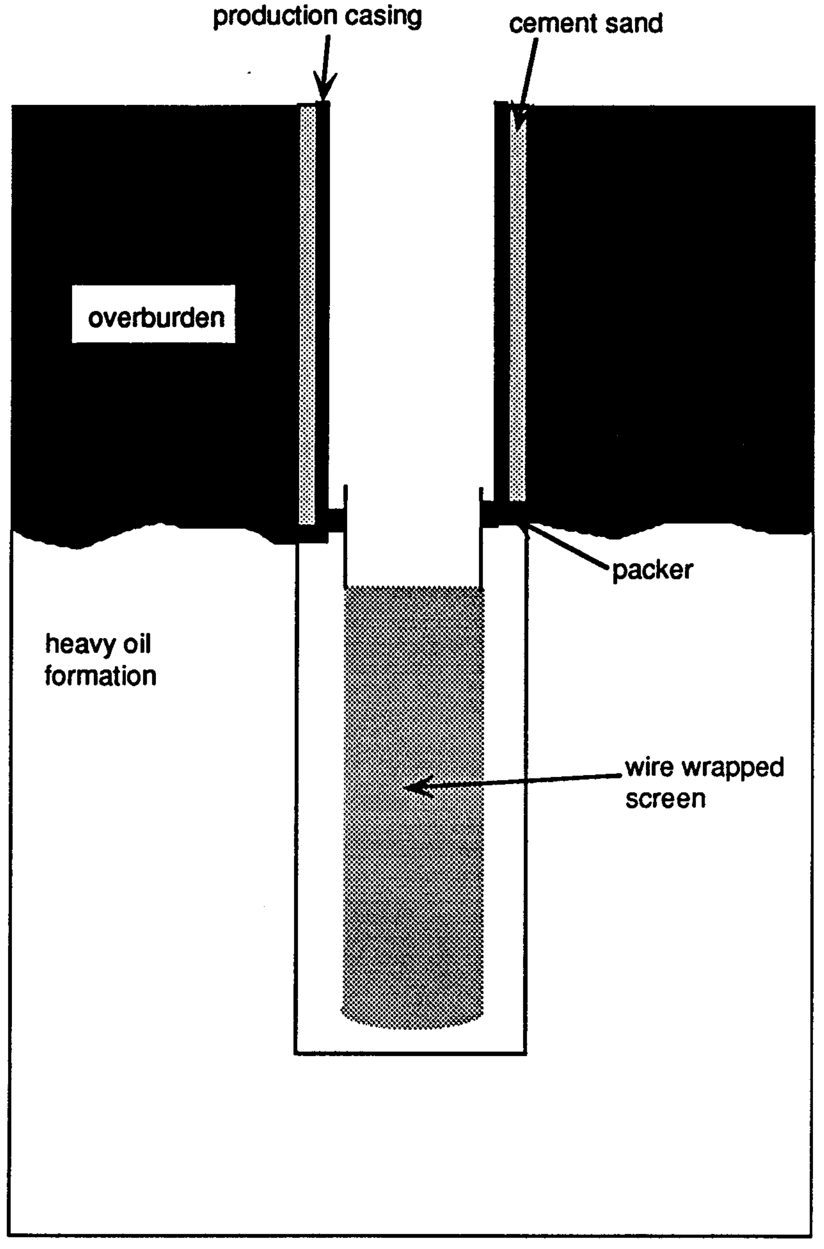

Figure 3: Open Hole Well Completion with Wire Wrapped Screen

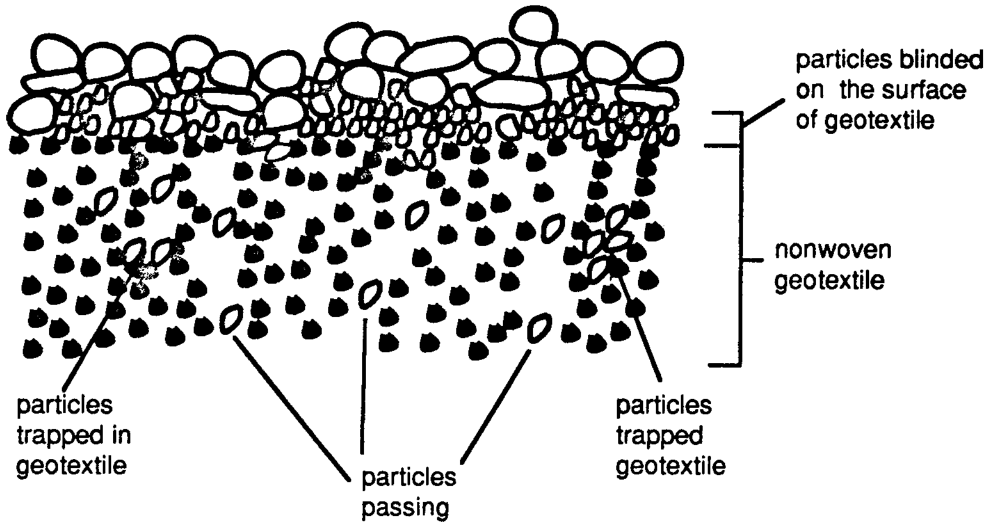

Figure 4: Blinding and Clogging of Geotextiles

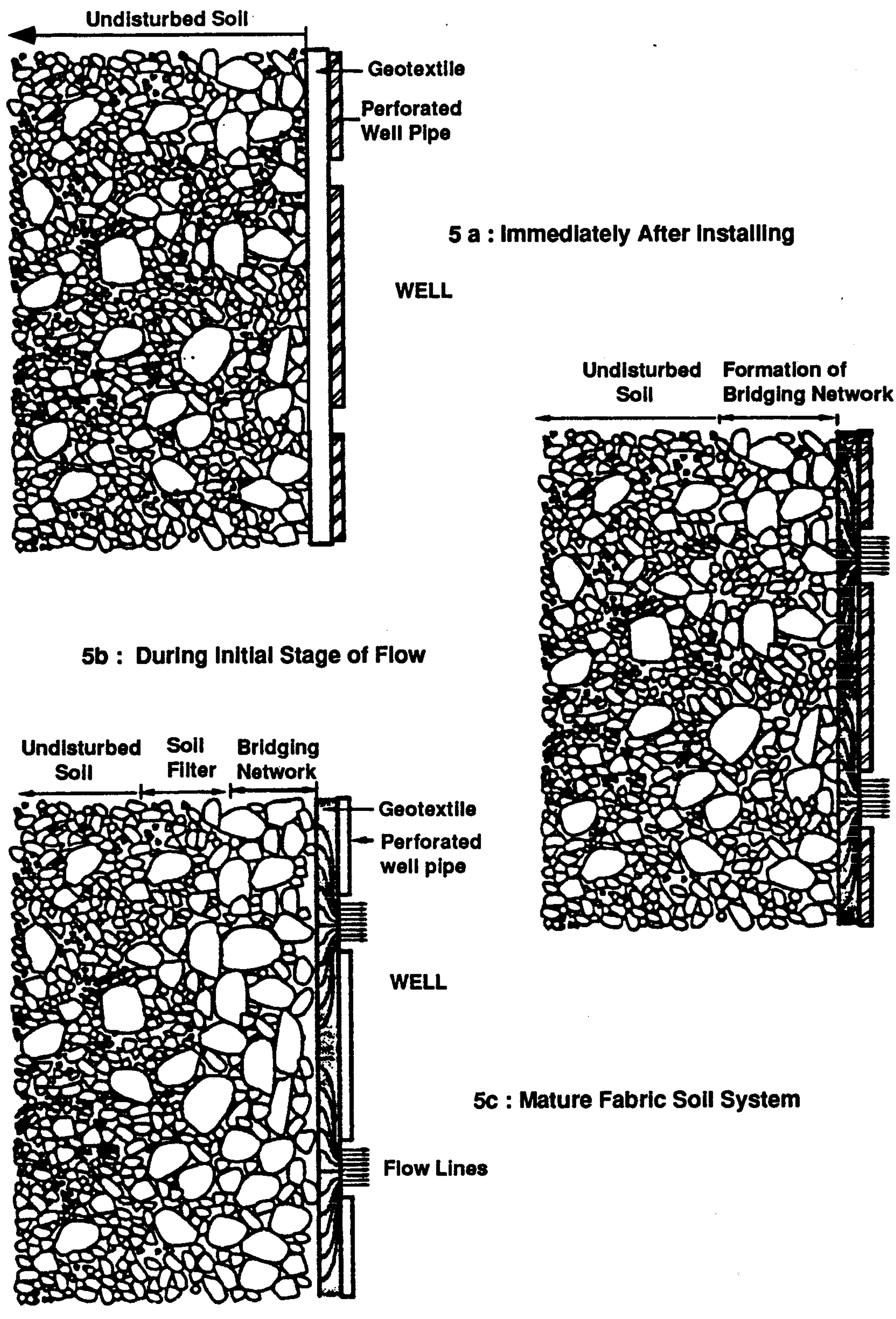

Figure 5 : Soil - Geotextile Interaction on Filtration Properties

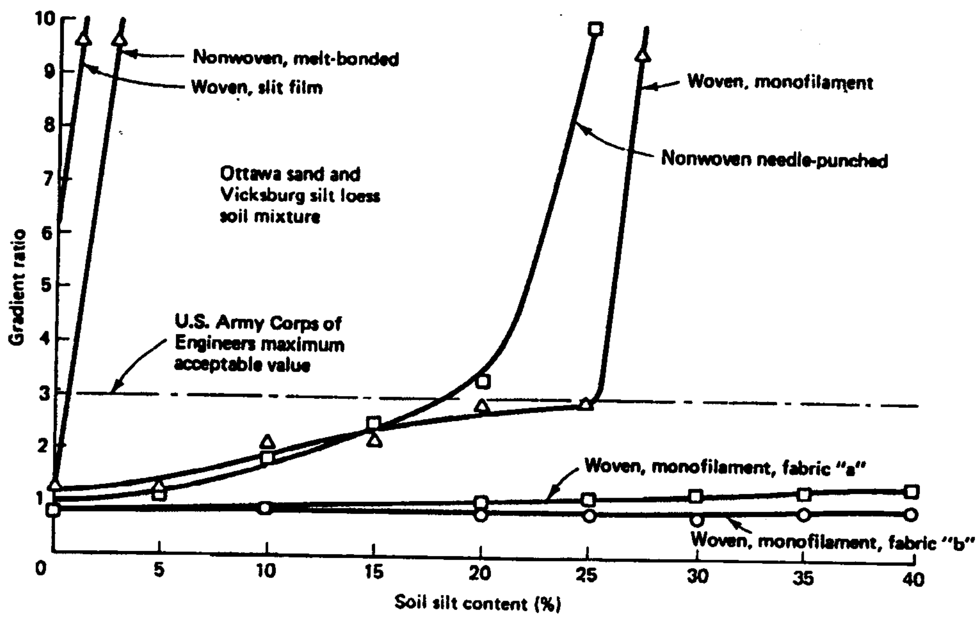

Figure 6 : Gradient Ratio as a Function of Soil Silt Content for Geotextile Tested (from Haliburton & Wood, 1982)

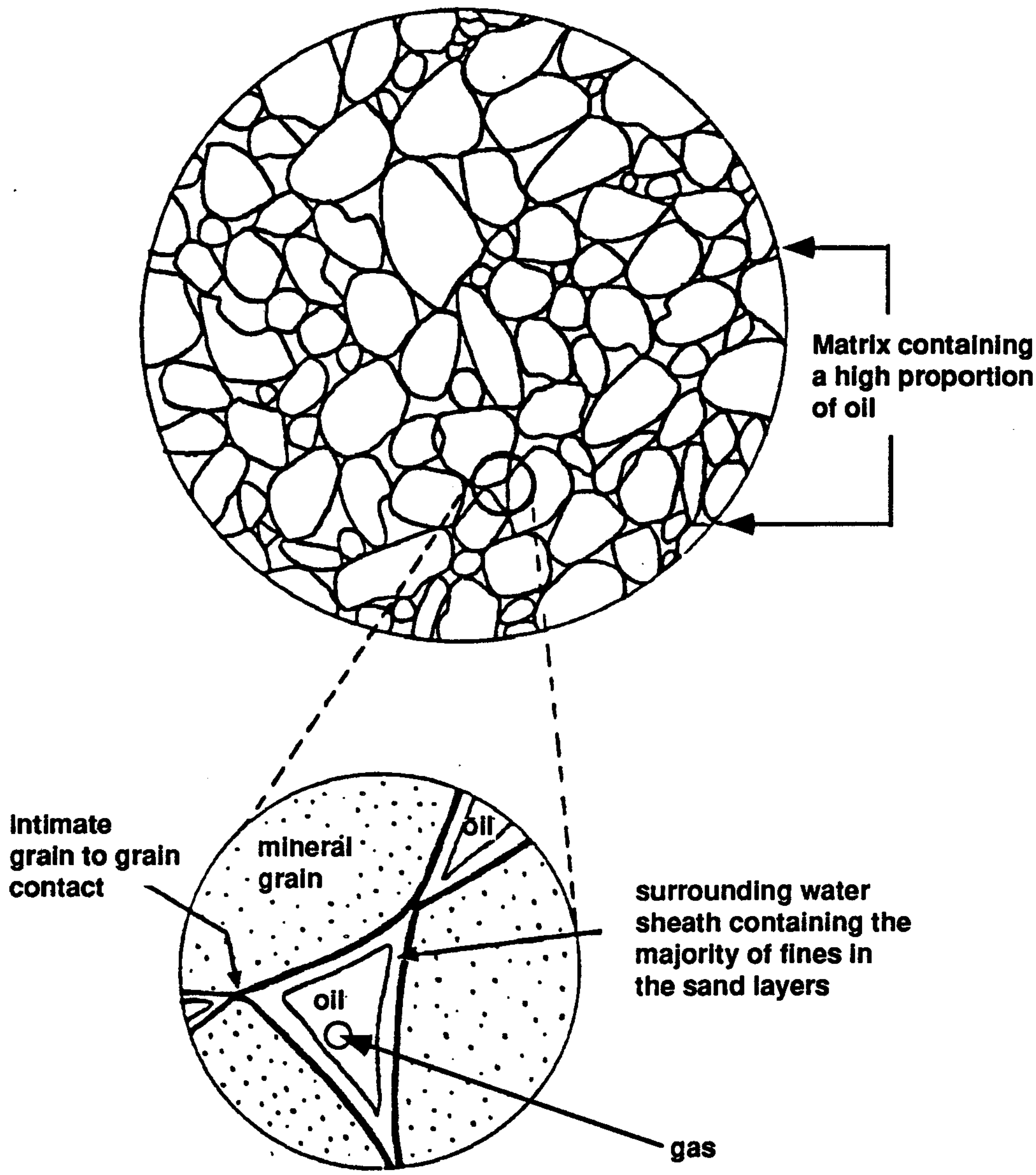

Figure 7 : In-situ Structure of Oil Sand

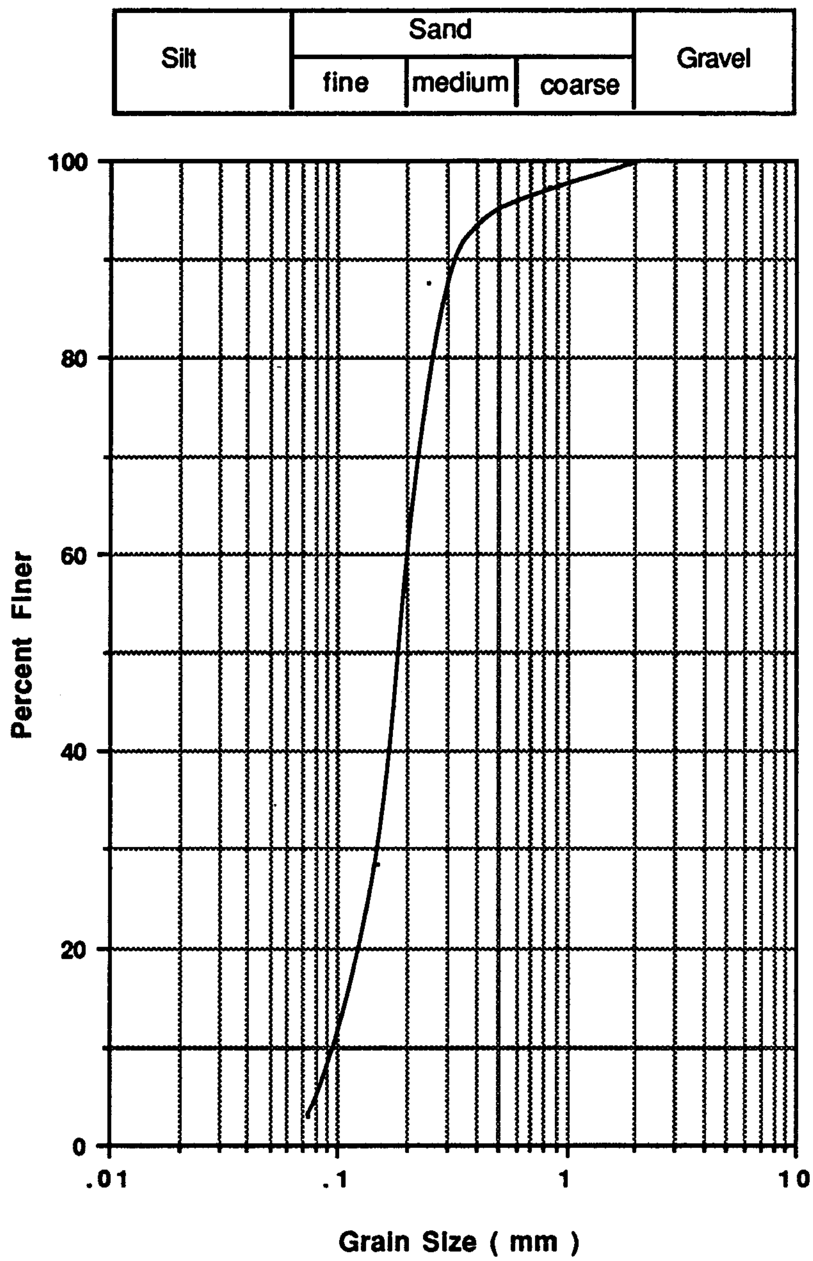

Figure 8: Grain Size Distribution of McMurray Formation Sand

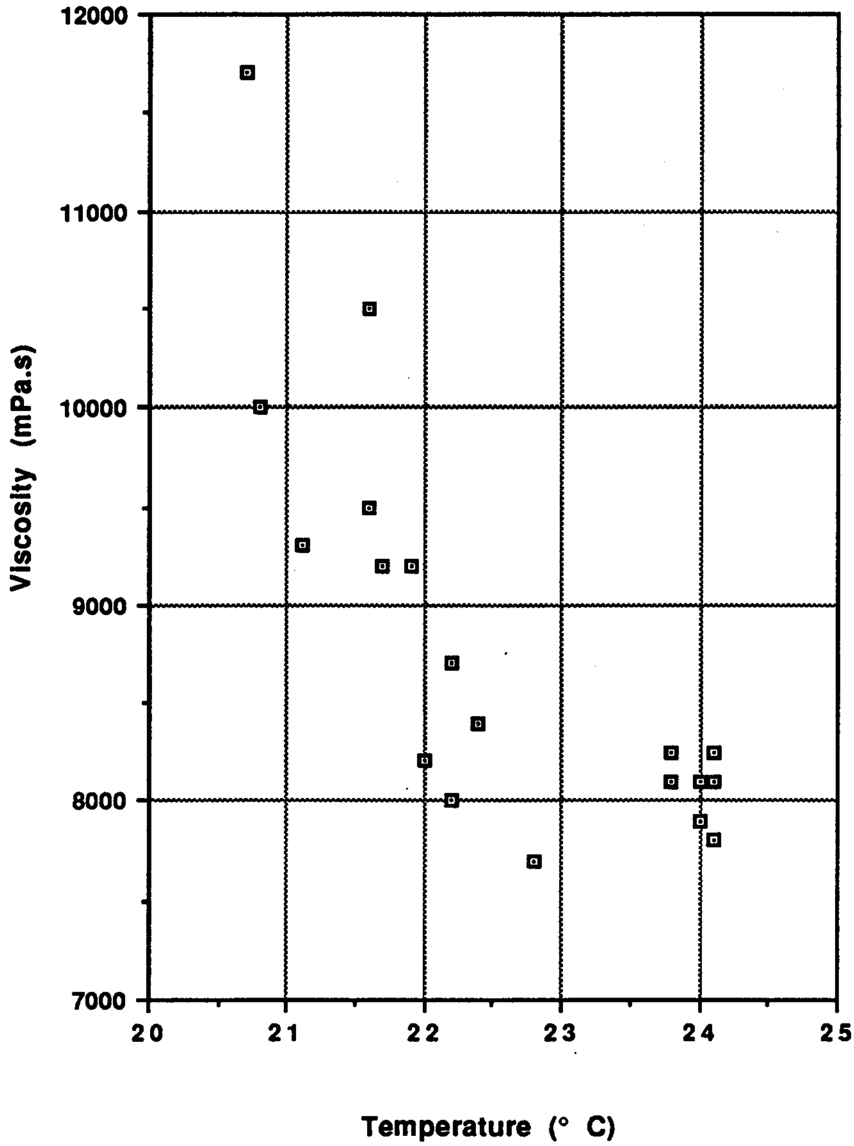

Figure 9 : Effect of Temperature on Viscosity (Lloyminister Heavy Oil)

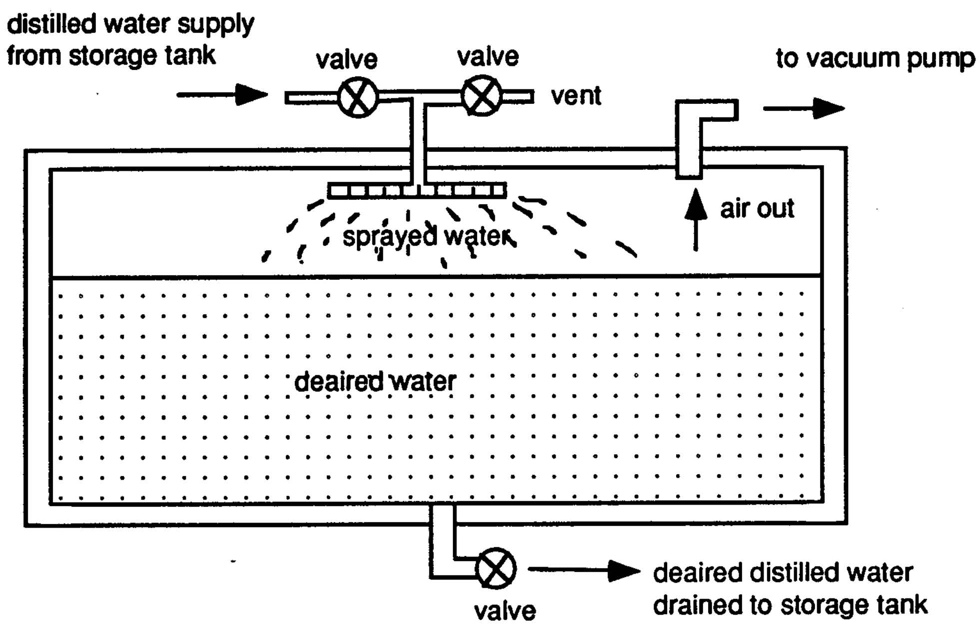

Figure 10 : Sectional View of a Water Deairing Device

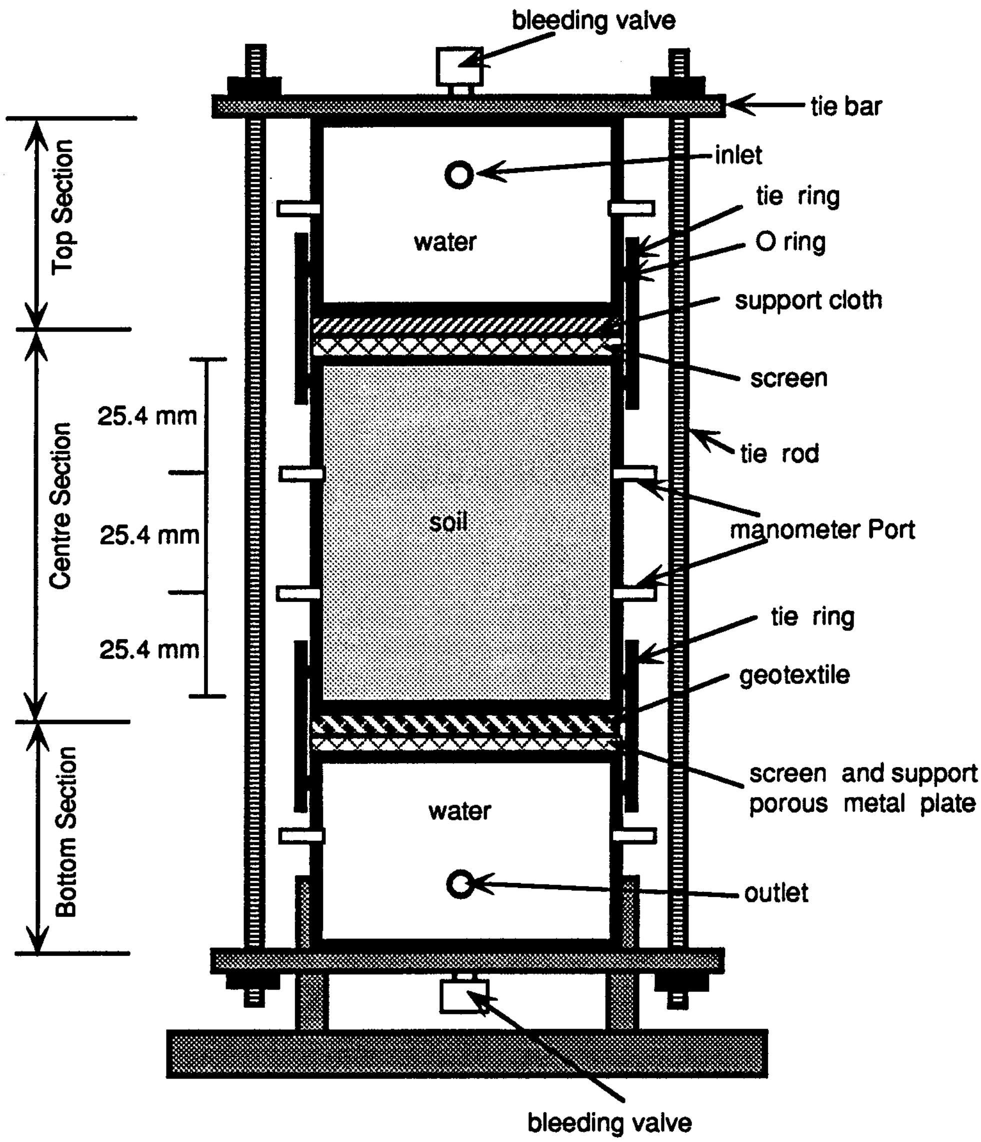

Figure 11 : Sectional View of the Gradient Ratio Apparatus

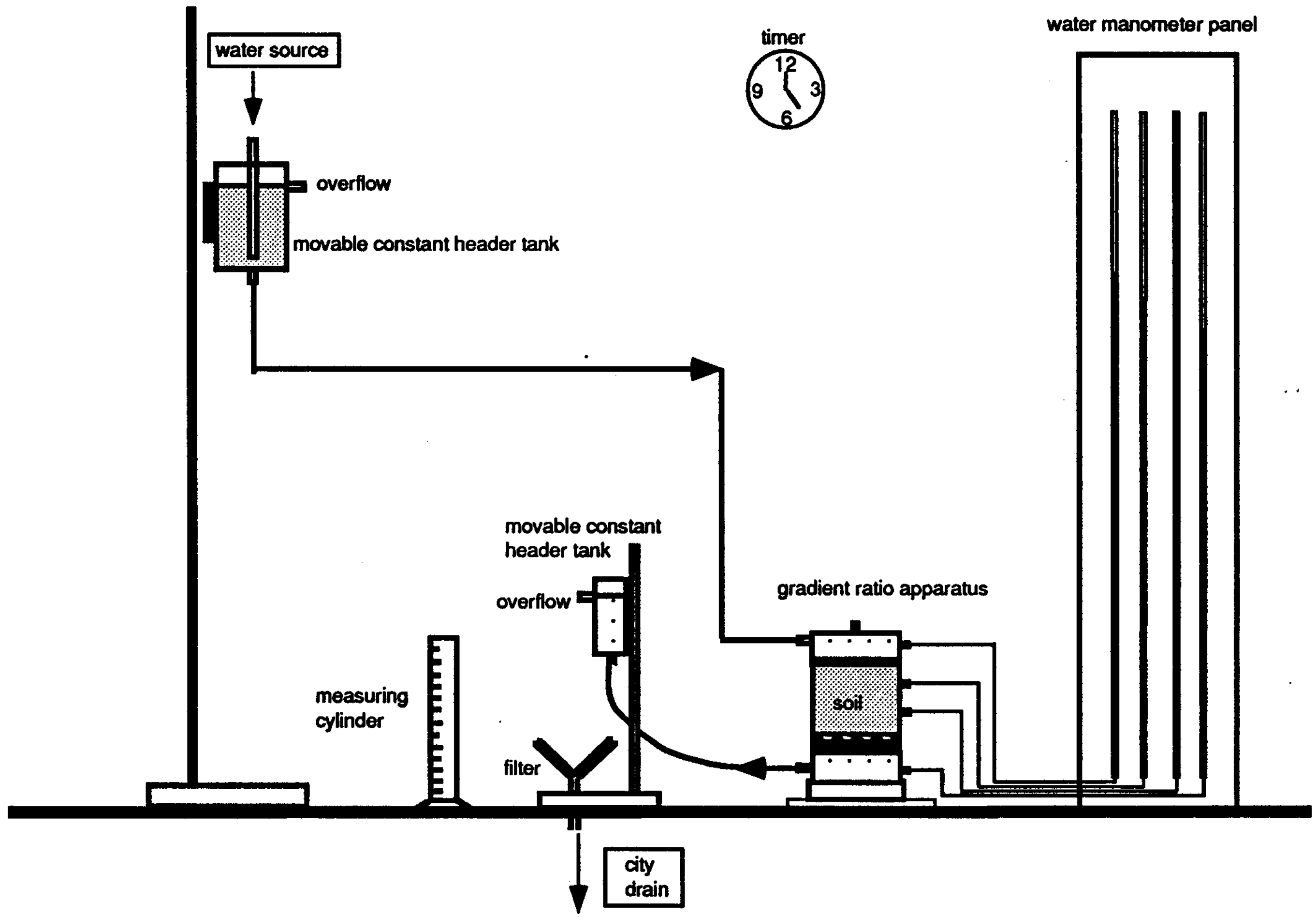

Figure 12 : System Layout for Gradient Ratio Test

$$\text{Gradient Ratio} = \frac{\frac{dhsf}{Lsf}}{\frac{dhs}{Ls}}$$

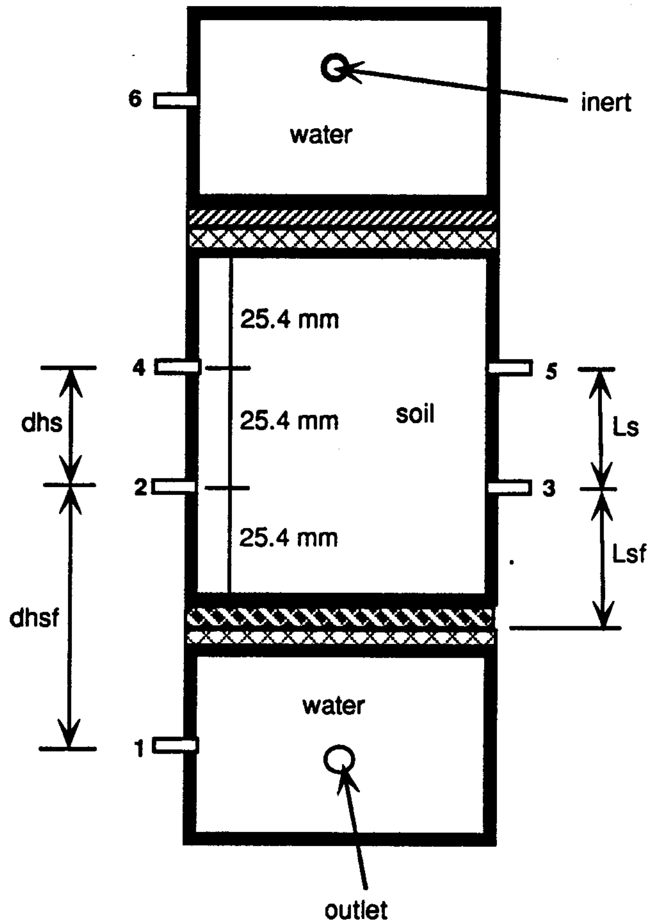

Figure 13 : Values of Gradient Ratio Calculations for the Gradient Ratio Apparatus

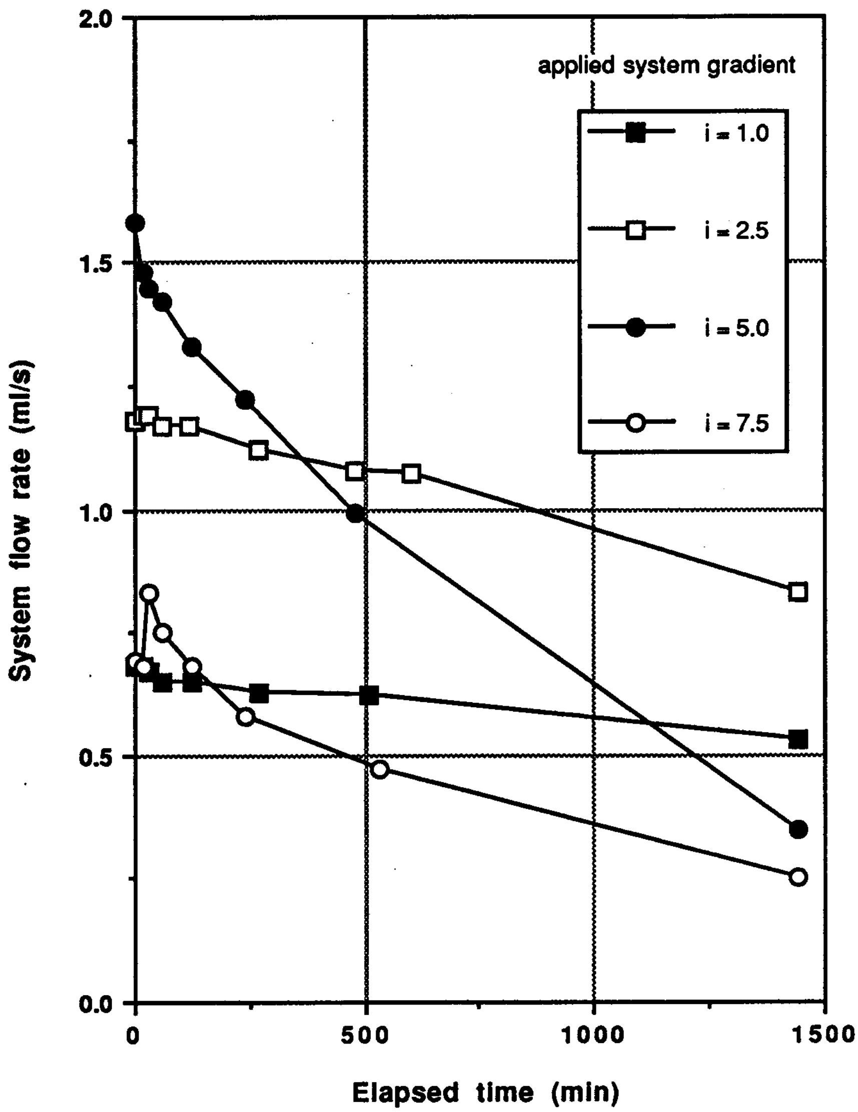

Figure 14 : Flow Rate for Armtec in Gradient Ratio Test

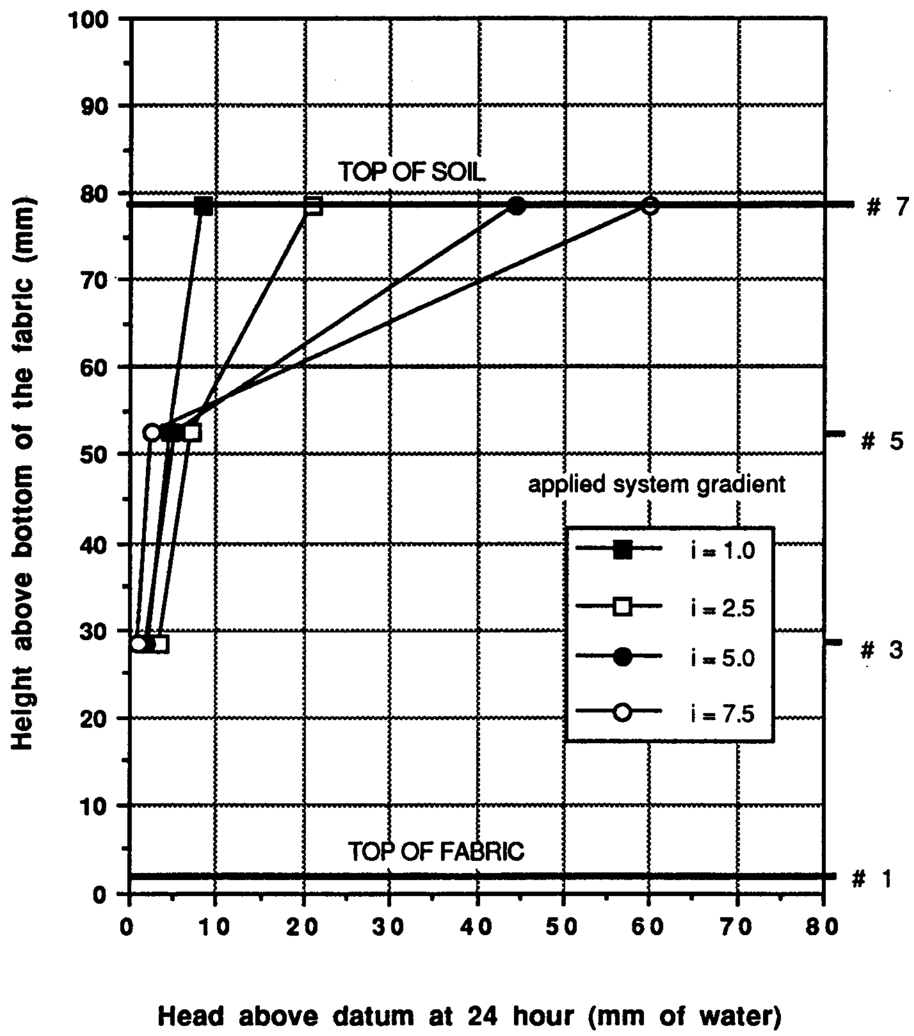

Figure 15 : Head Loss in the Sand-Geotextile System for Armtec in Gradient Ratio Test

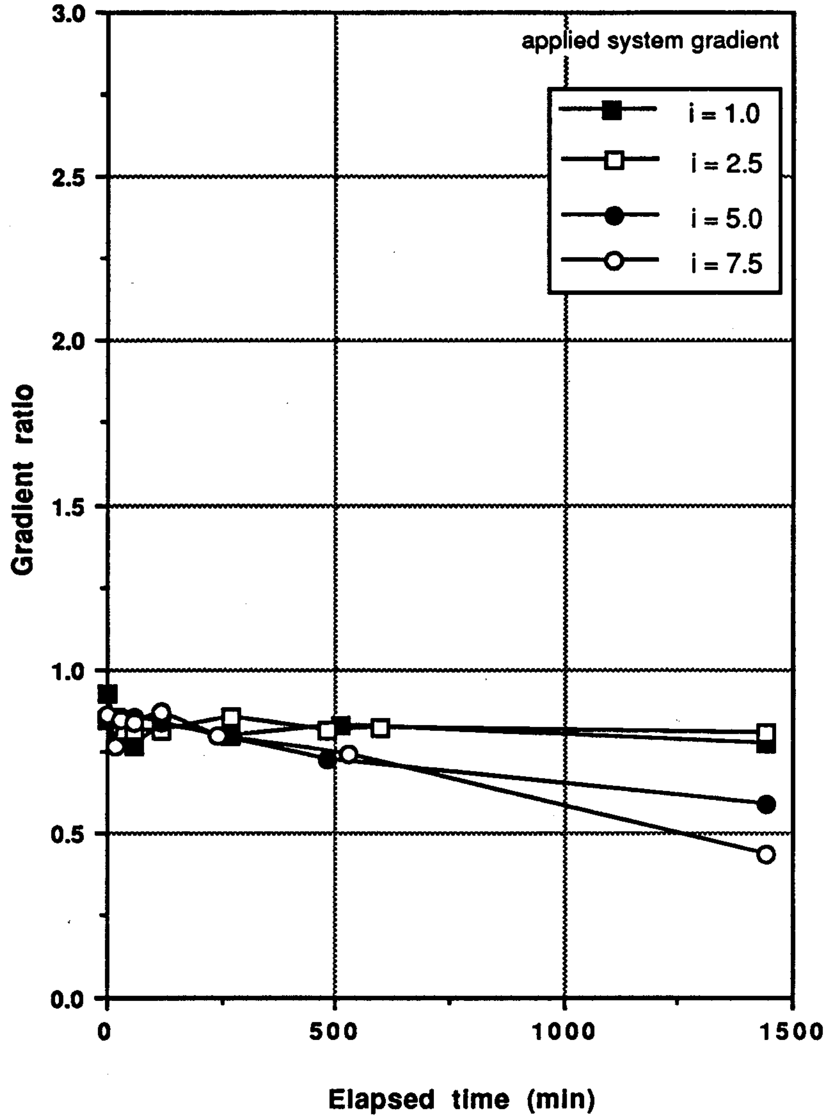

Figure 16 : Gradient Ratio for Armtec in Gradient Ratio Test

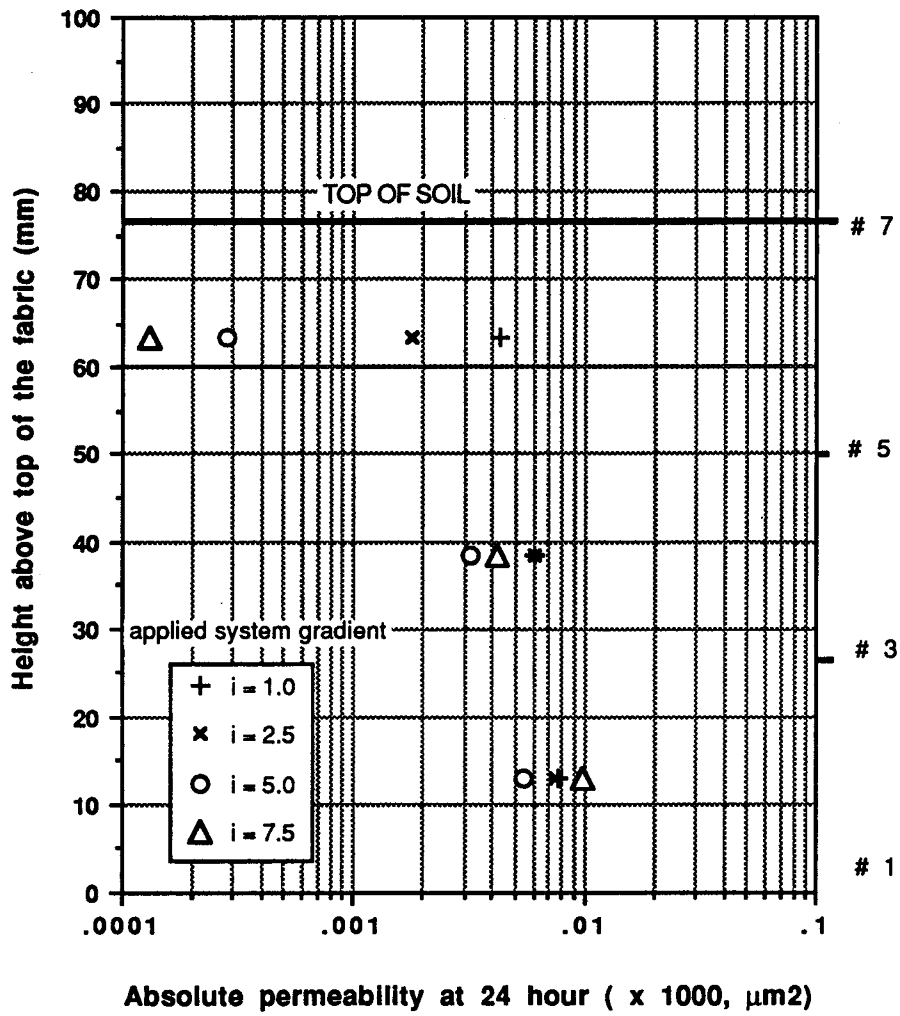

Figure 17 : Absolute Permeability of the Sand-Geotextile System for Armtec in Gradient Ratio Test

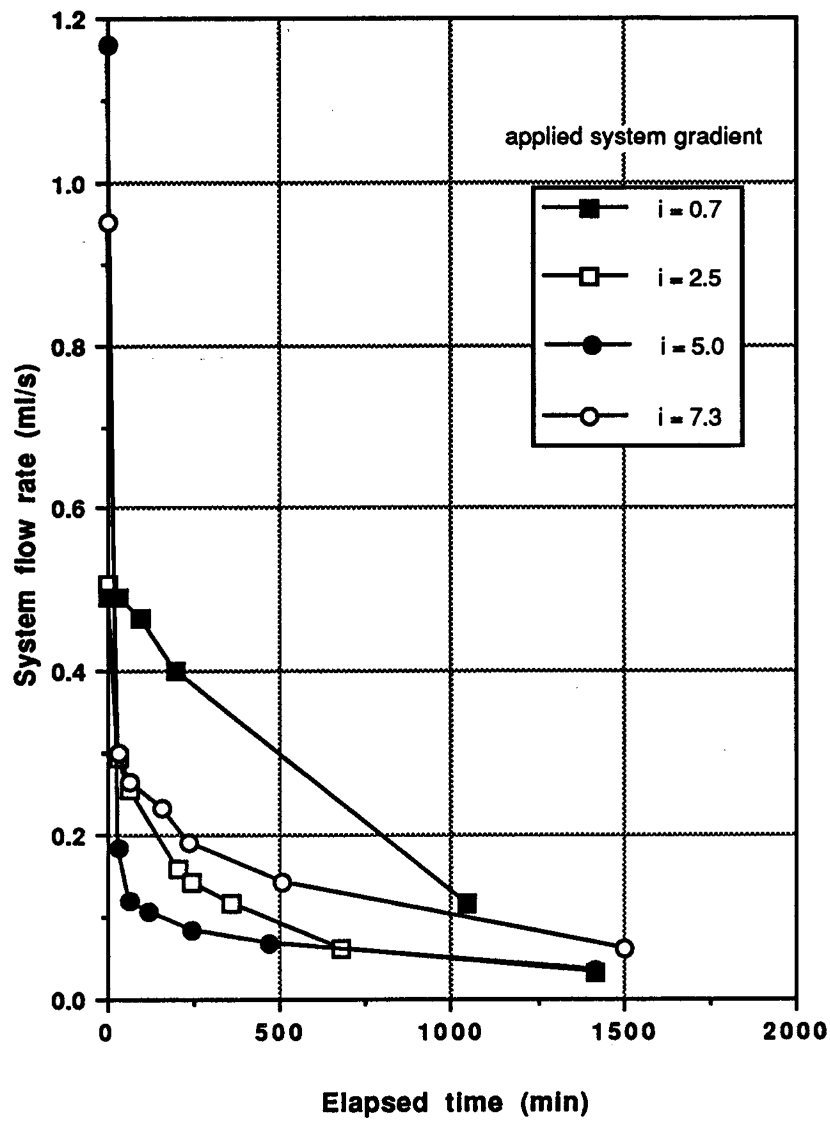

Figure 18 : Flow Rate Bidim in Gradient Ratio Test

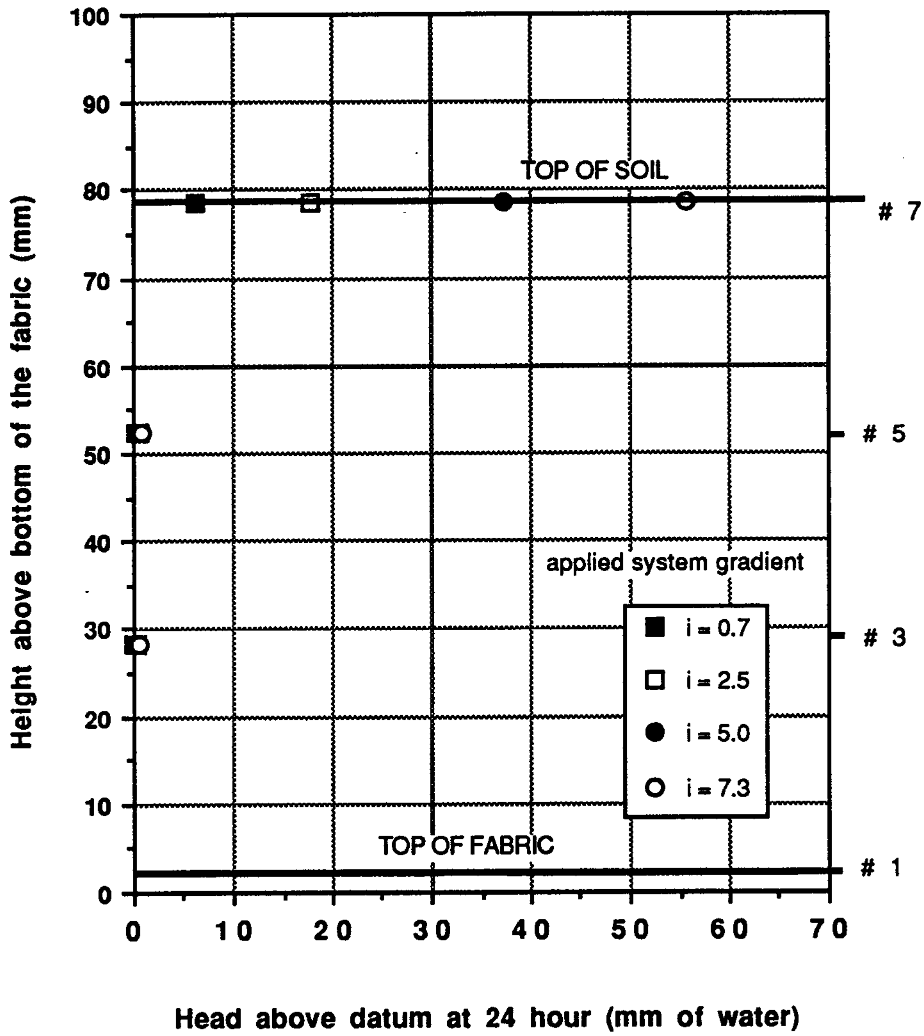

Figure 19 : Head Loss in the Sand-Geotextile System for Bidim in Gradient Ratio Test

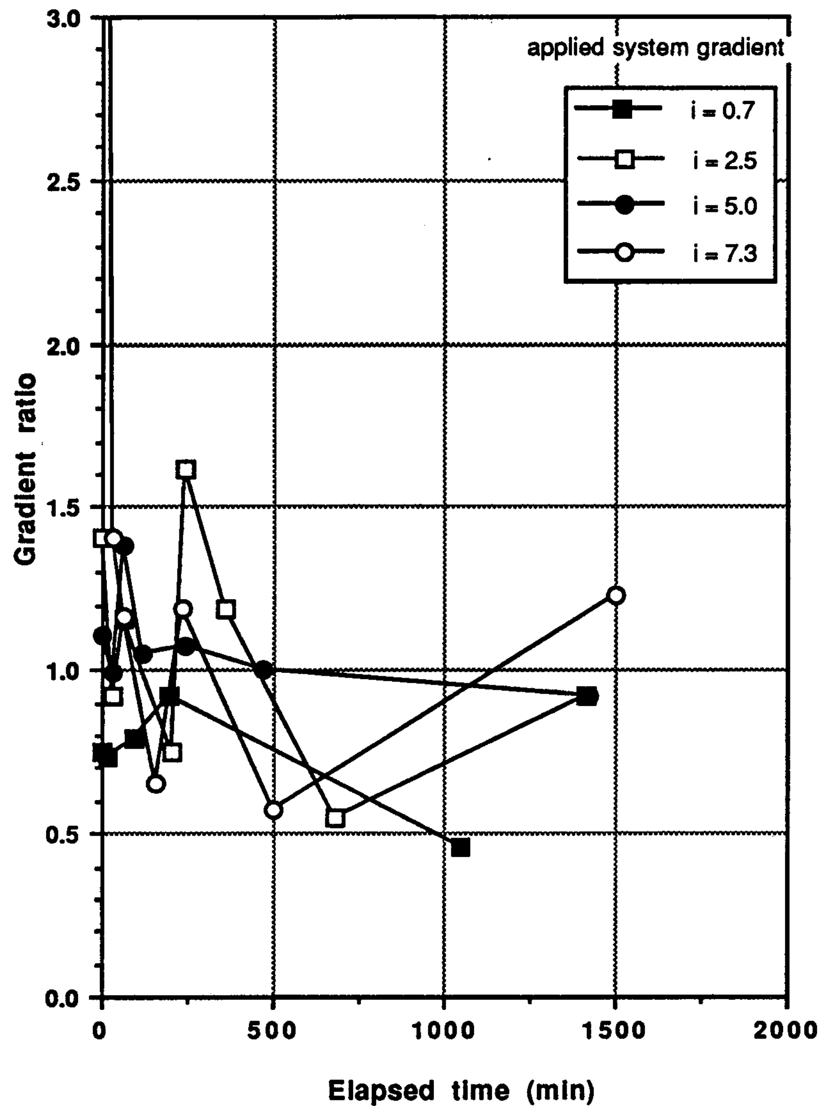

Figure 20: Gradient Ratio for Bidim in Gradient Ratio Test

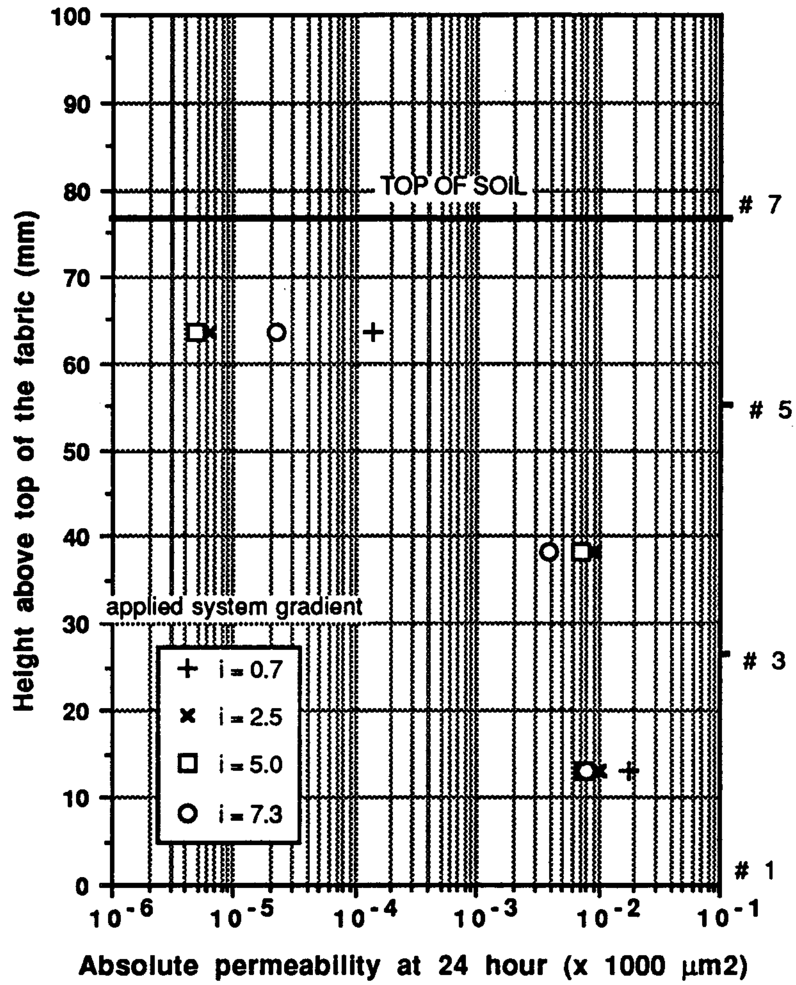

Figure 21: Absolute Permeability of the Sand-Geotextile System for Bidim in Gradient Ratio Test

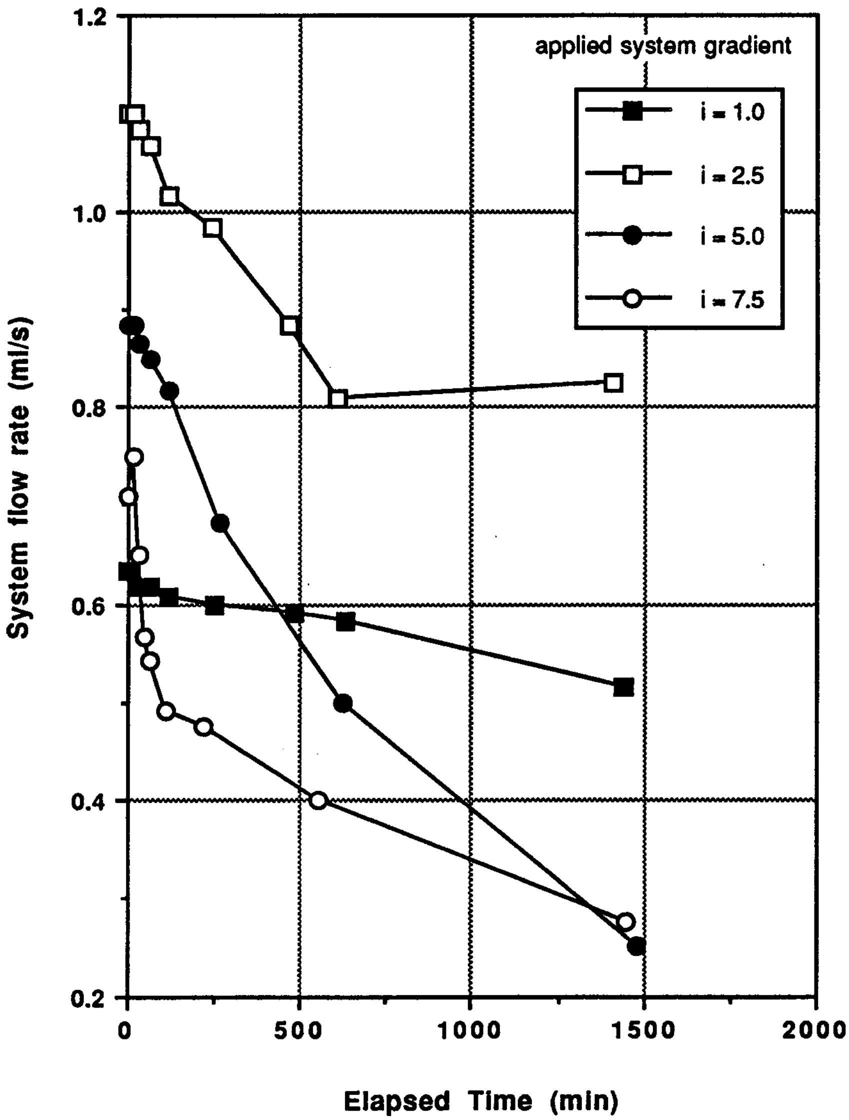

Figure 22 : Flow Rate for Polyfelt in Gradient Ratio Test

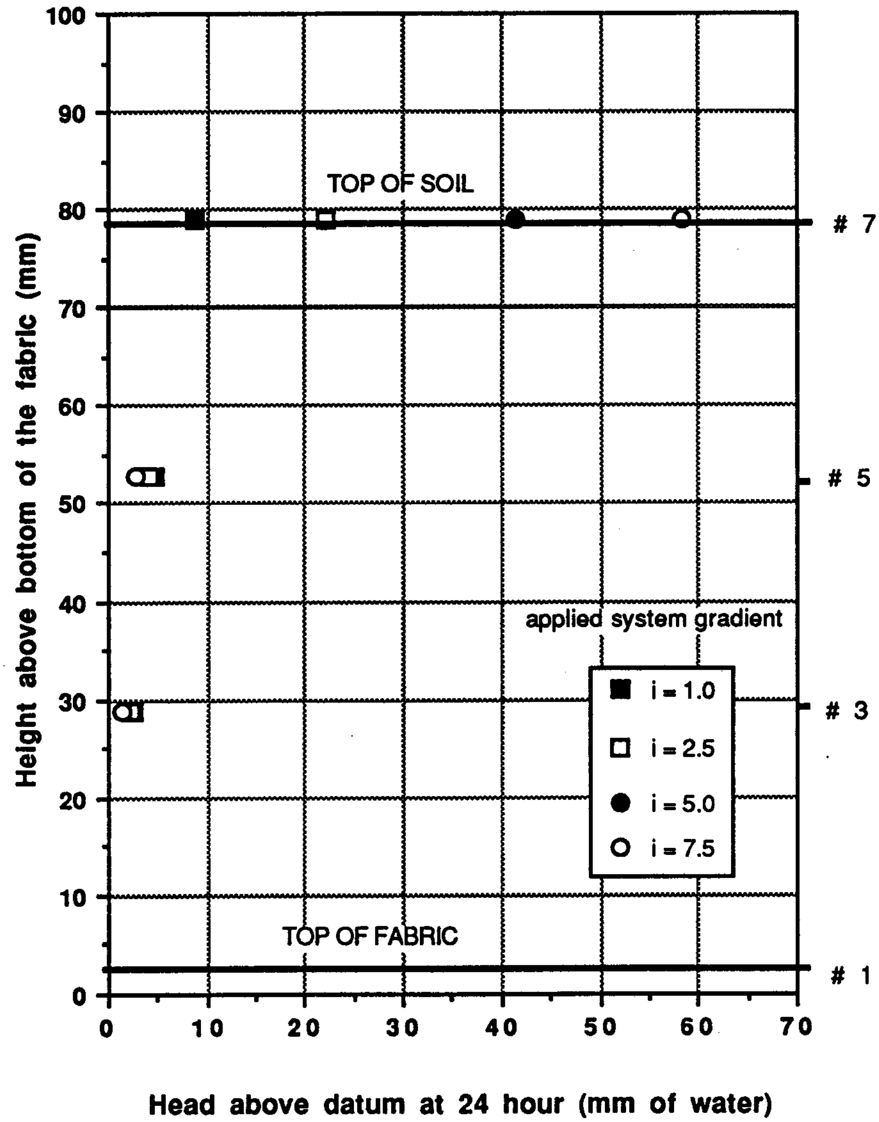

Figure 23 : Head Loss in the Sand-Geotextile System for Polyfelt in Gradient Ratio Test

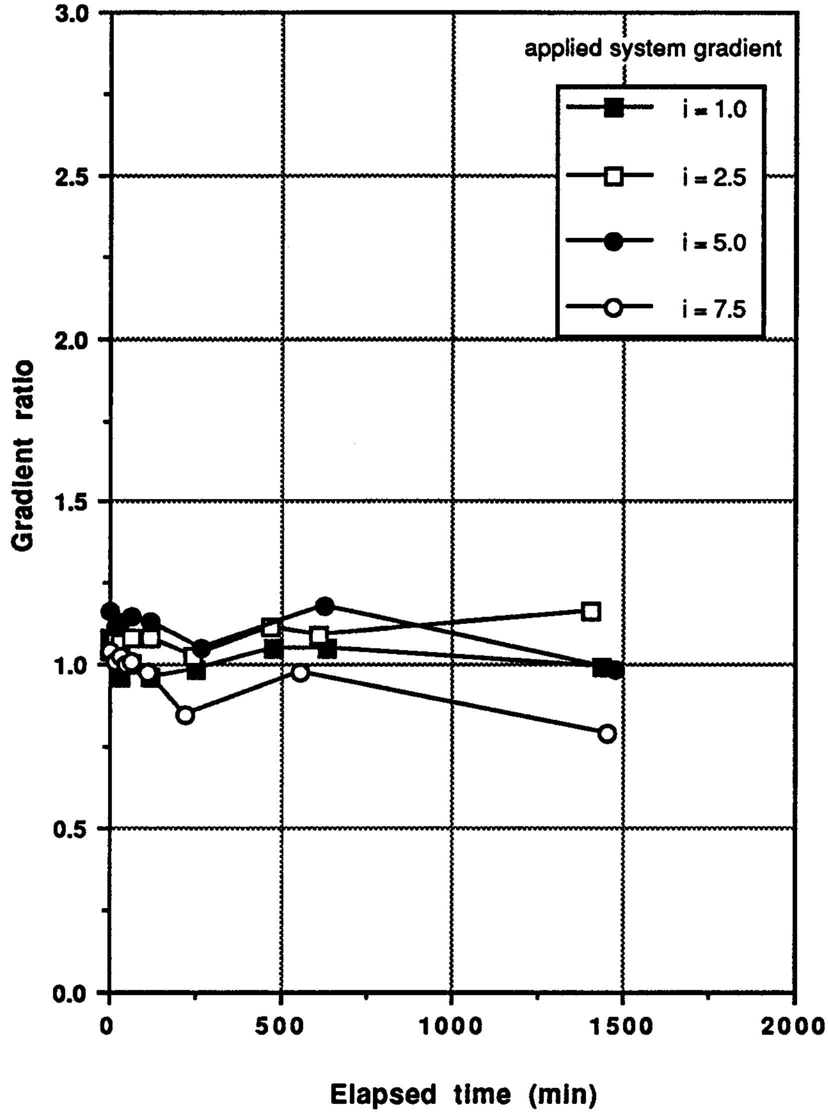

Figure 24 : Gradient Ratio for Polyfelt in Gradient Ratio Test

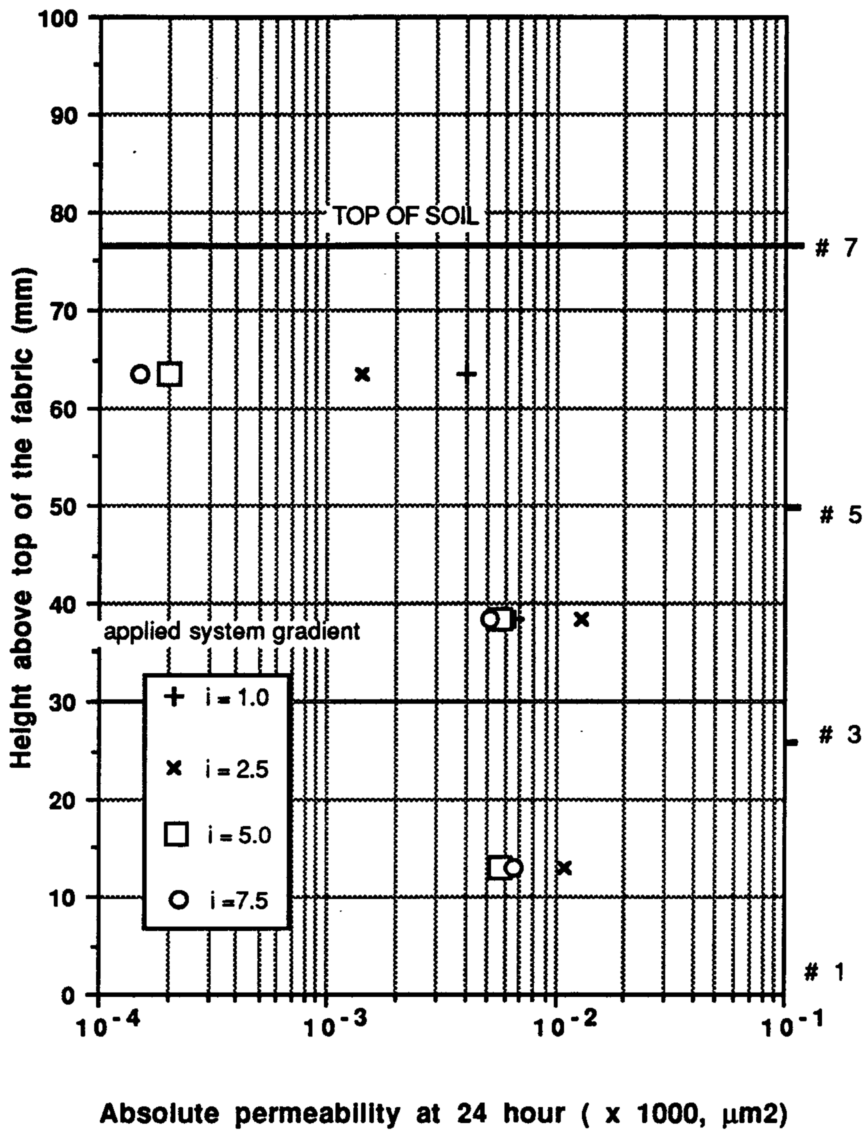

Figure 25: Absolute Permeability in the Sand-Geotextile System for Polyfelt in Gradient Ratio Test

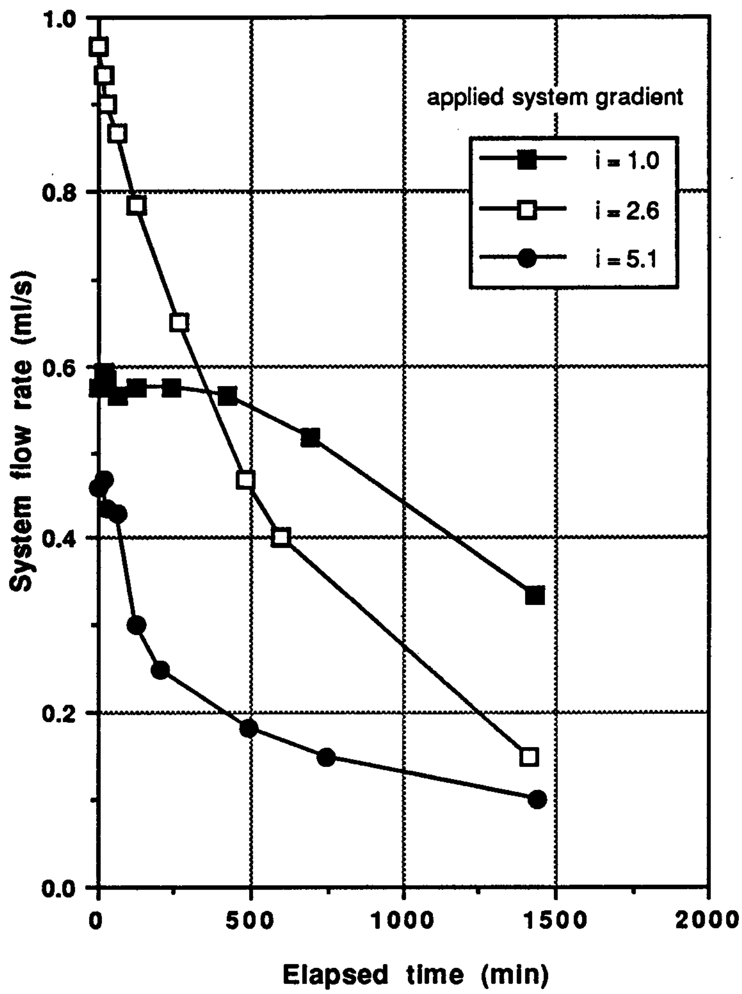

Figure 26 : Flow Rate for Trevira in Gradient Ratio Test

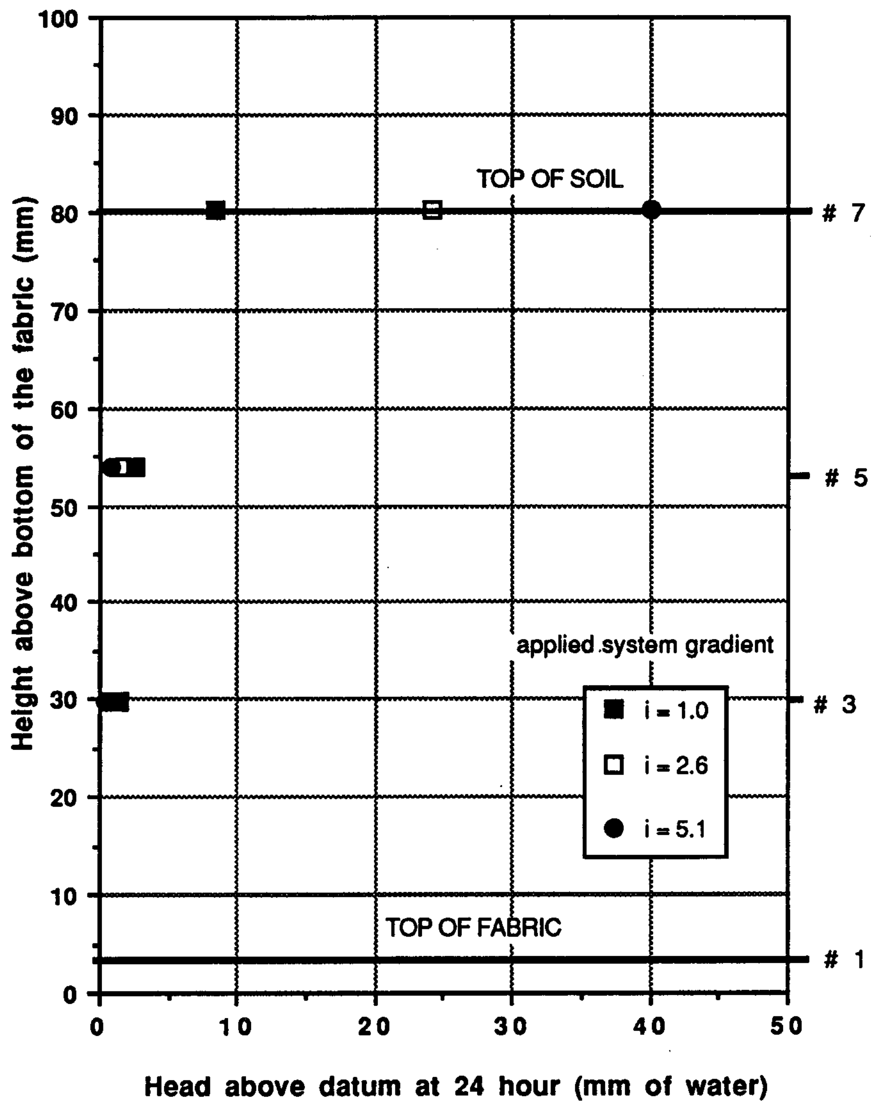

Figure 27 : Head Loss in the Sand - Geotextile System for Trevira in Gradient Ratio Test

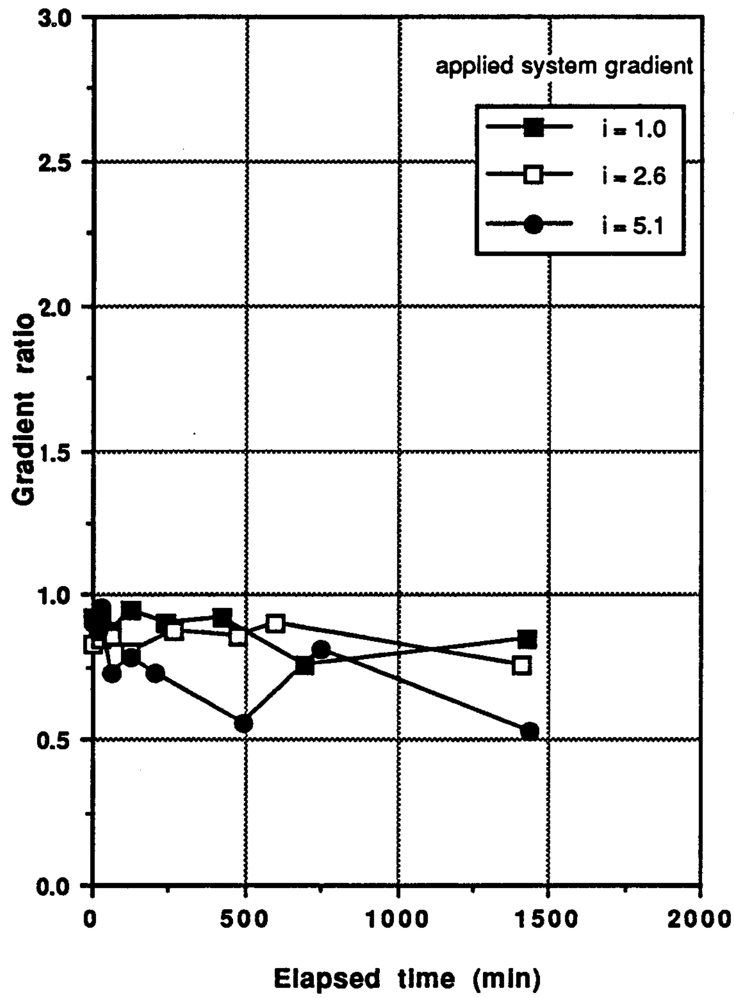

Figure 28 : Gradient Ratio for Trevira in Gradient Ratio Test

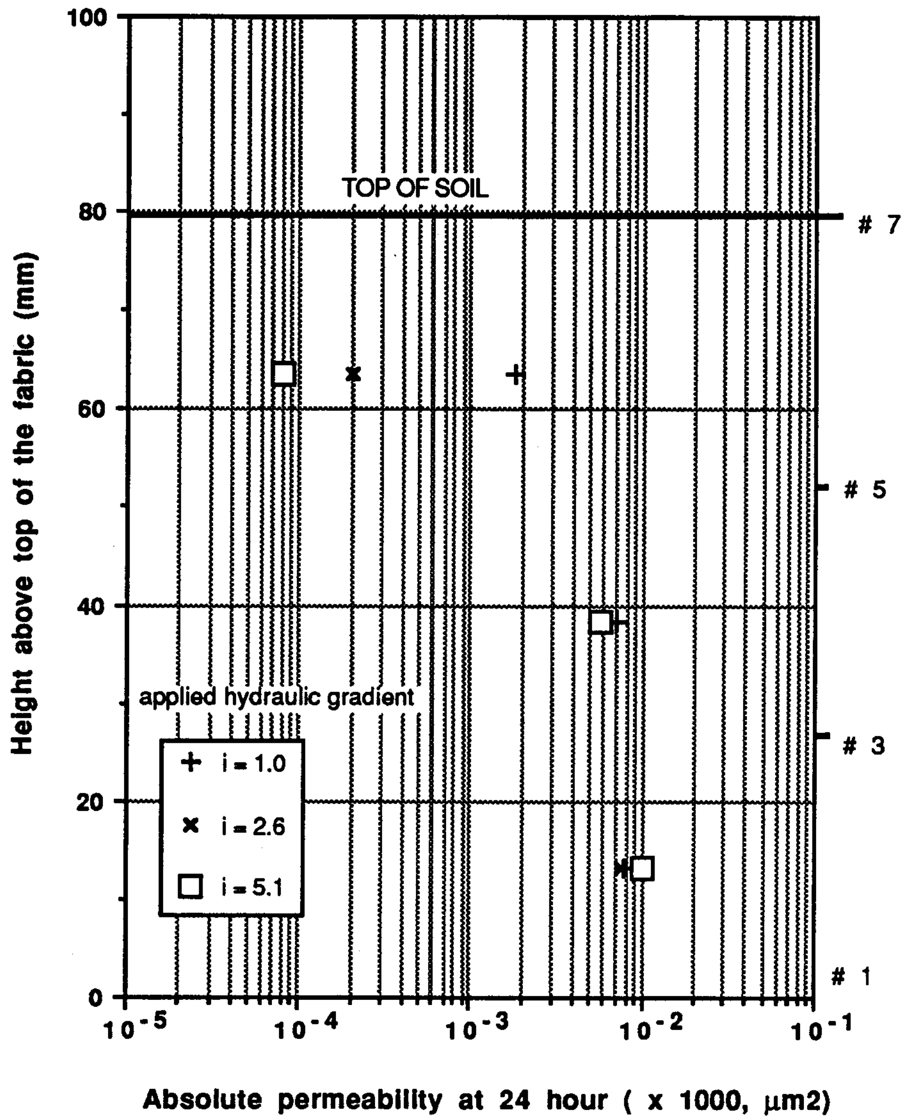

Figure 29: Absolute Permeability in the Sand - Geotextile System for Trevira in Gradient Ratio Test

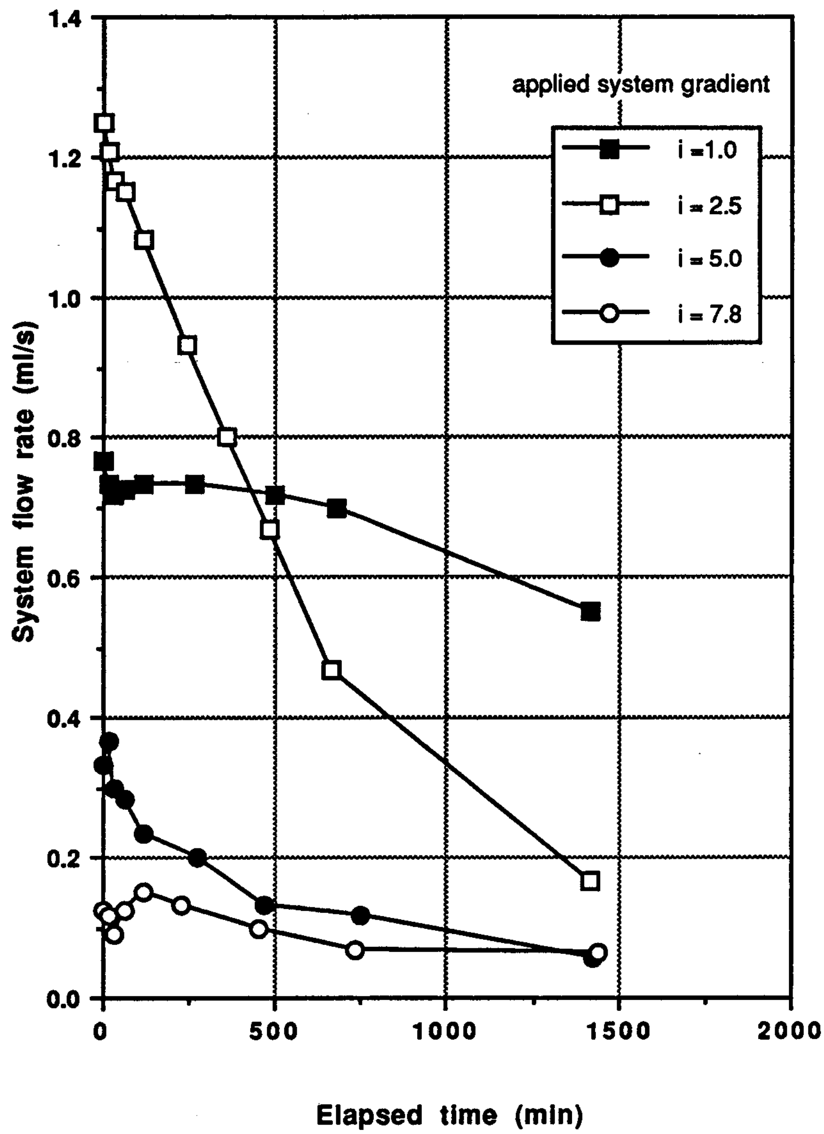

Figure 30 : Flow Rate for Bidimrock in Gradient Ratio Test

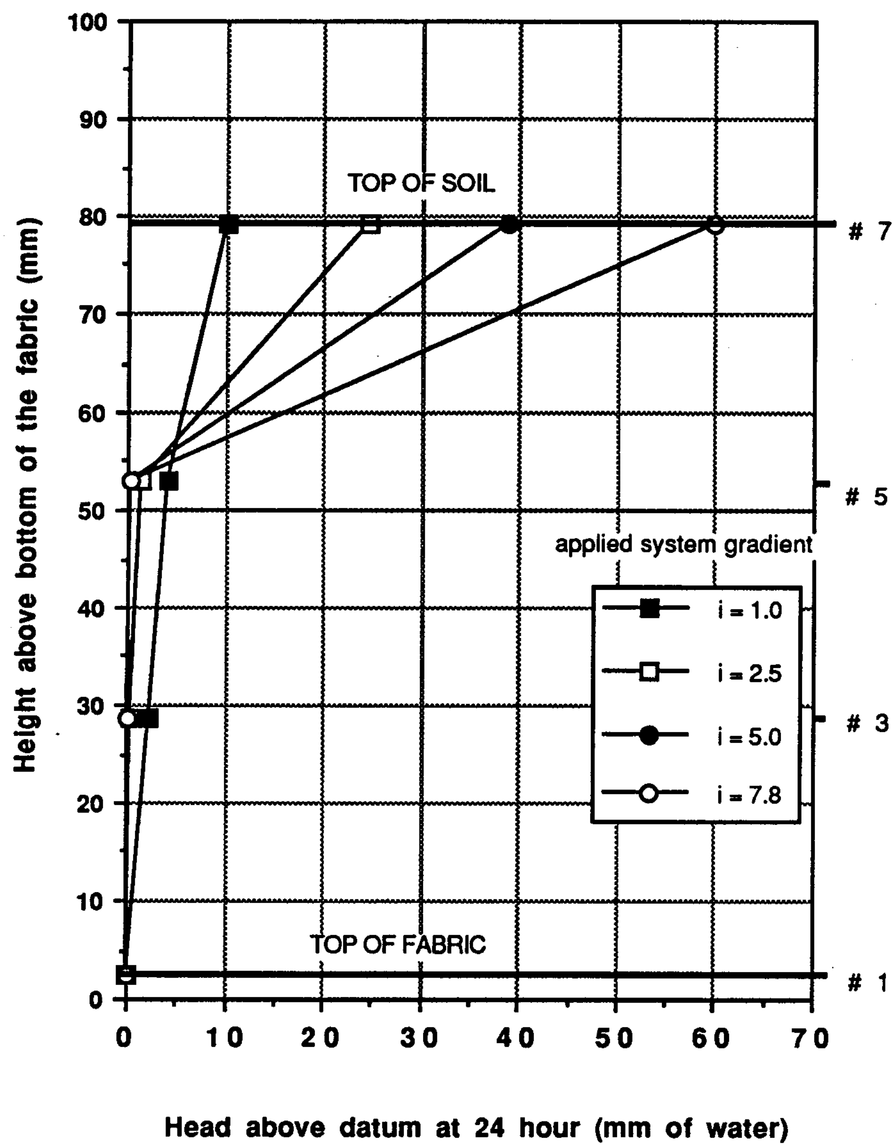

Figure 31 : Head Loss in the Sand - Geotextile System for Bidimrock in Gradient Ratio Test

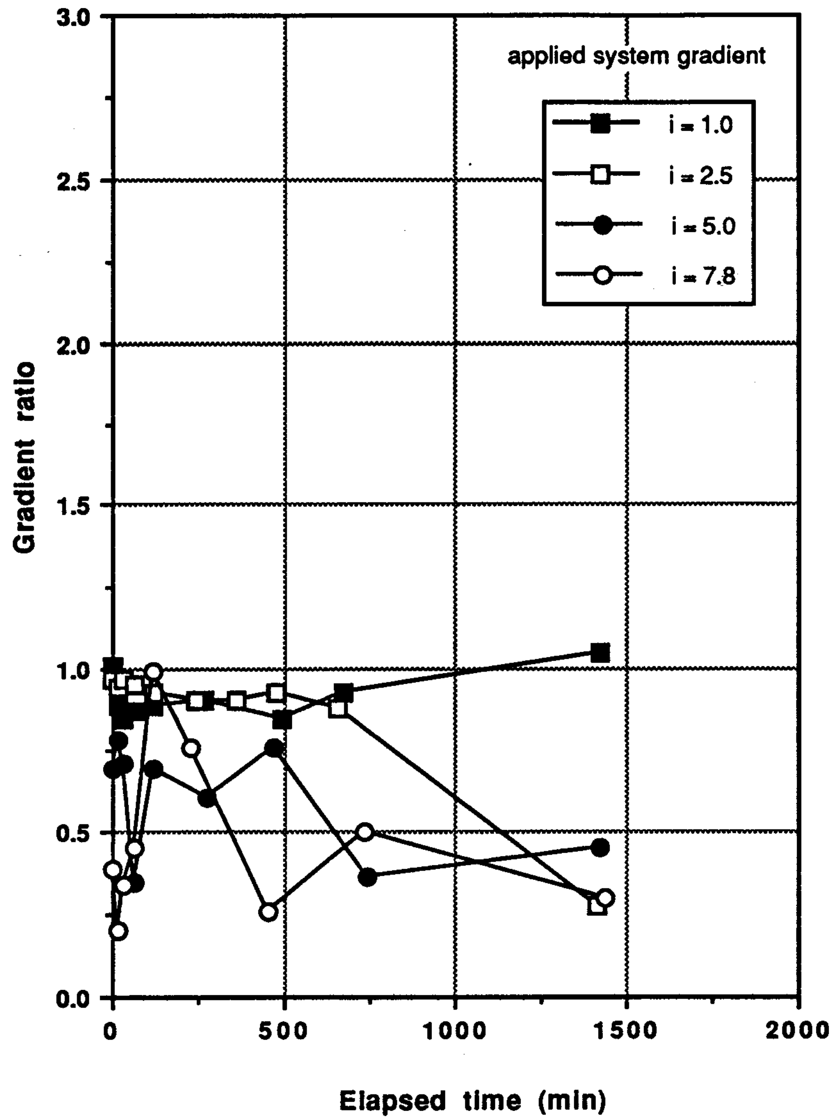

Figure 32: Gradient Ratio for Bidimrock in Gradient Ratio Test

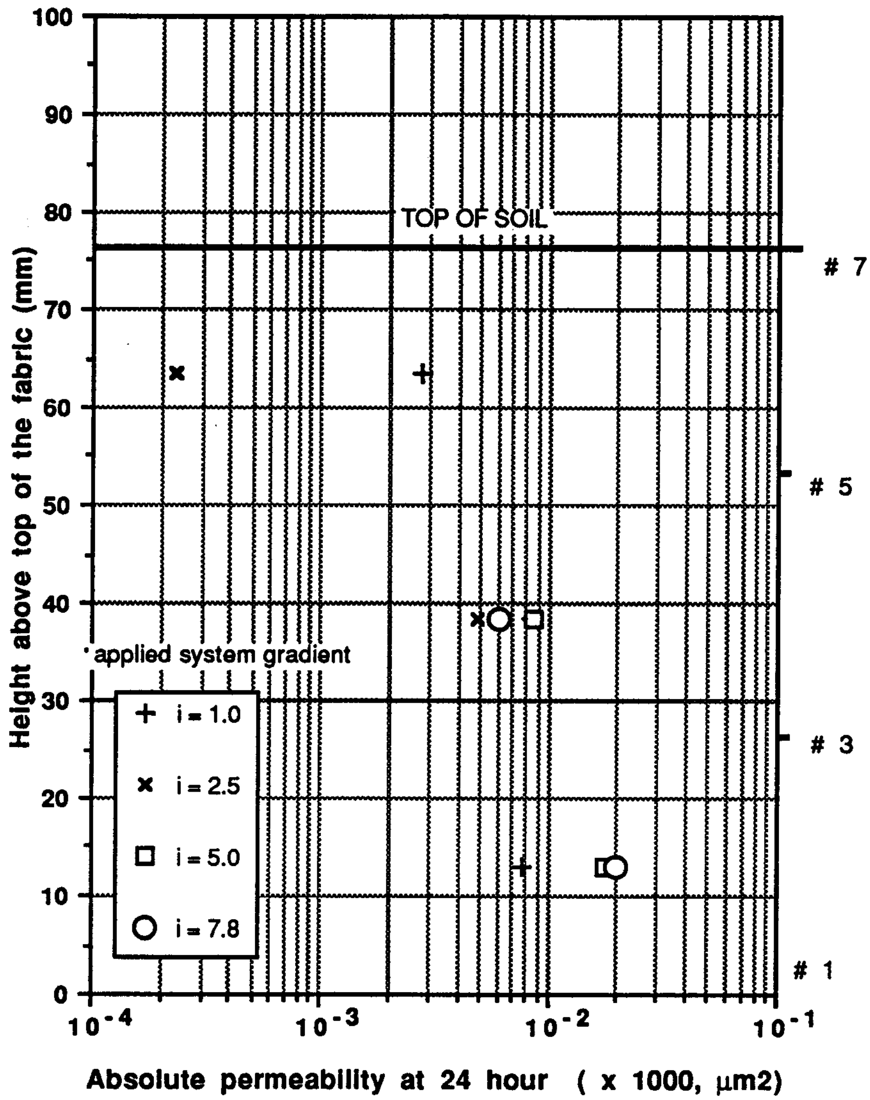

Figure 33: Absolute Permeability of the Sand-Geotextile System for Bidimrock in Gradient Ratio Test

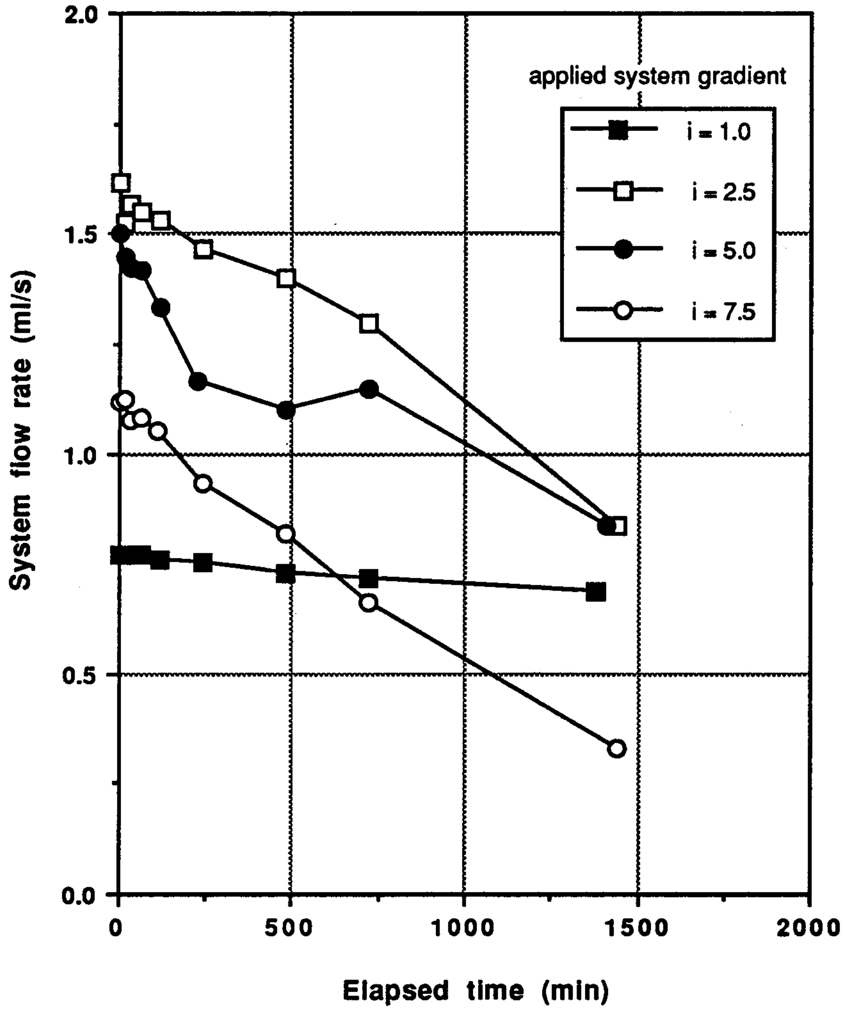

Figure 34 : Flow Rate for Exxon in Gradient Ratio Test

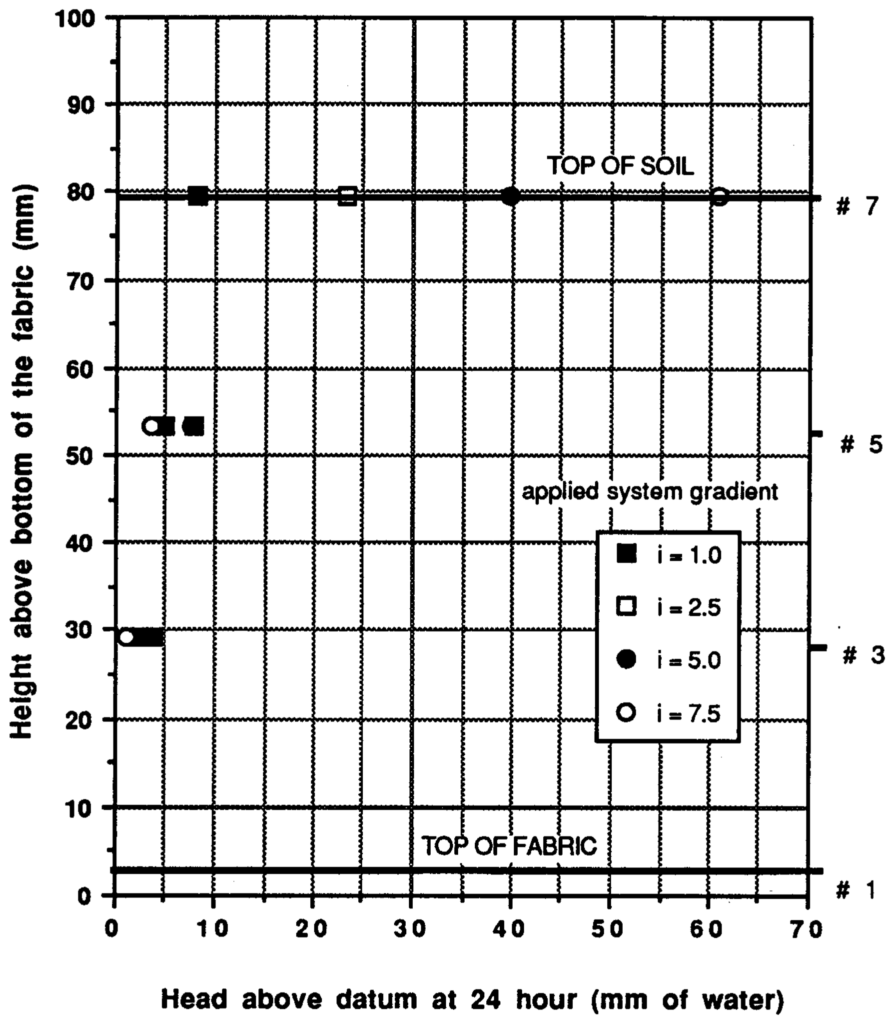

Figure 35 : Head Loss in the Sand-Geotextile System for Exxon in Gradient Ratio Test

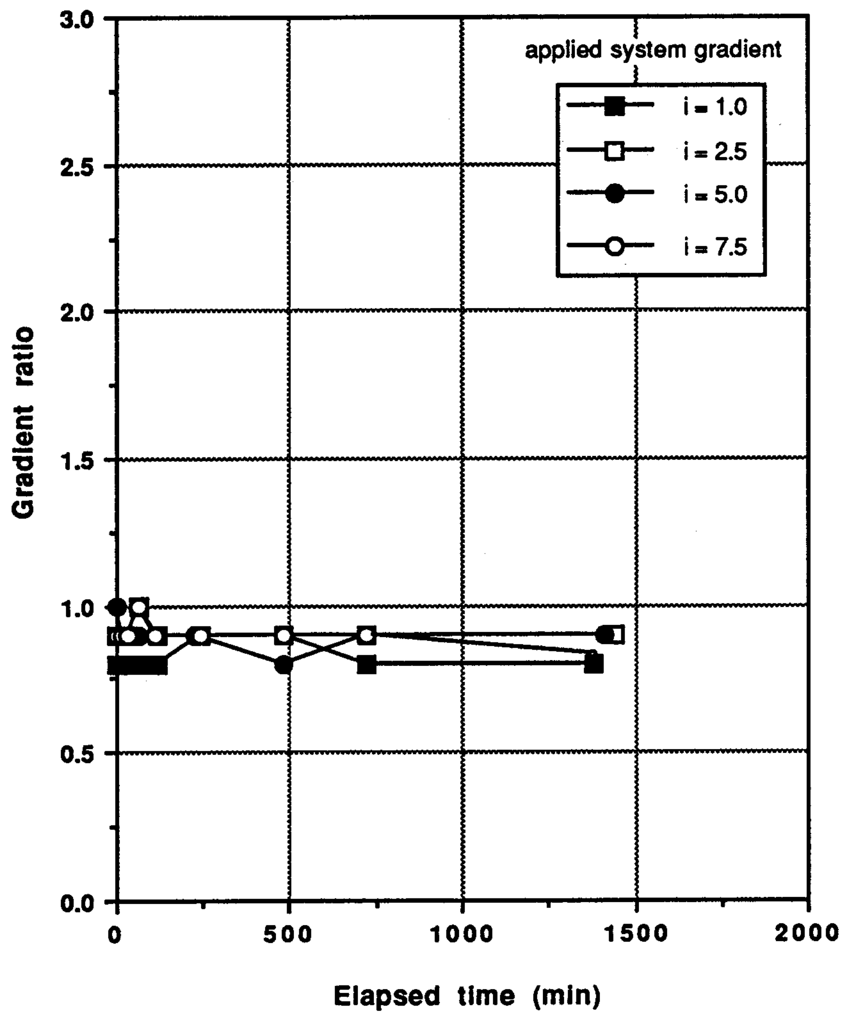

Figure 36: Gradient Ratio for Exxon in Gradient Ratio Test

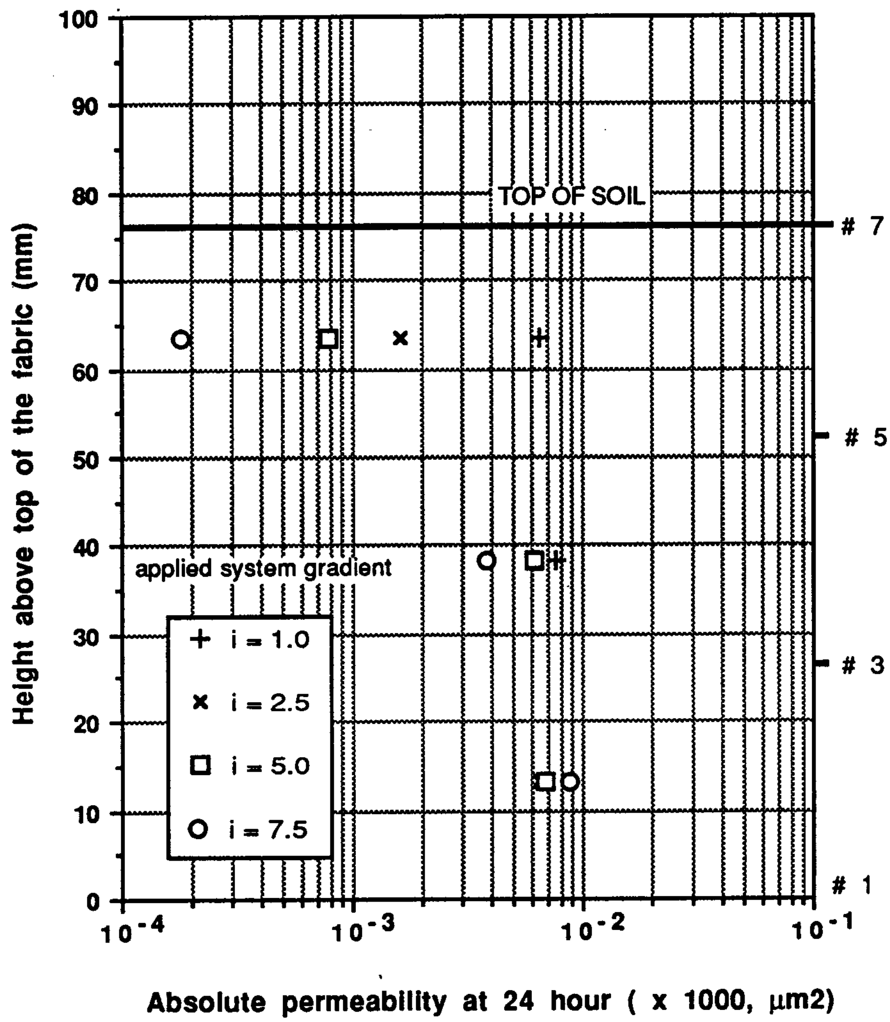

Figure 37 : Absolute Permeability in the Sand-Geotextile System for Exxon in Gradient Ratio Test

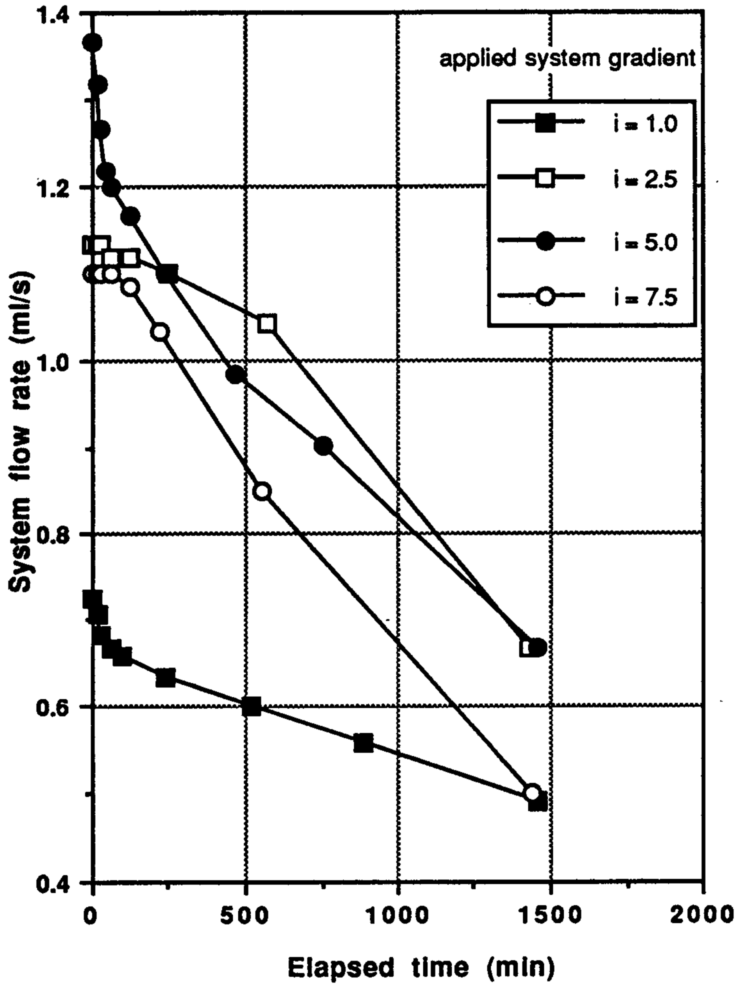

Figure 38 : Flow Rate for Quline in Gradient Ratio Test

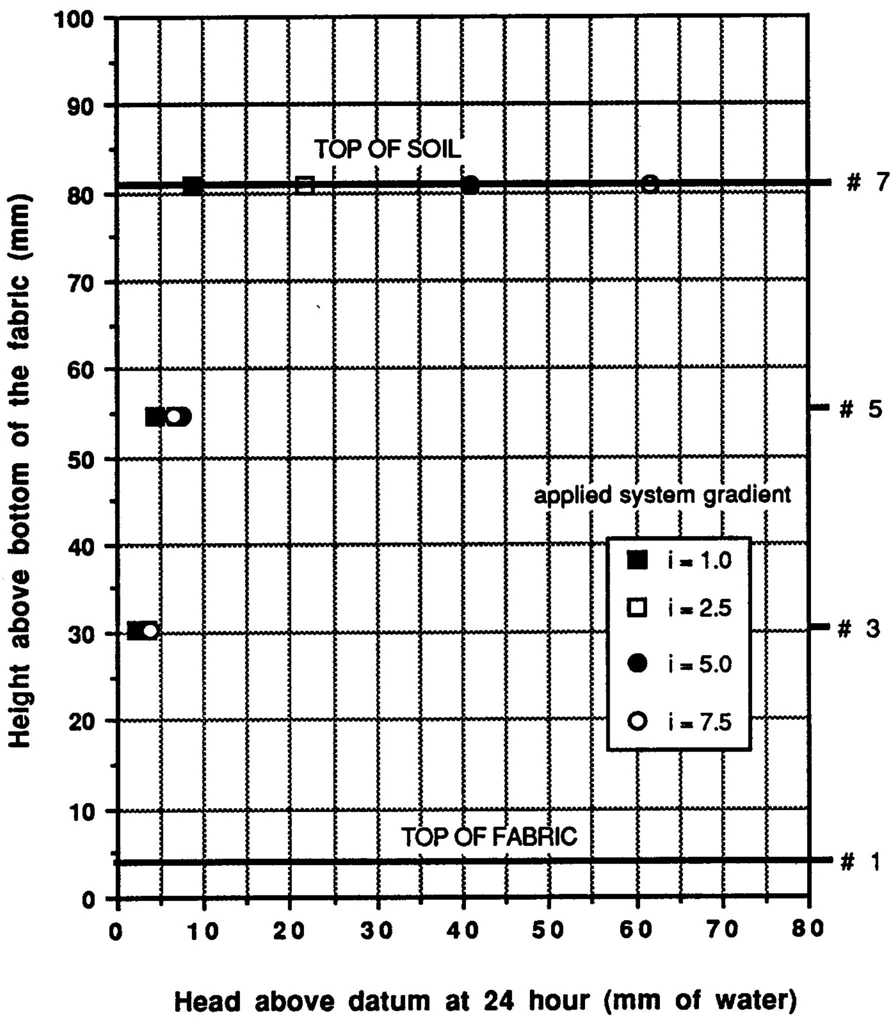

Figure 39 : Head Loss in the Sand - Geotextile System for Quline in Gradient Ratio Test

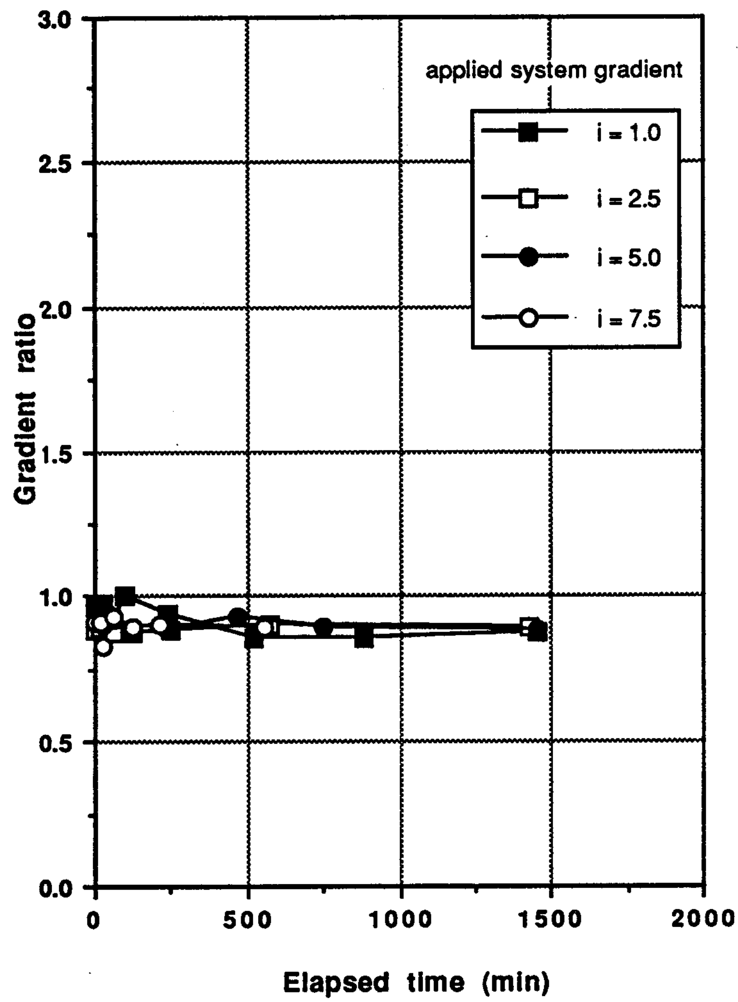

Figure 40: Gradient Ratio for Quline in Gradient Ratio Test

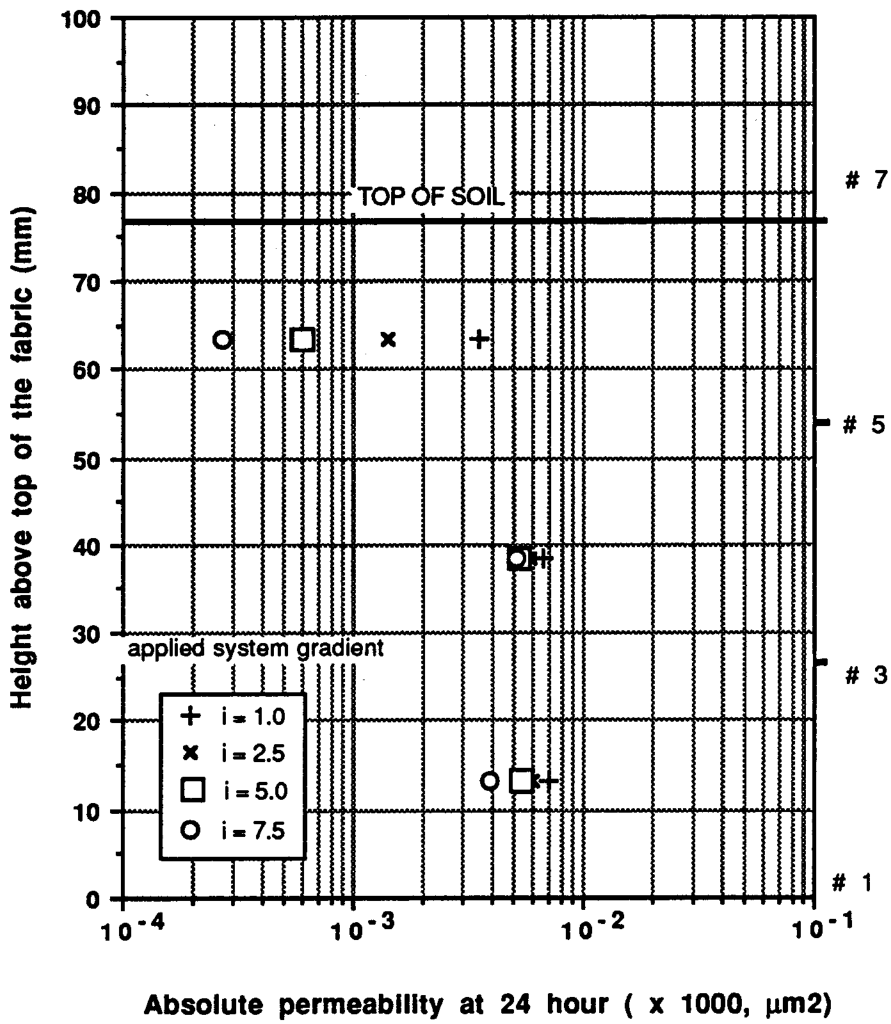

Figure 41 : Absolute Permeability in the Sand-Geotextile System for Quline in Gradient Ratio Test

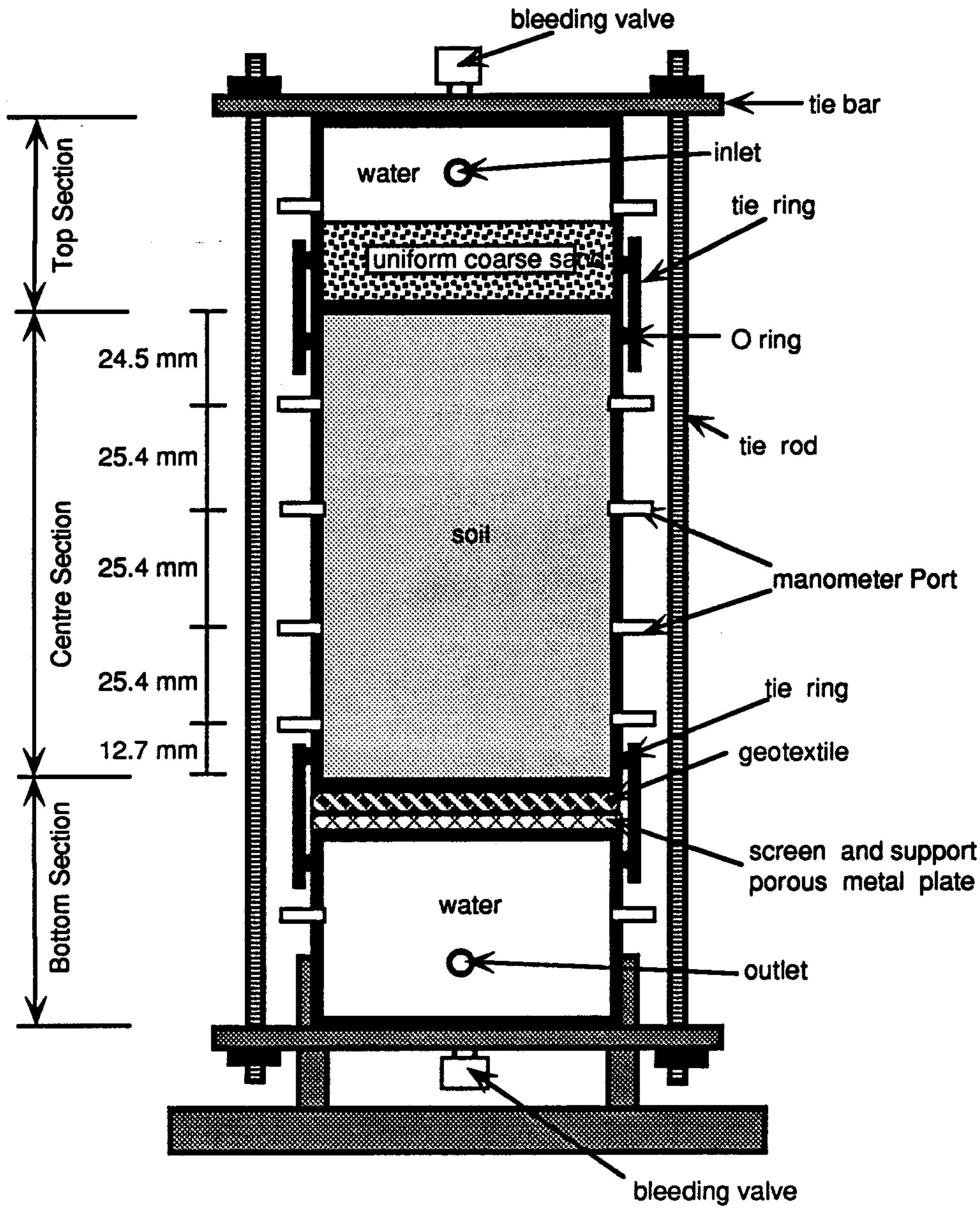

Figure 42 : Sectional View of the Modified Gradient Ratio Apparatus

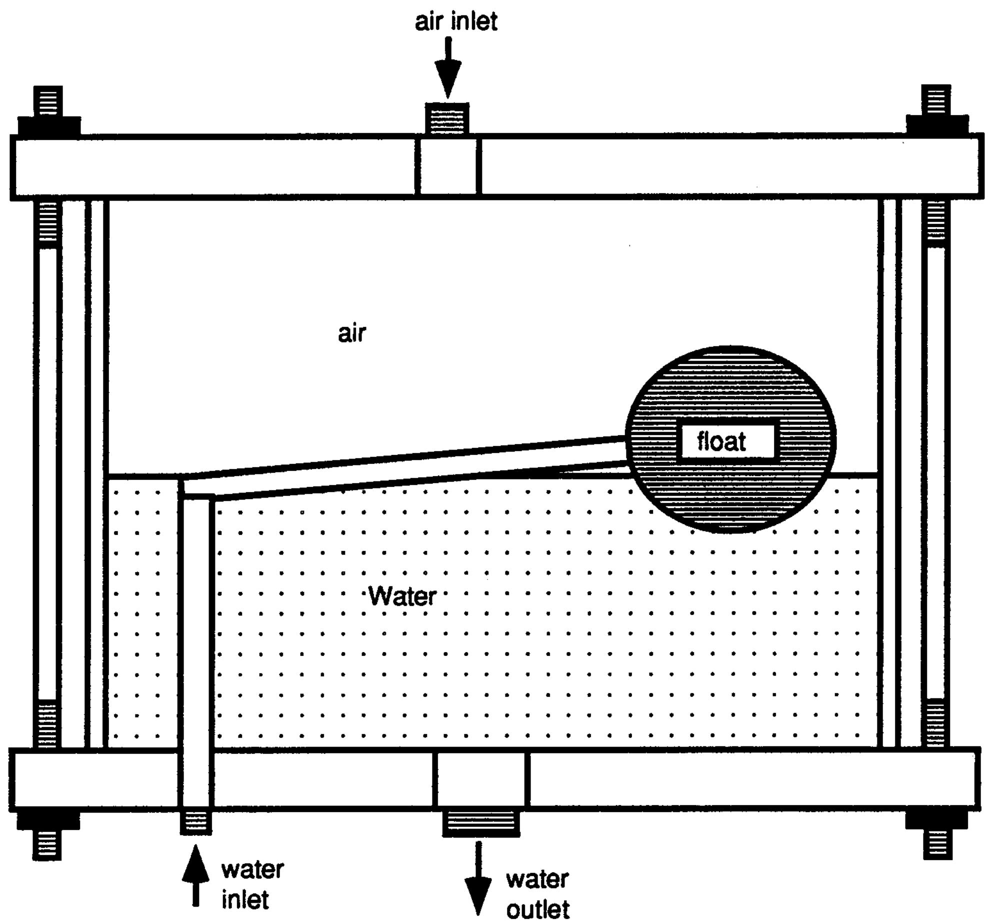

Figure 43 : Sectional View of the Air Pressurized Constant Head Device

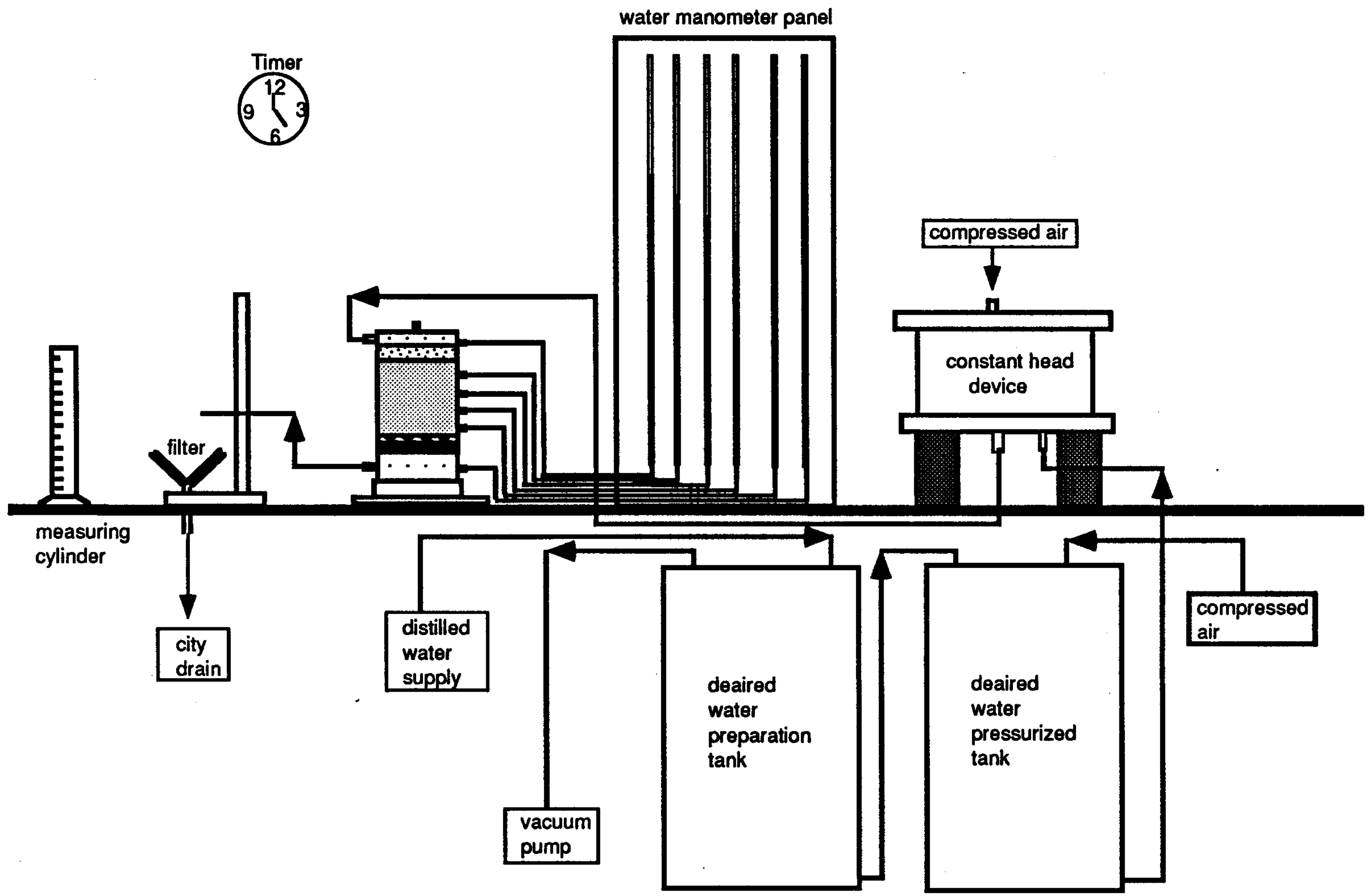

Figure 44 : Schematic Layout of the Modified Gradient Ratio System

$$\text{Gradient Ratio} = \frac{\dfrac{dhsf}{Lsf}}{\dfrac{dhs}{Ls}}$$

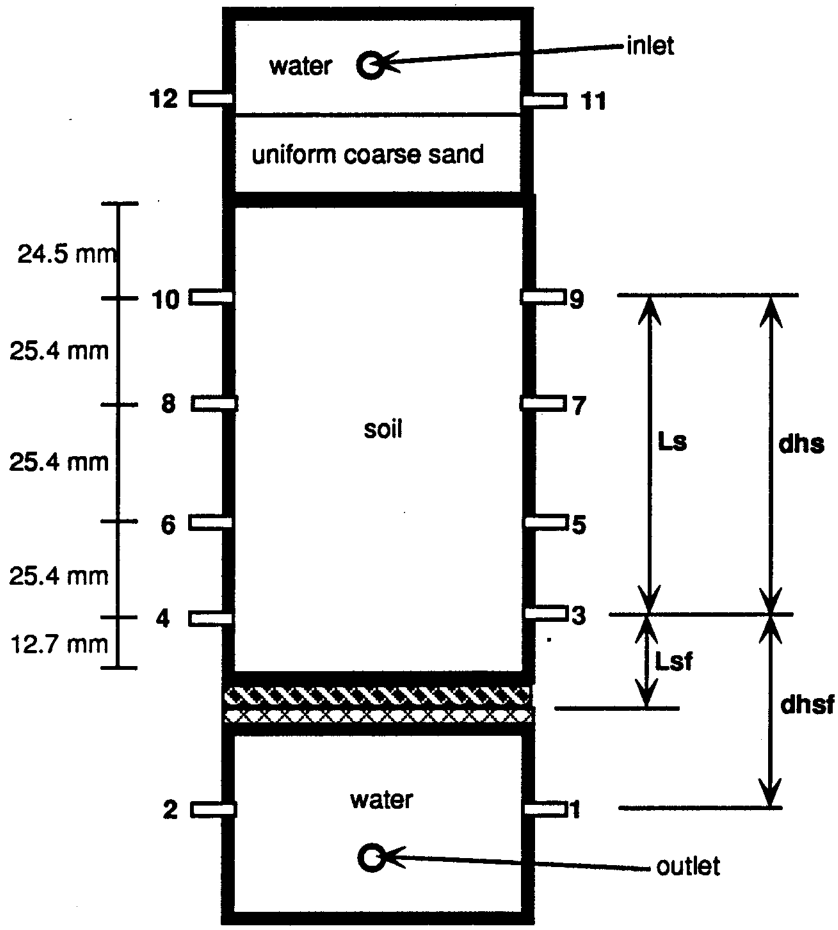

Figure 45: Values for Gradient Ratio Calculation for the Modified Gradient Ratio Apparatus

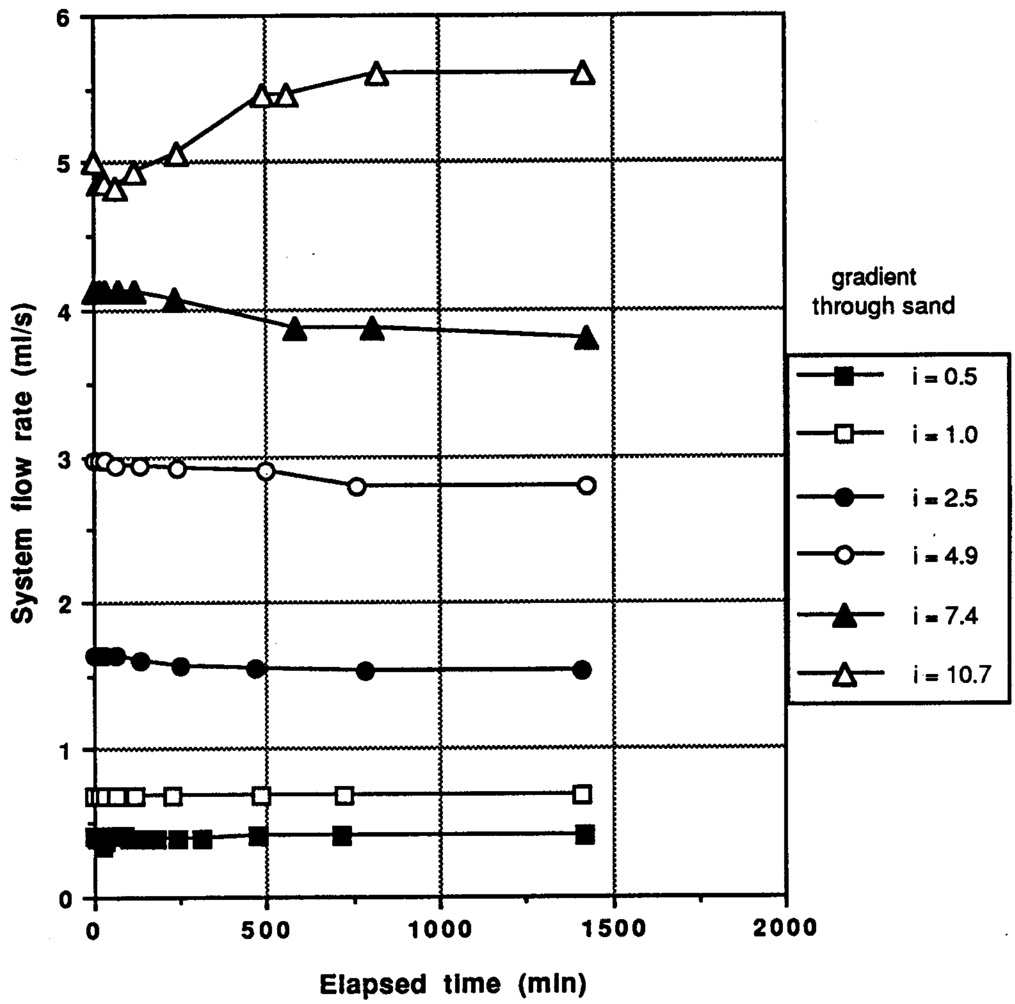

Figure 46 : Flow Rate for Bidimrock in Modified Gradient Ratio Test

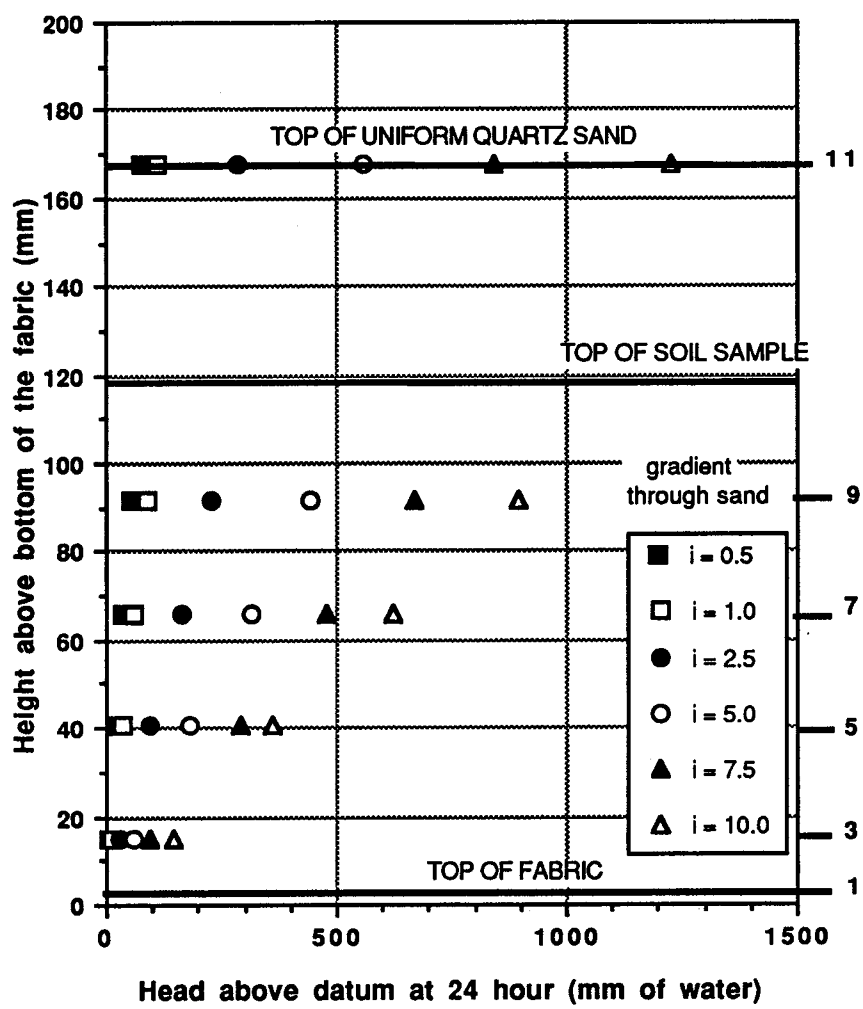

Figure 47 : Head Loss in the Sand - Geotextile System for Bidimrock in Modified Gradient Ratio Test

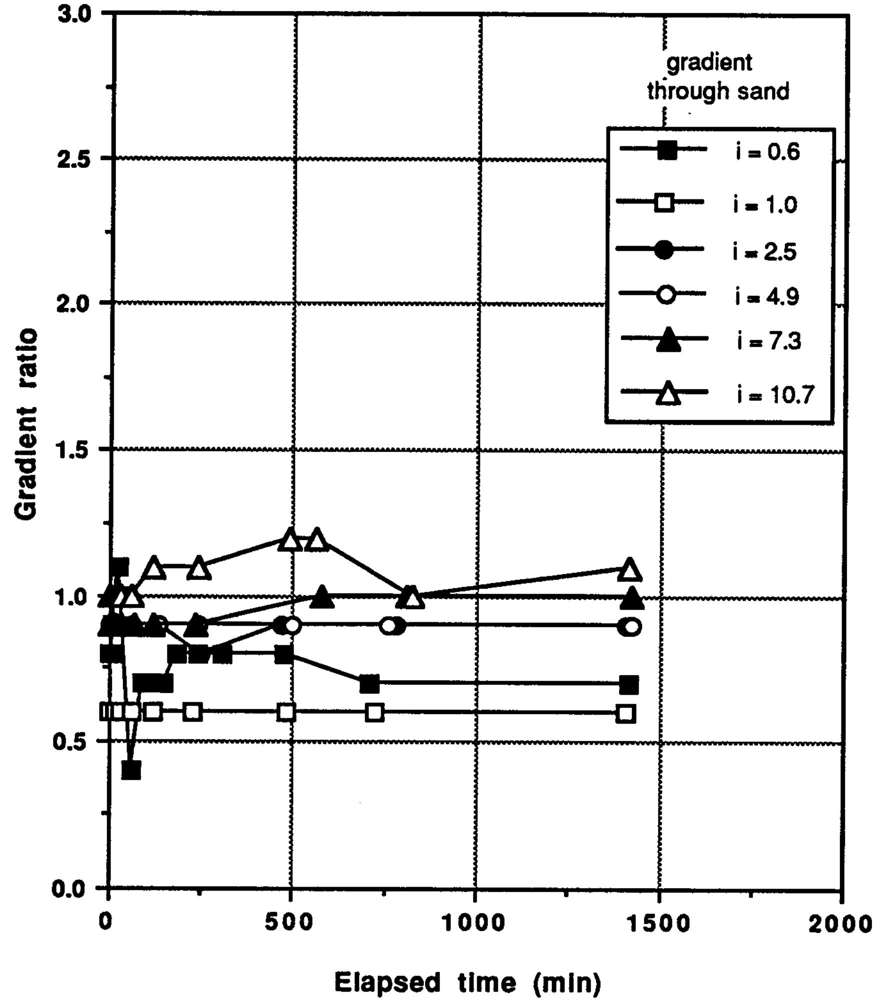

Figure 48: Gradient Ratio for Bidimrock in Modified Gradient Ratio Test

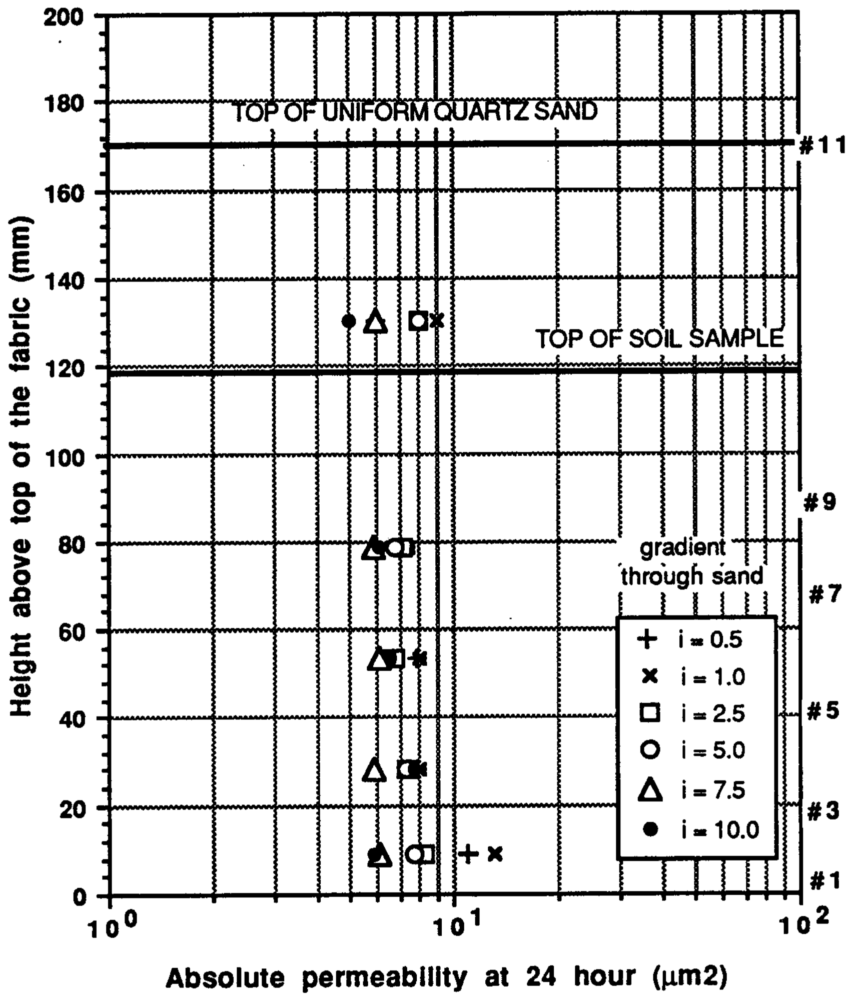

Figure 49 : Absolute Permeability of the Sand-Geotextile System for Bidimrock in Modified Gradient Ratio Test

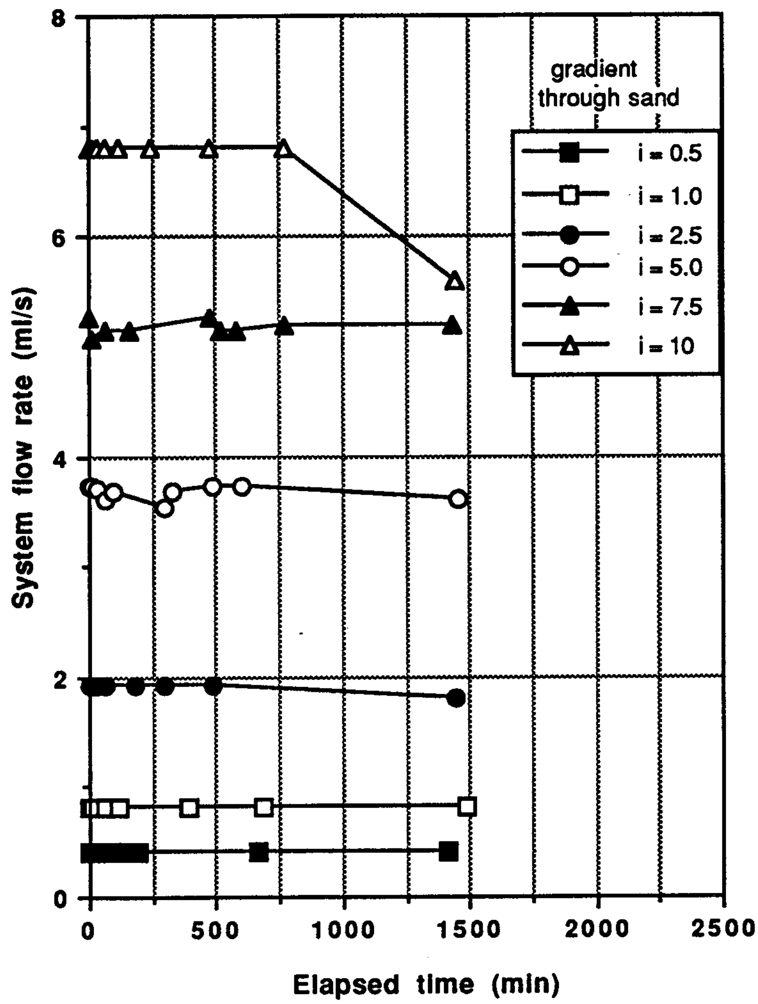

Figure 50 : Flow Rate for Exxon in Modified Gradient Ratio Test

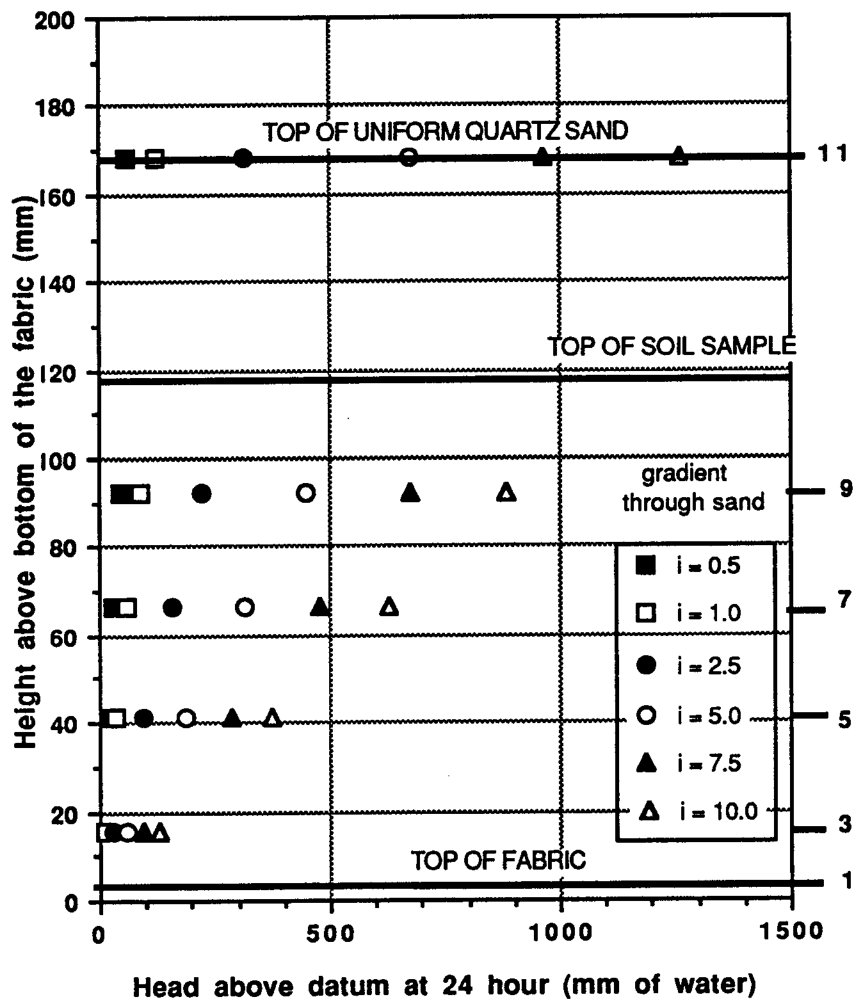

Figure 51 : Head Loss in the Sand-Geotextile System for Exxon in Modified Gradient Ratio Test

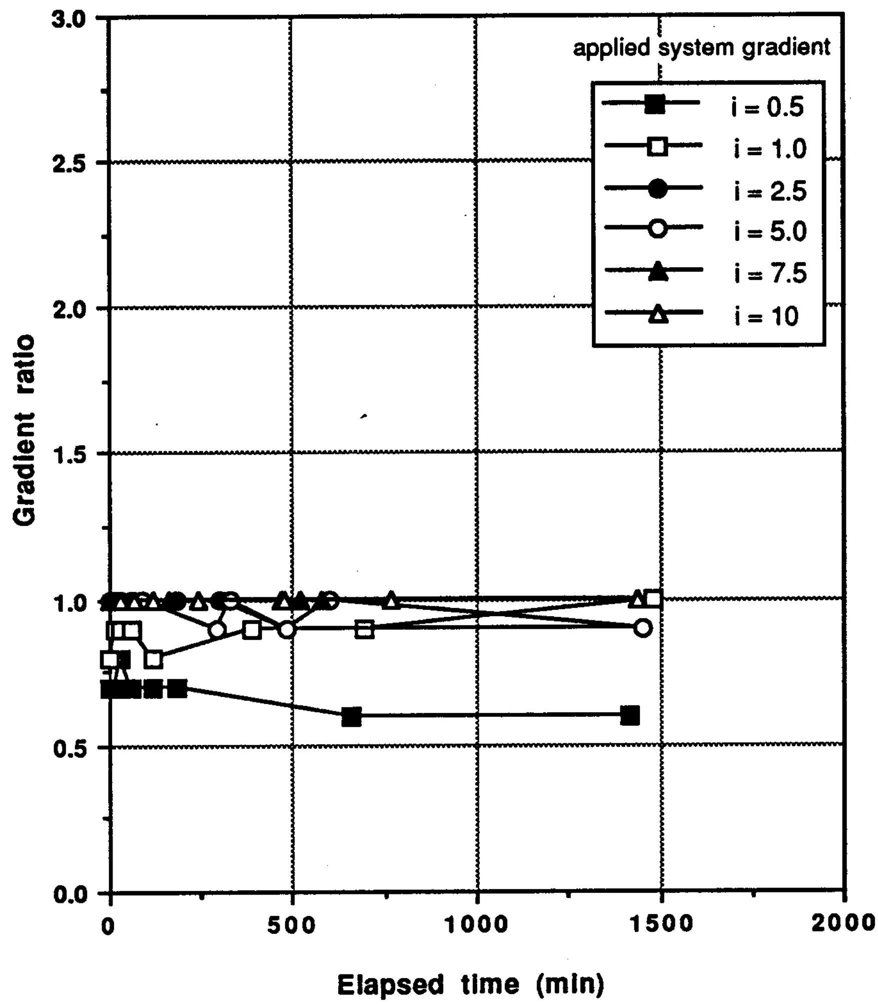

Figure 52 : Gradient Ratio for Exxon in Modified Gradient Ratio Test

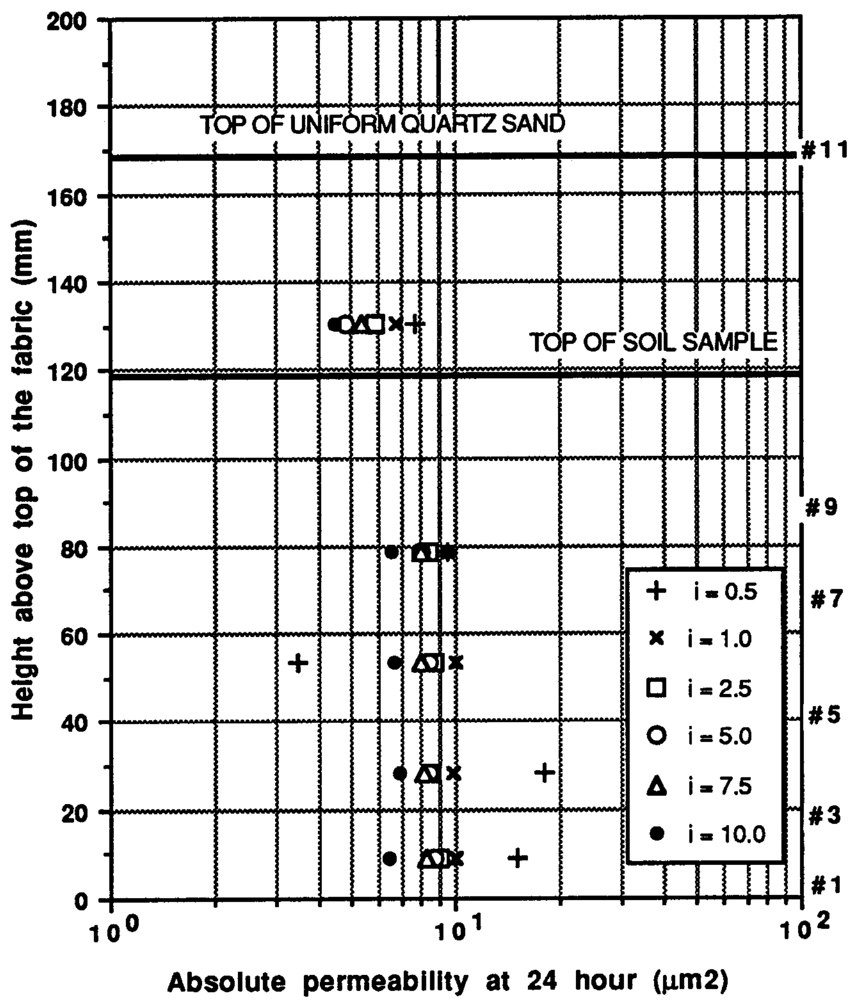

Figure 53 : Absolute Permeability of the Sand-Geotextile System for Exxon in Modified Gradient Ratio Test

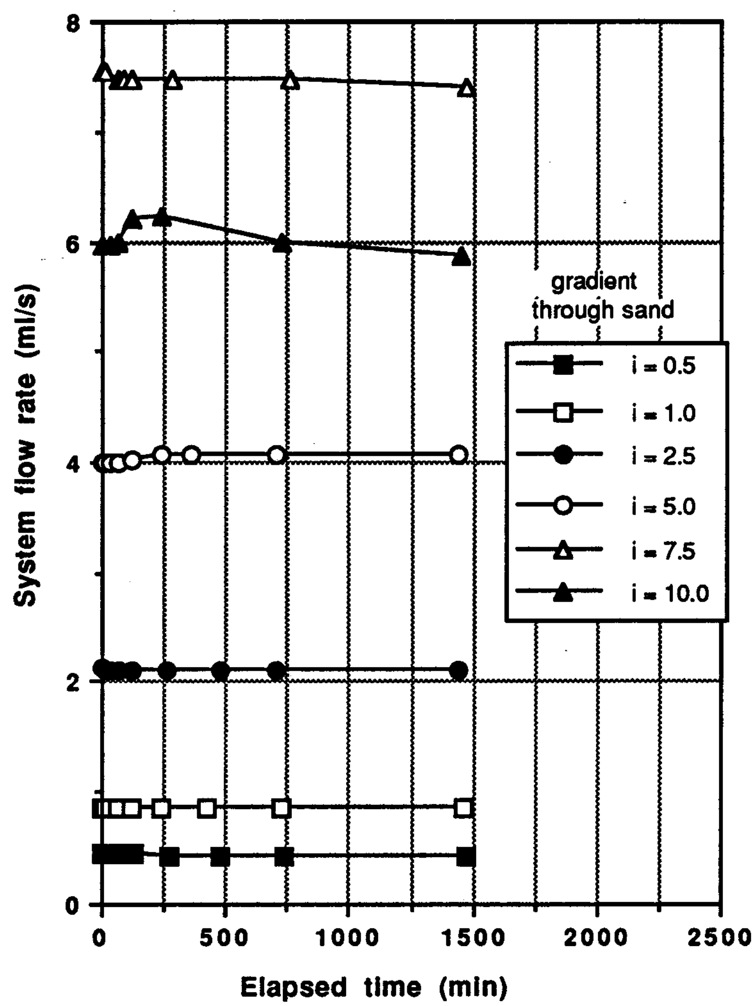

Figure 54 : Flow Rate for Quline in Modified Gradient Ratio Test

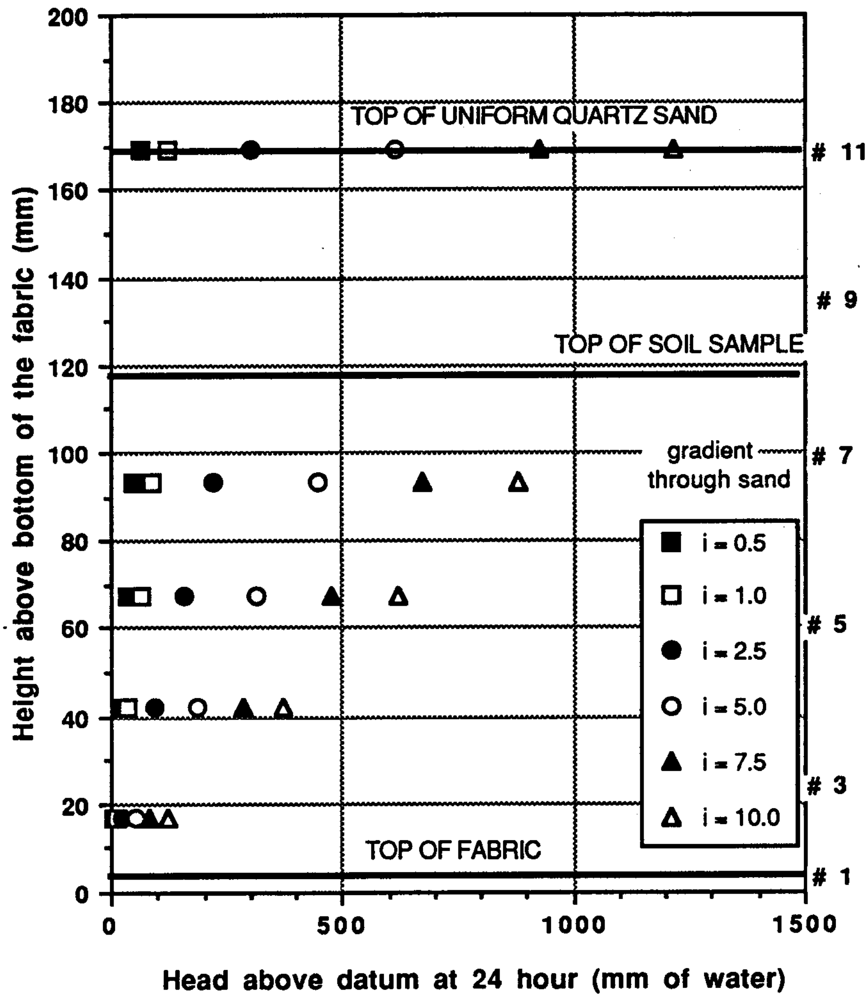

Figure 55 : Head Loss in the Sand - Geotextile System for Quline in Modified Gradient Ratio Test

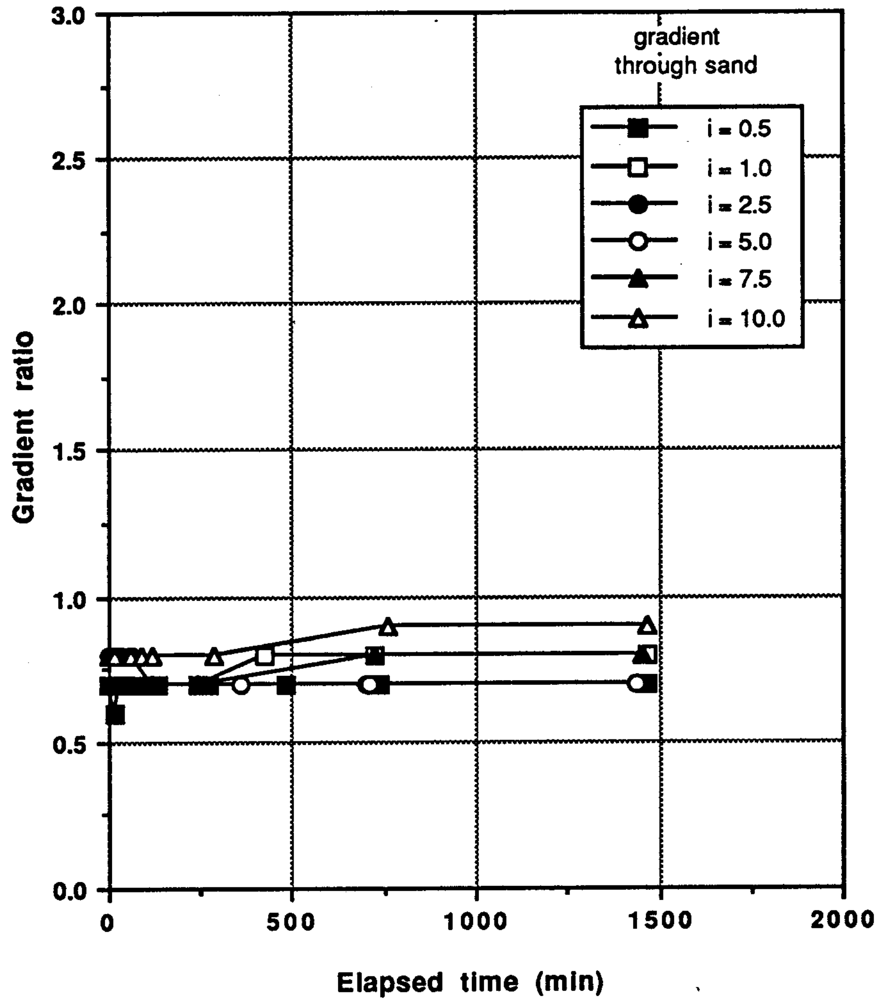

Figure 56: Gradient Ratio for Quline in Modified Gradient Ratio Test

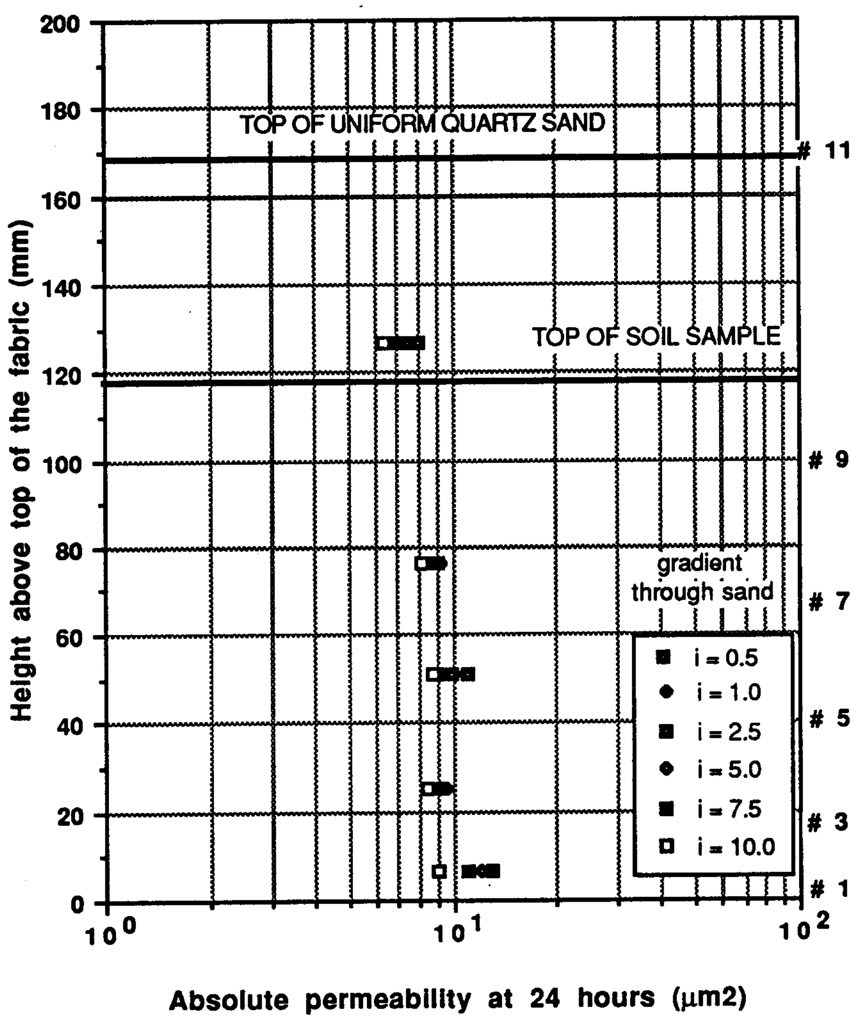

Figure 57 : Absolute Permeability of the Sand - Geotextile System for Quline in Modified Gradient Ratio Test

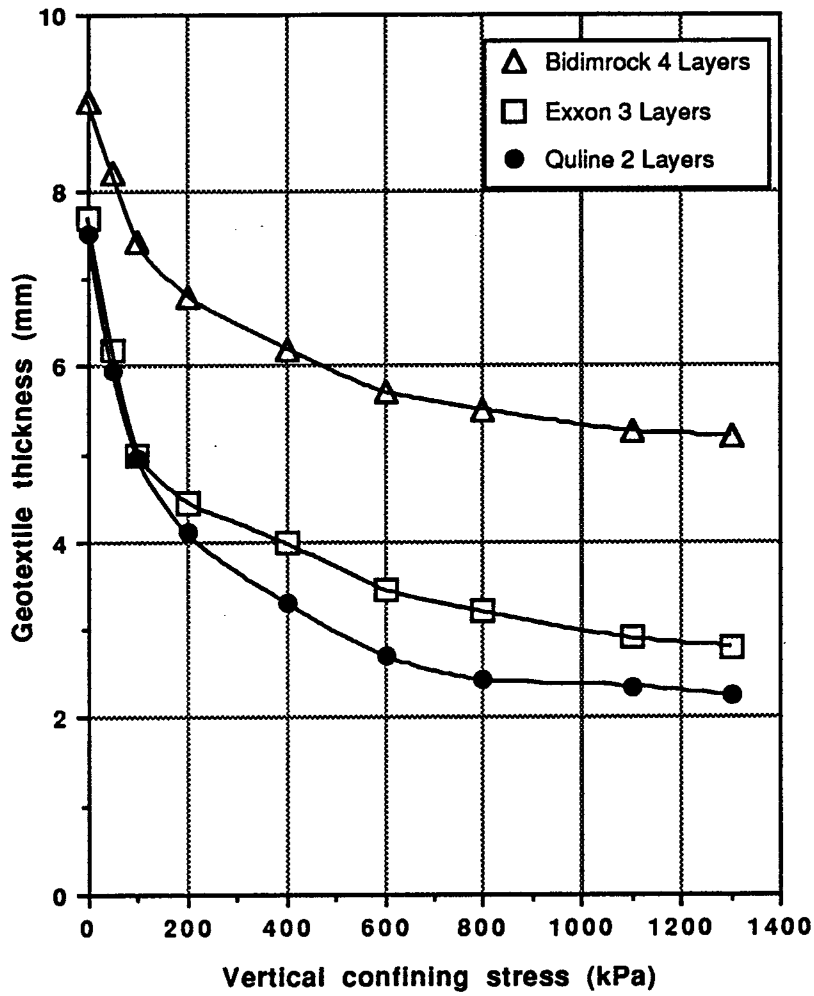

Figure 58 : Effect of Vertical Confining Stress on Geotextile Thickness

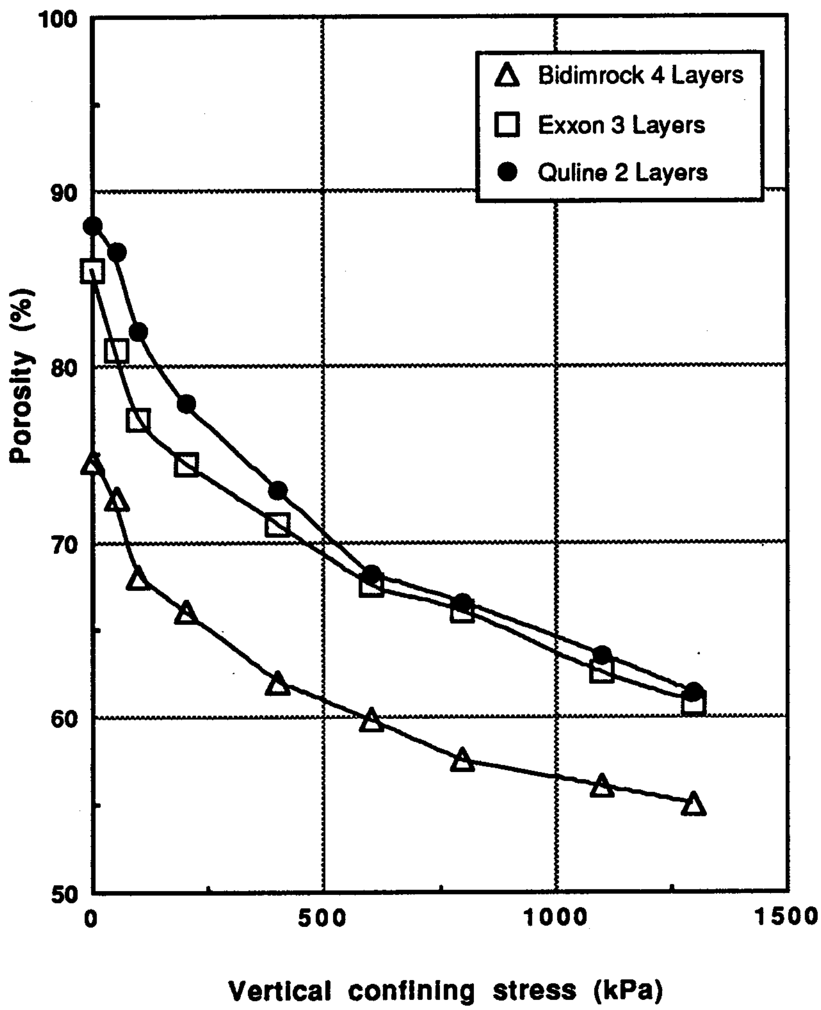

Figure 59 : Effect of Vertical Confining Stress on Porosity

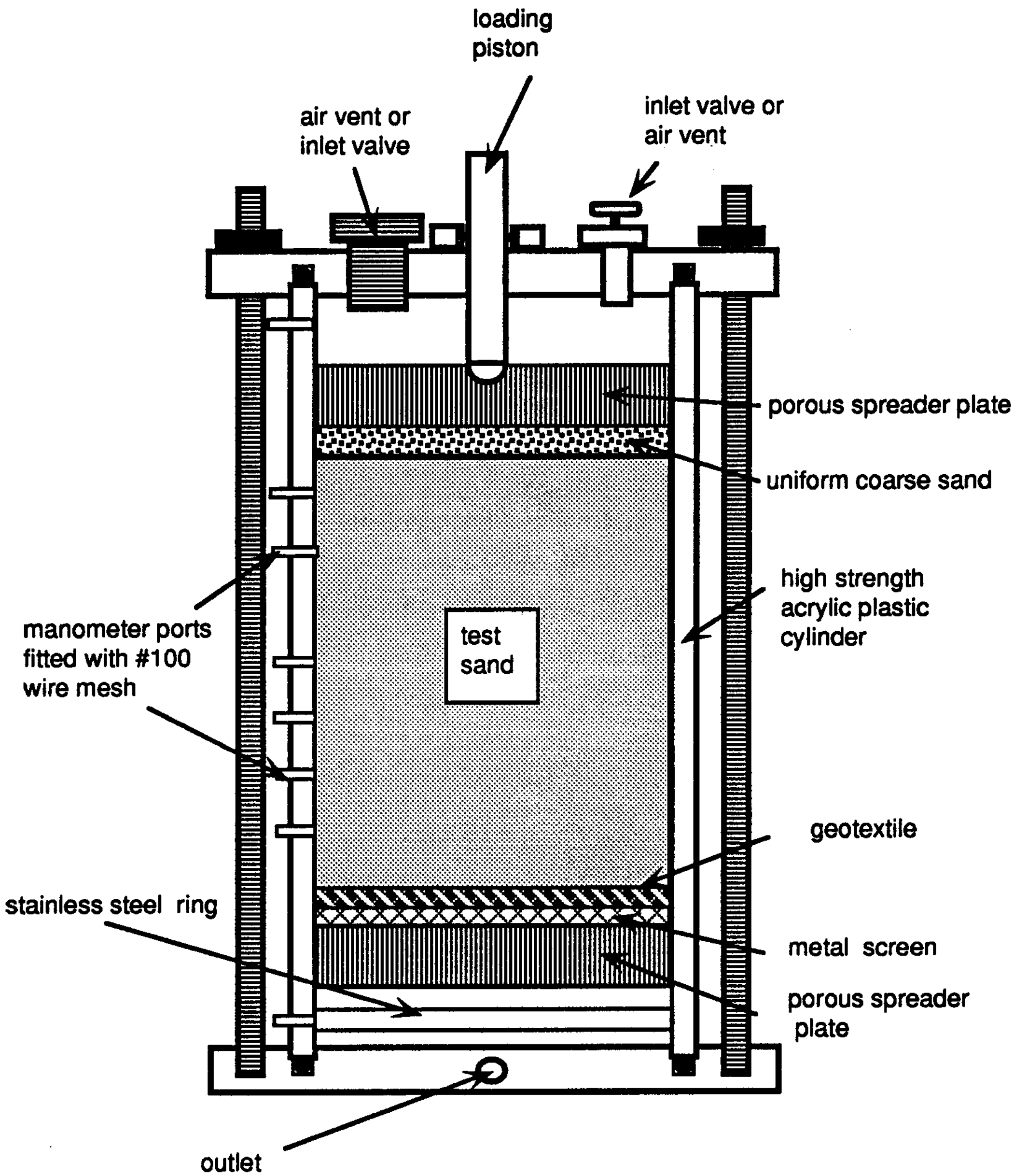

Figure 60 : Sectional View of the High Confining Stress Fitration Apparatus

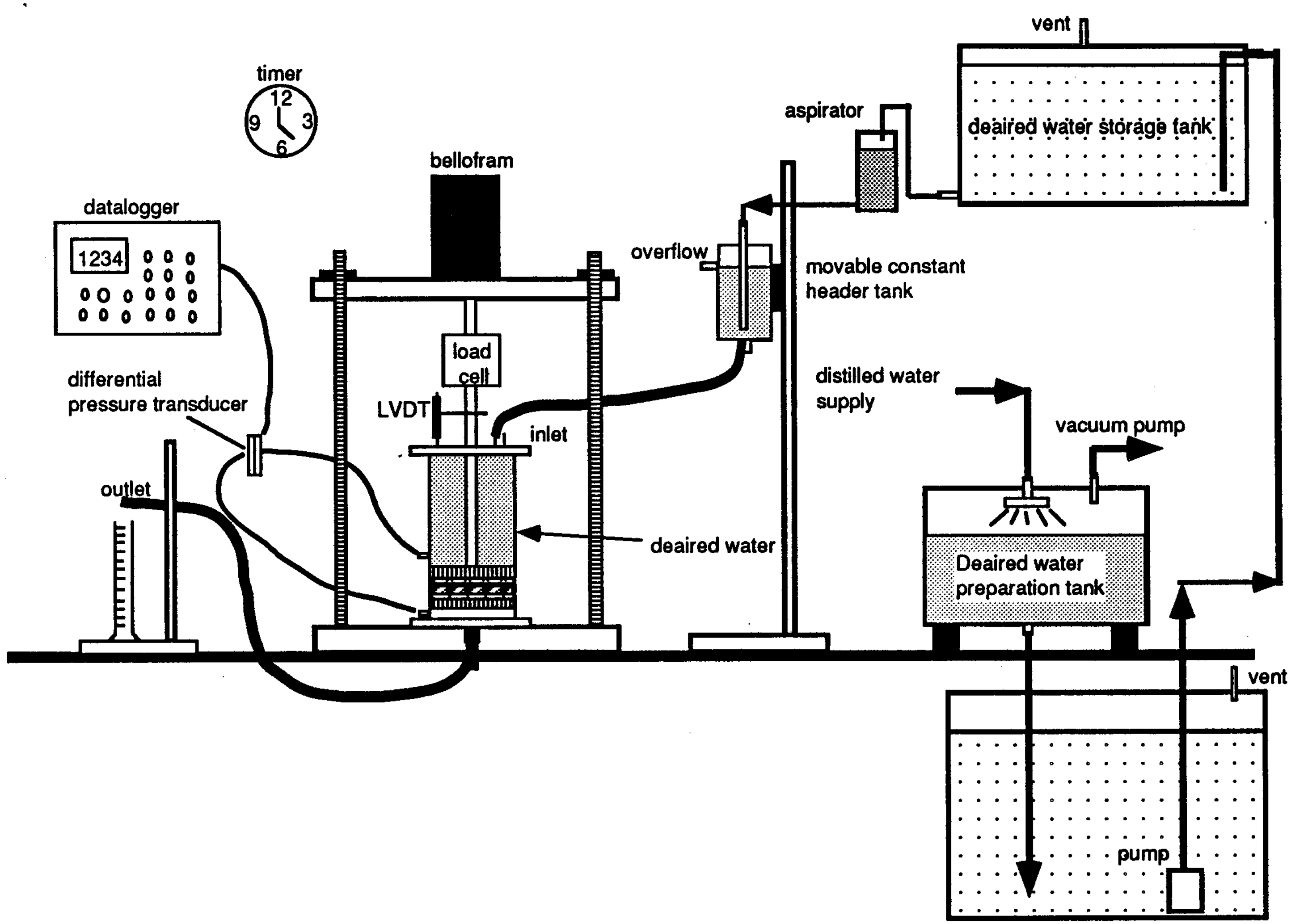

Figure 61 : System Layout for High Confining Stress Permittivity Testing with Water as Permeant

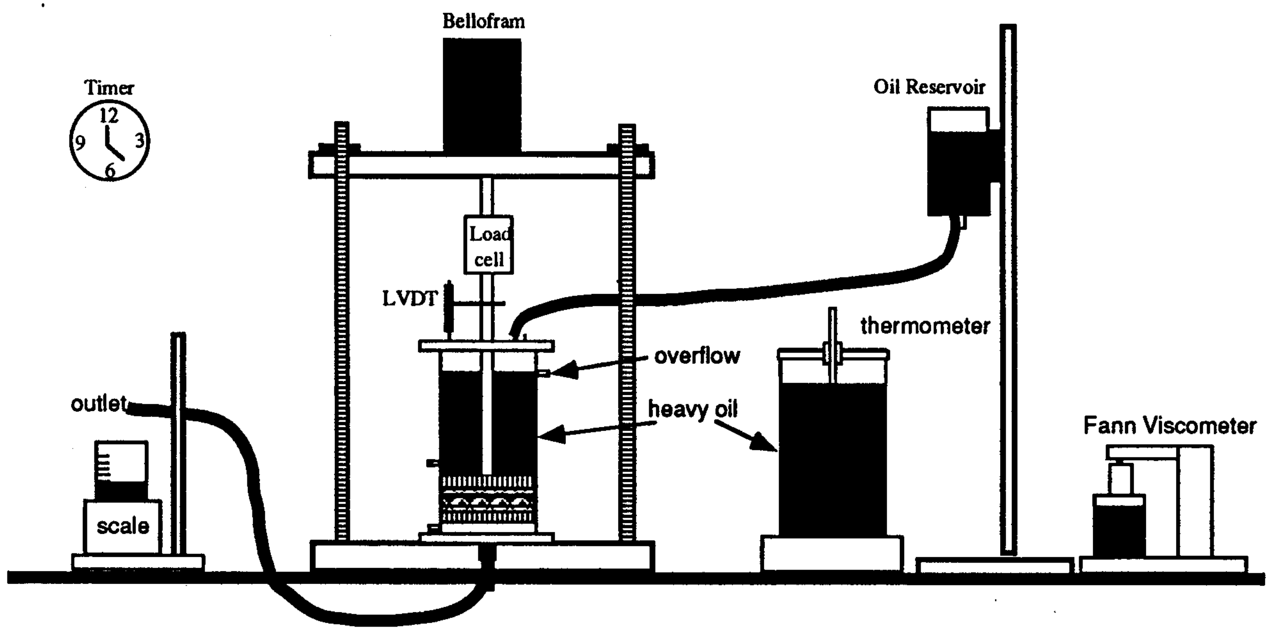

Figure 62 : System Layout for High Confining Stress Permittivity Testing with Heavy Oil as Permeant

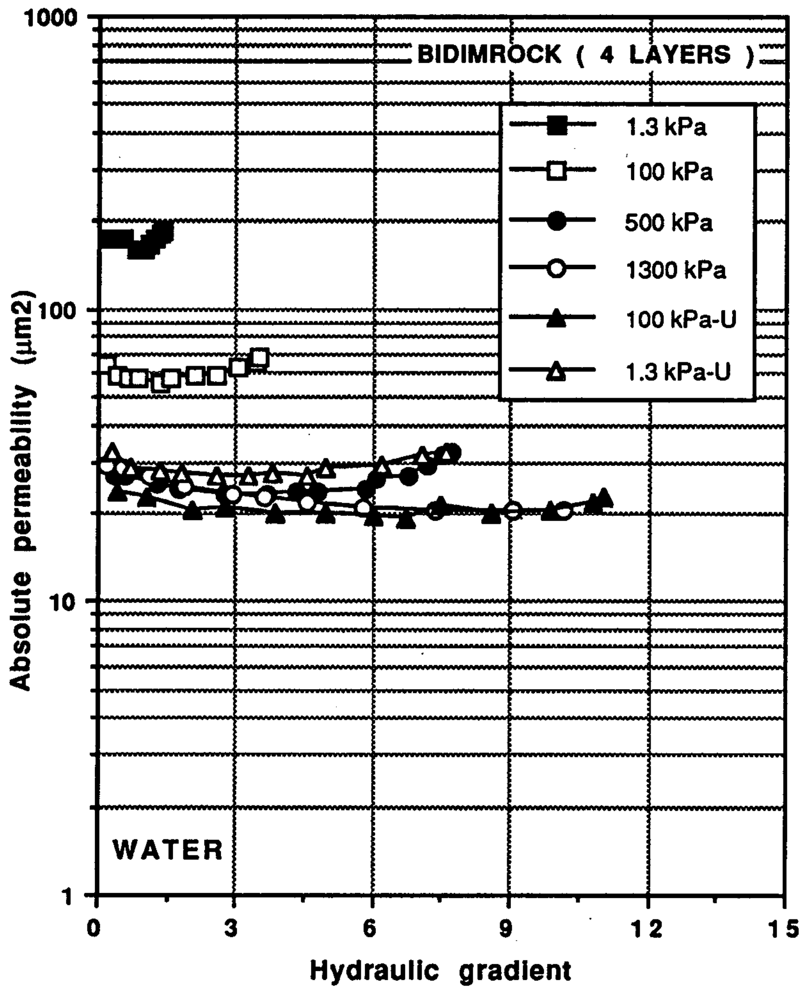

Figure 63 : Permittivity of Bidimrock to Water

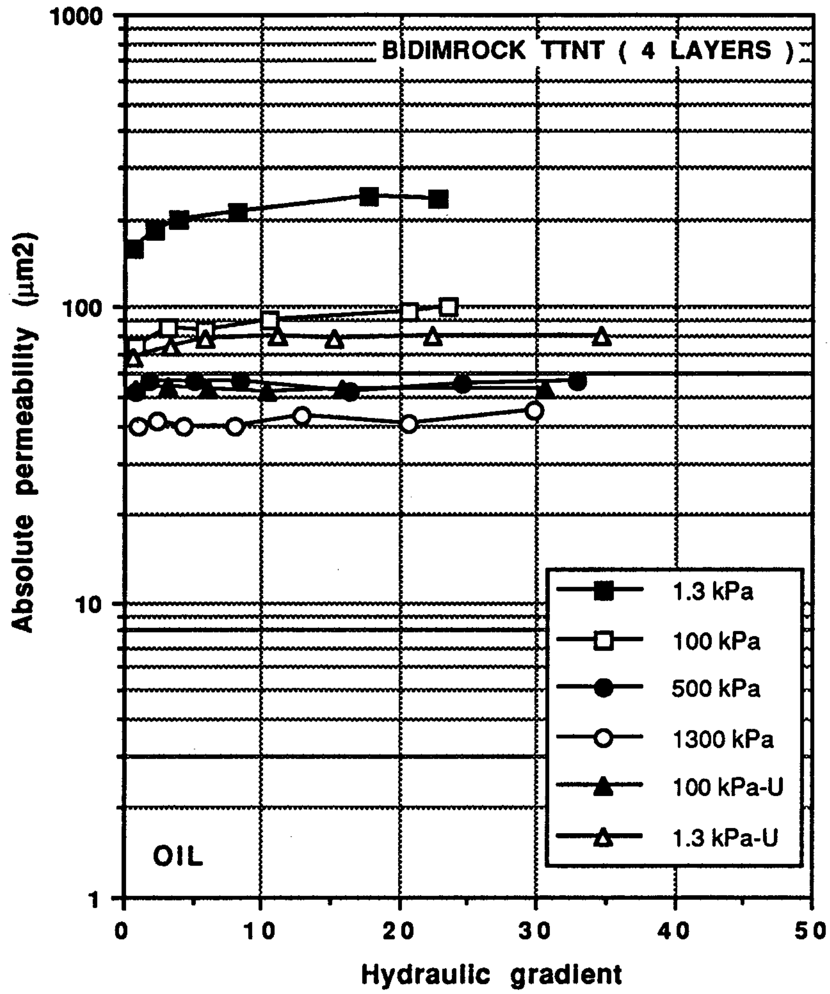

Figure 64 : Permittivity of Bidimrock to Heavy Oil

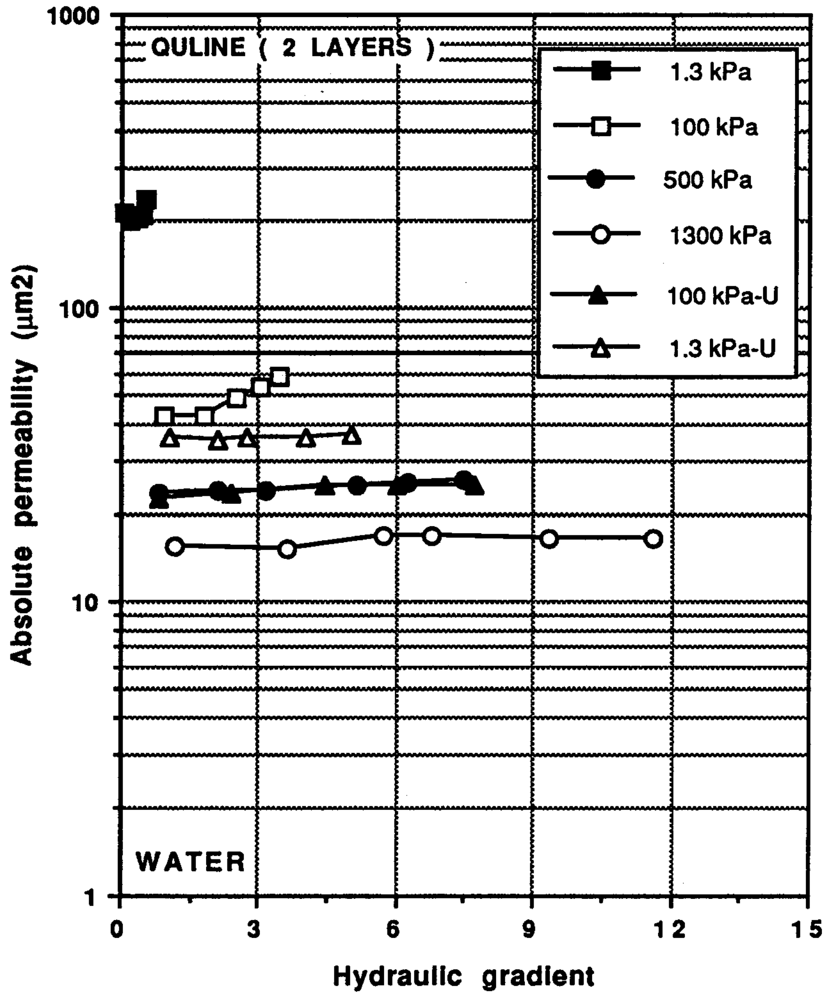

Figure 65 : Permittivity of Quline to Water

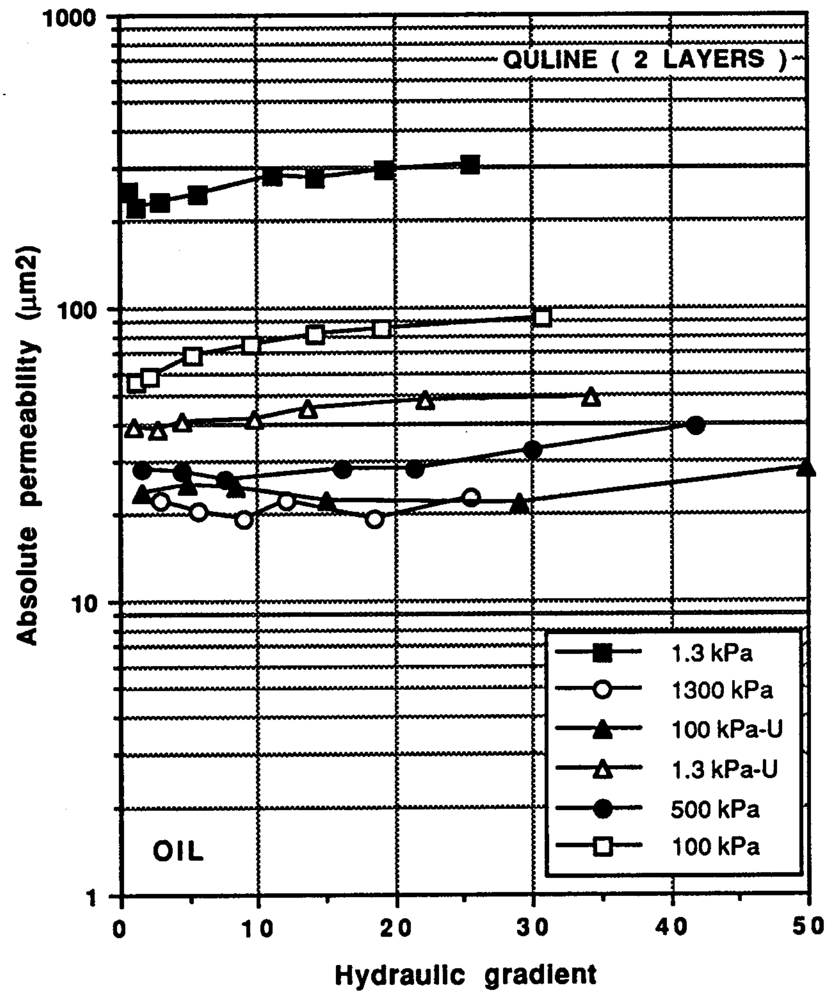

Figure 66 : Permittivity of Quline to Heavy Oil

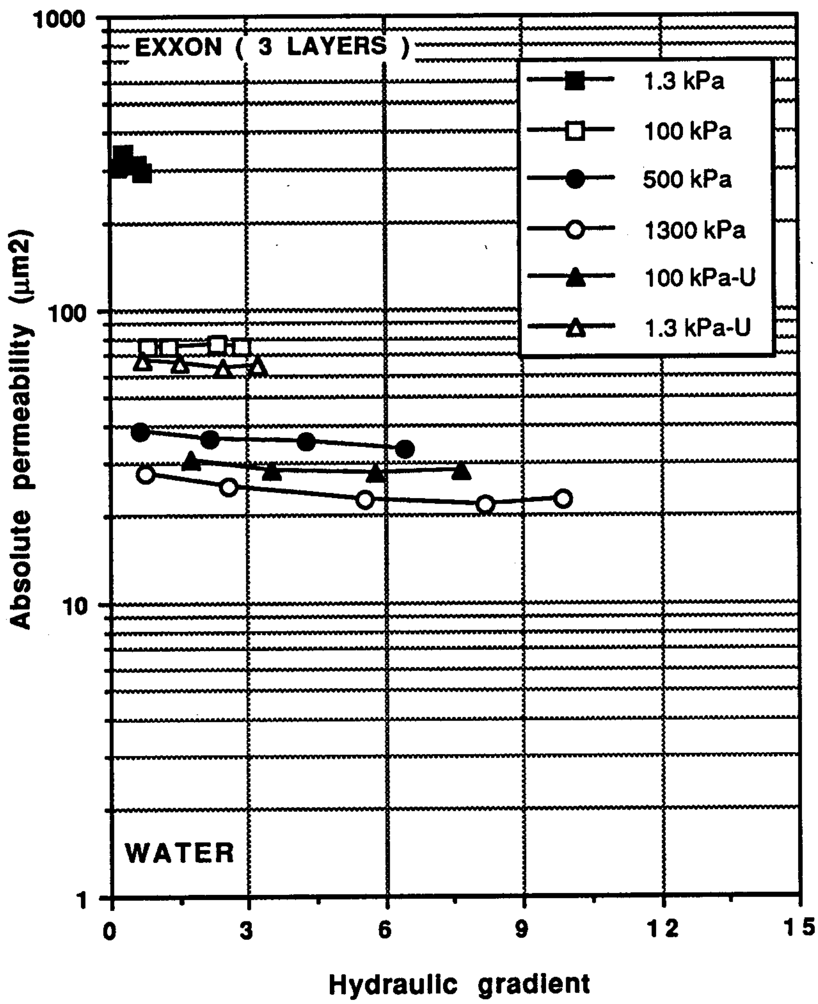

Figure 67 : Permittivity of Exxon to Water

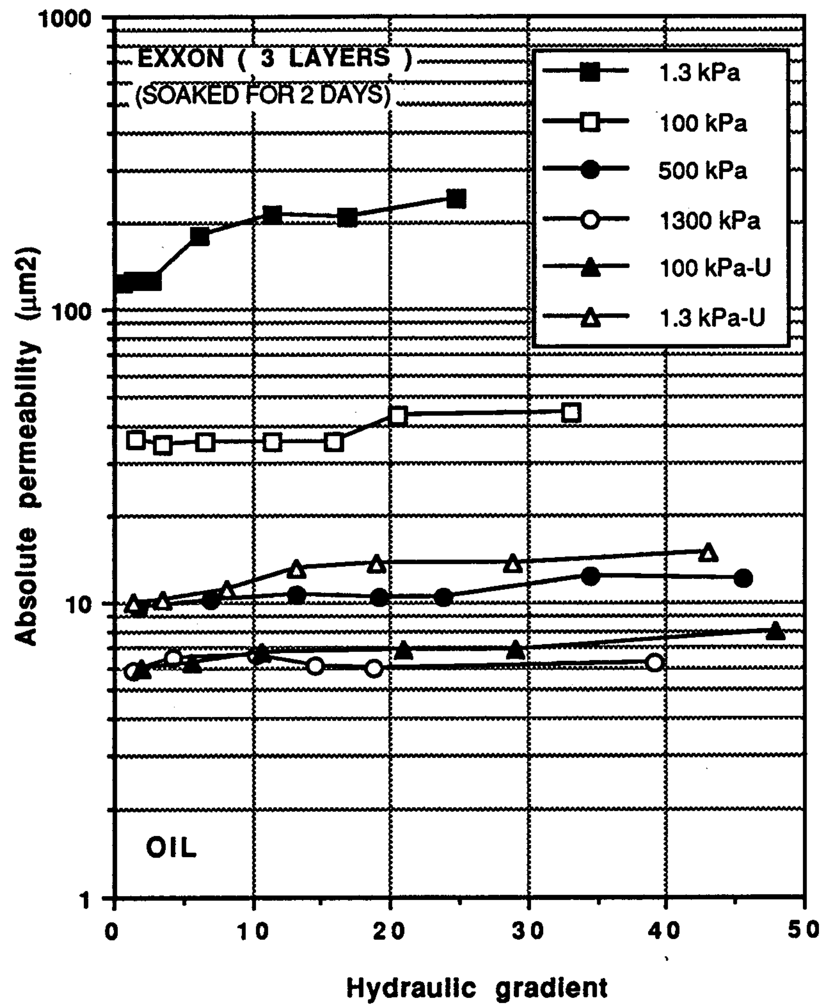

Figure 68 : Permittivity of Exxon to Heavy Oil with Fabric Soaked for 2 Days

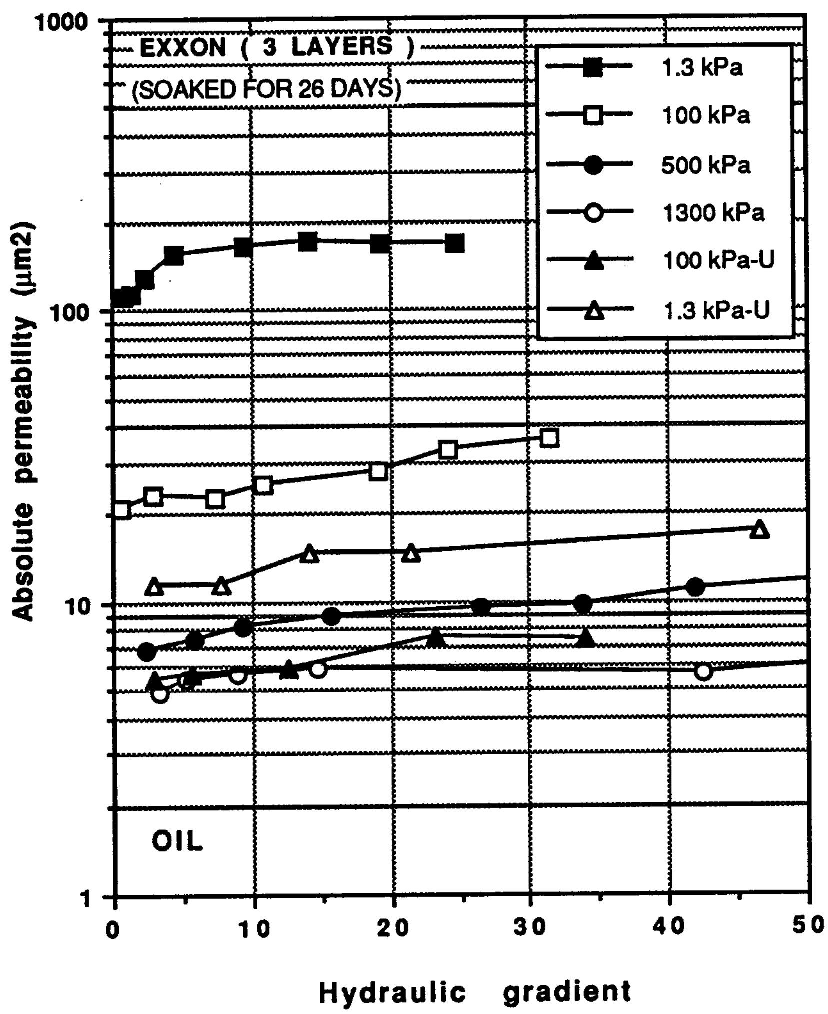

Figure 69 : Permittivity of Exxon to Heavy Oil with Fabric Soaked for 26 Days

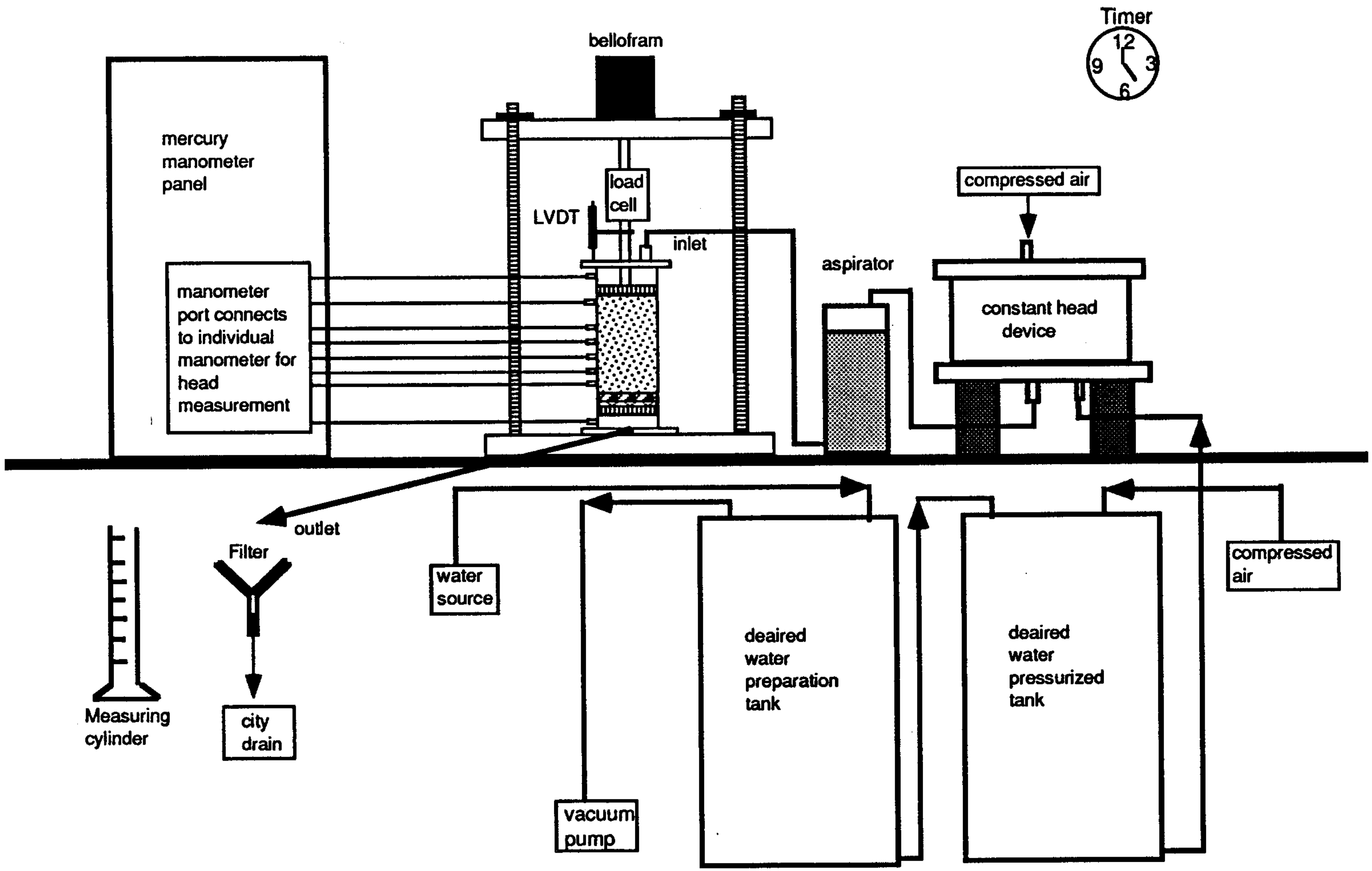

Figure 70 : Schematic System Setup for High Confining Stress Sand-Geotextile Filtration Testing

$$\text{Gradient Ratio} = \frac{\dfrac{dhsf}{Lsf}}{\dfrac{dhs}{Ls}}$$

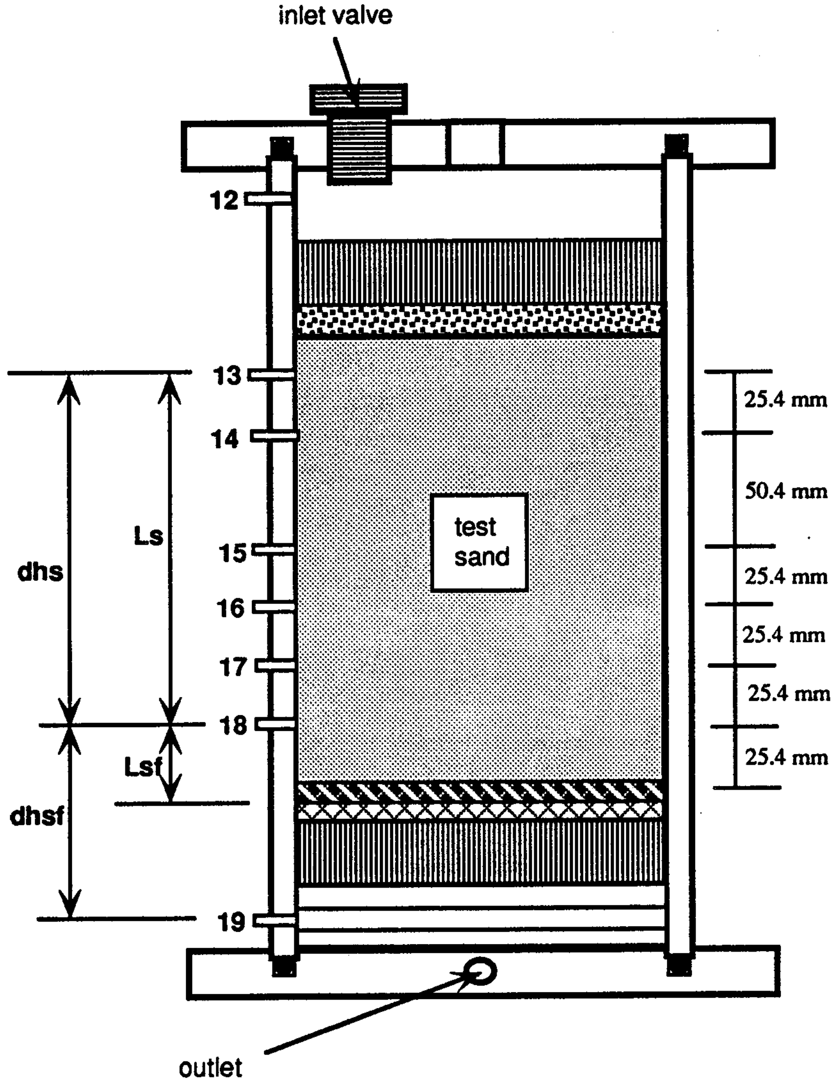

Figure 71 : Sectional View of the High Confining Stress Fitration Apparatus

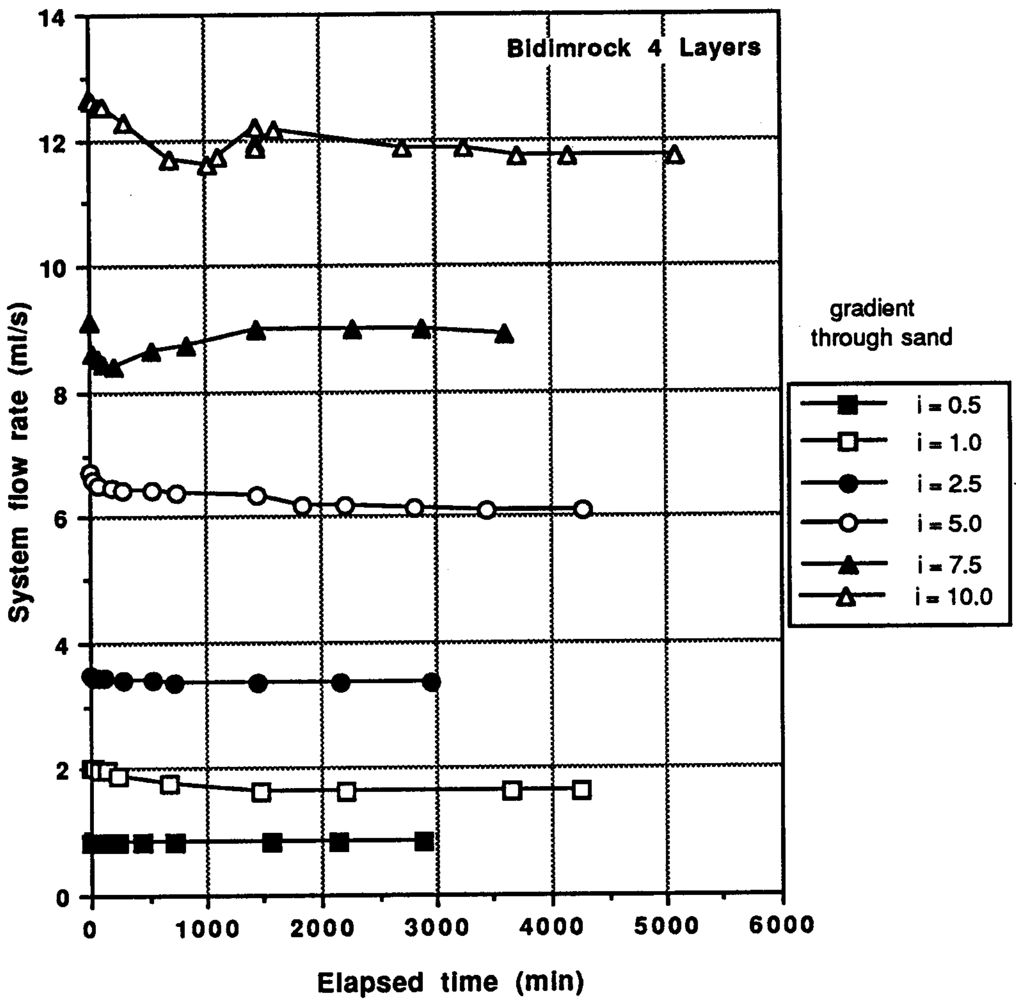

Figure 72 : Flow Rate for Bidimrock in High Confining Stress Filtration Test

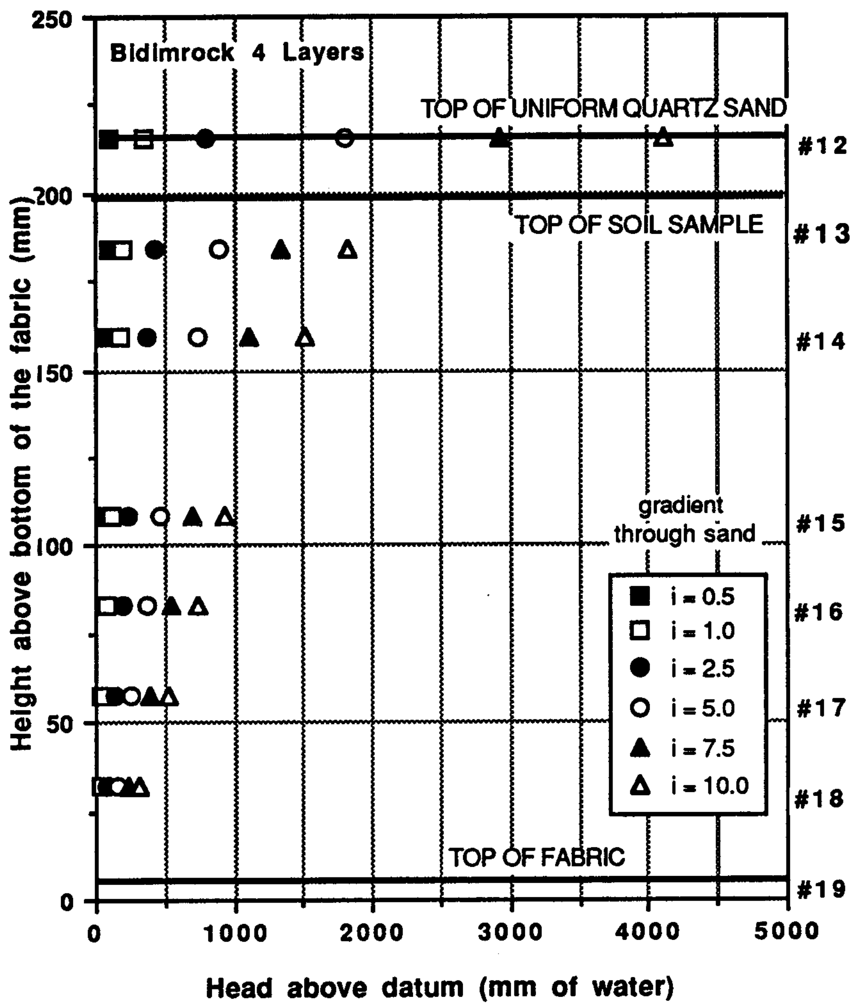

Figure 73 : Head Loss in the Sand - Geotextile System for Bidimrock in High Confining Stress Filtration Test

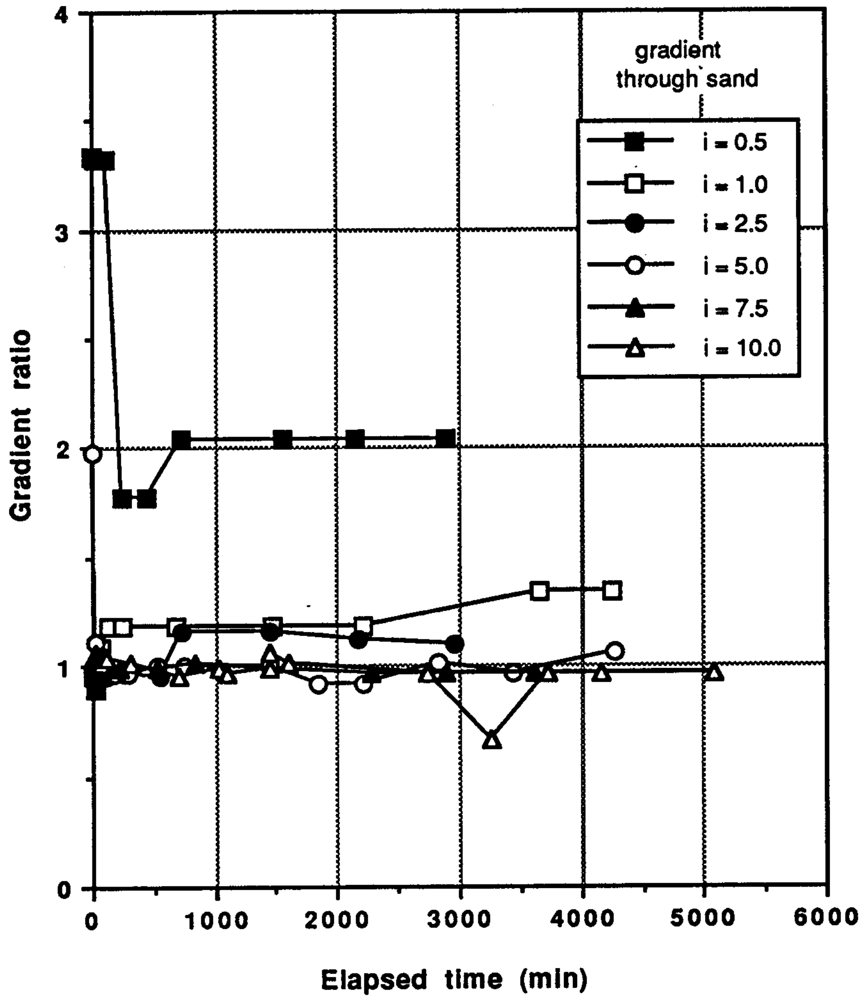

Figure 74 : Gradient Ratio for Bidimrock in High Confining Stress Filtration Test

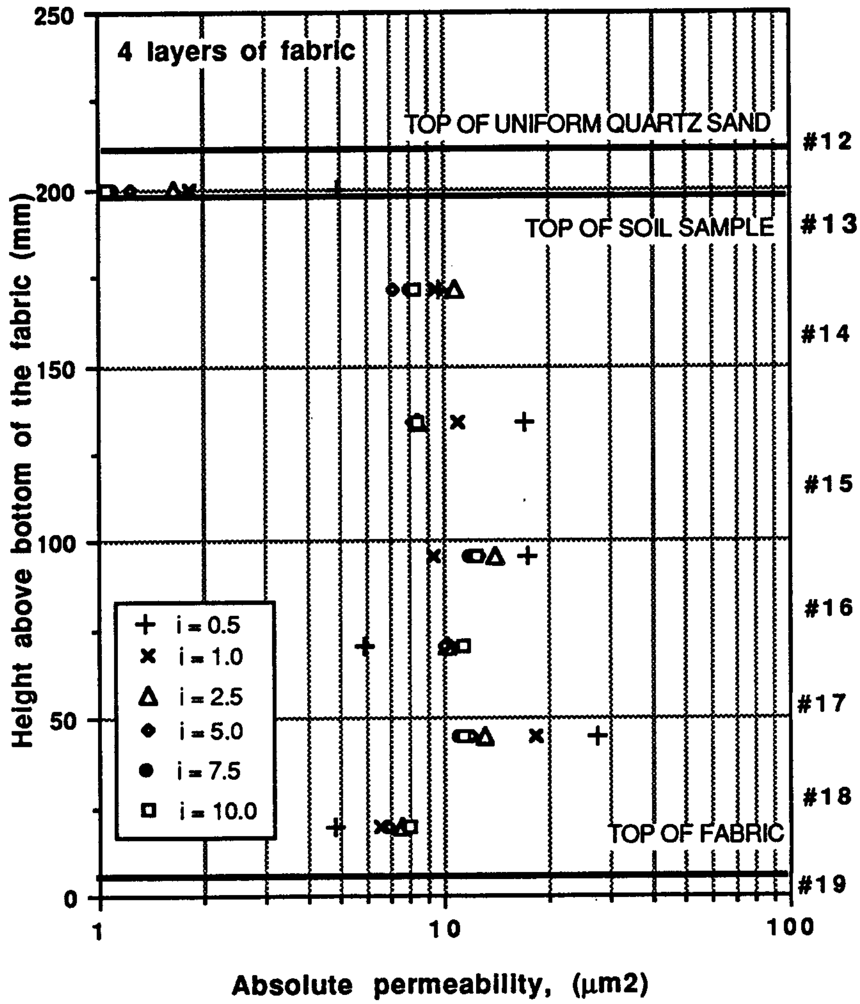

Figure 75: Absolute Permeability of the Sand-Geotextile System for Bidimrock in High Confining Stress Filtration Test

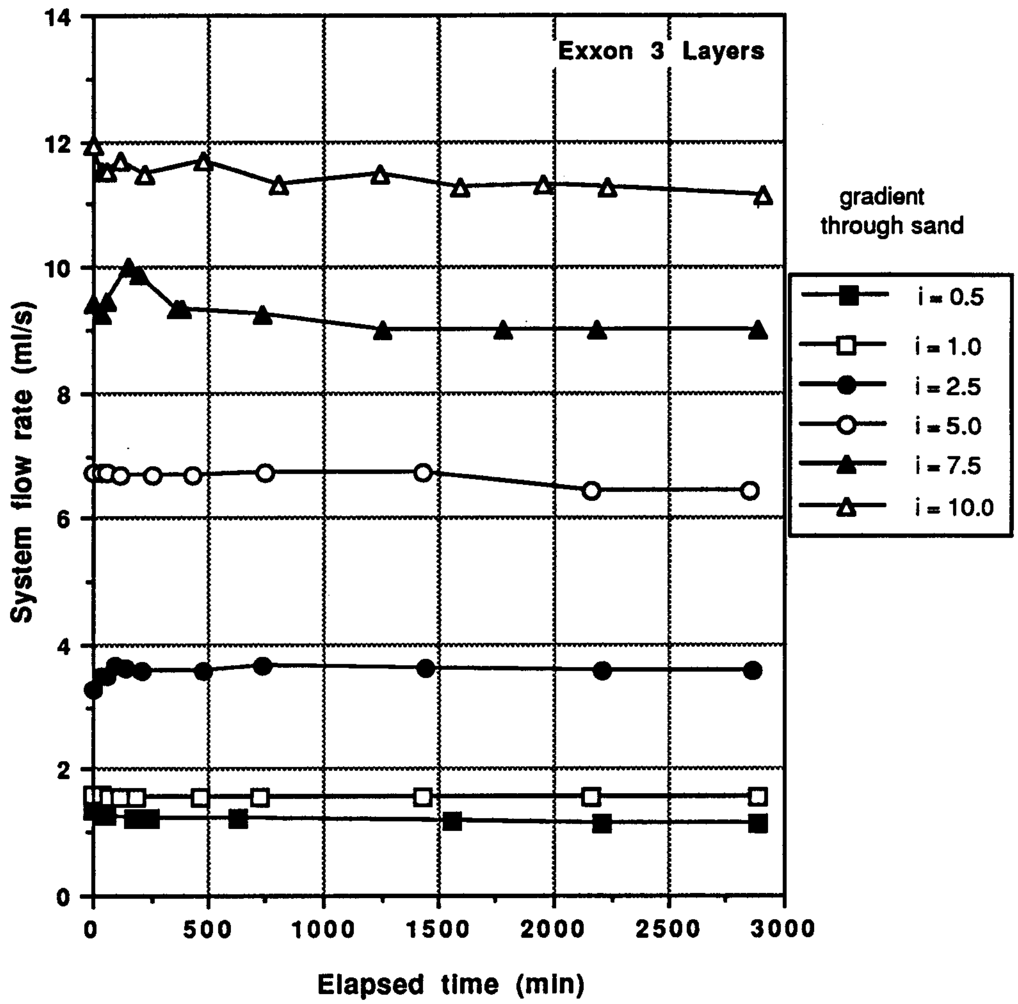

Figure 76 : Flow Rate for Exxon in High Confining Stress Filtration Test

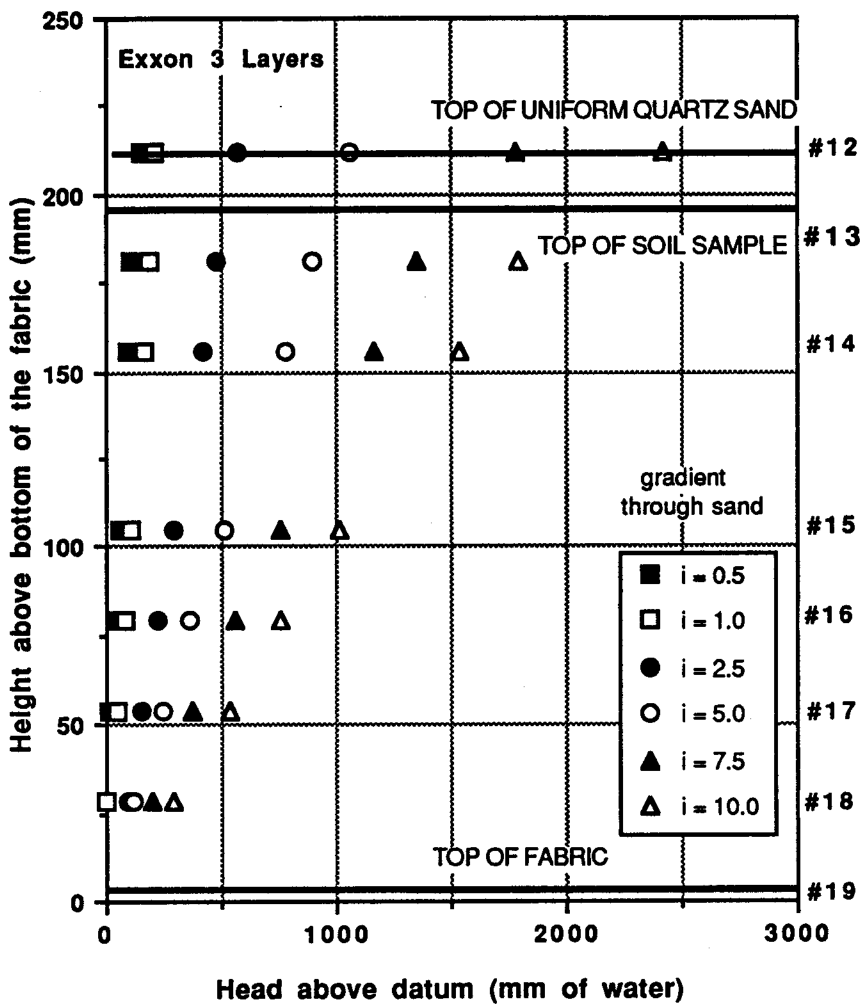

Figure 77 : Head Loss in the Sand - Geotextile System for Exxon in High Confining Stress Filtration Test

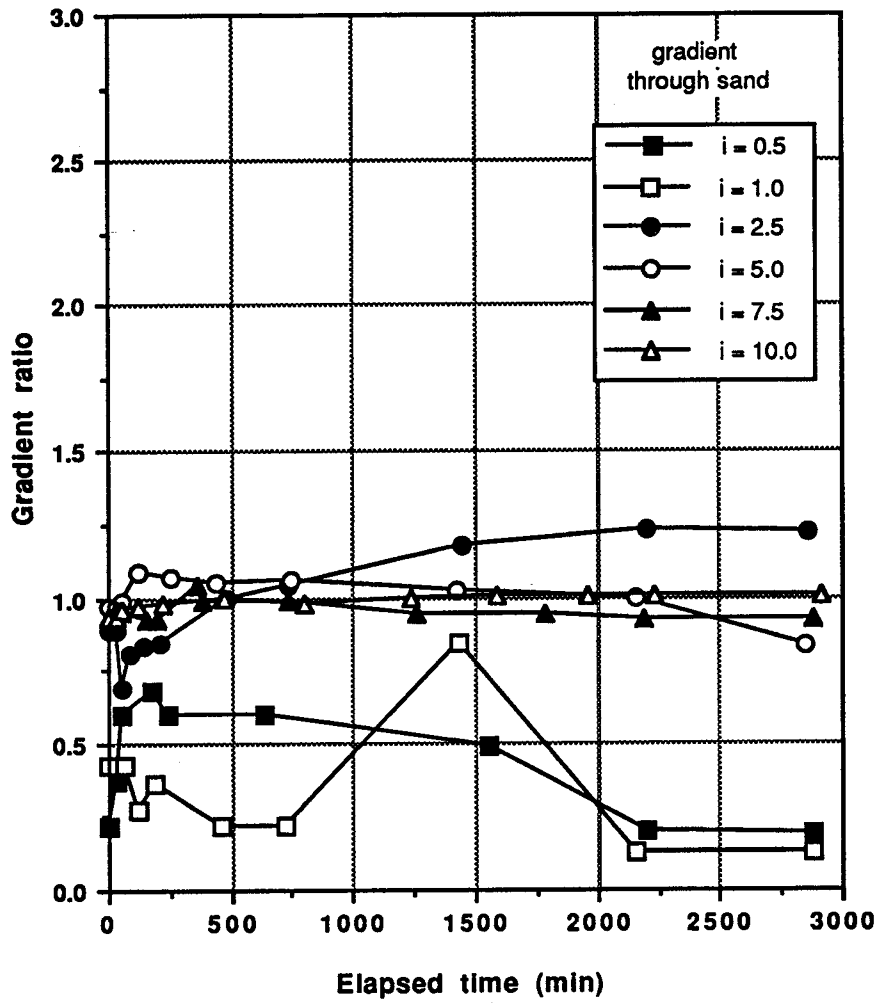

Figure 78: Gradient Ratio for Exxon in High Confining Stress Filtration Test

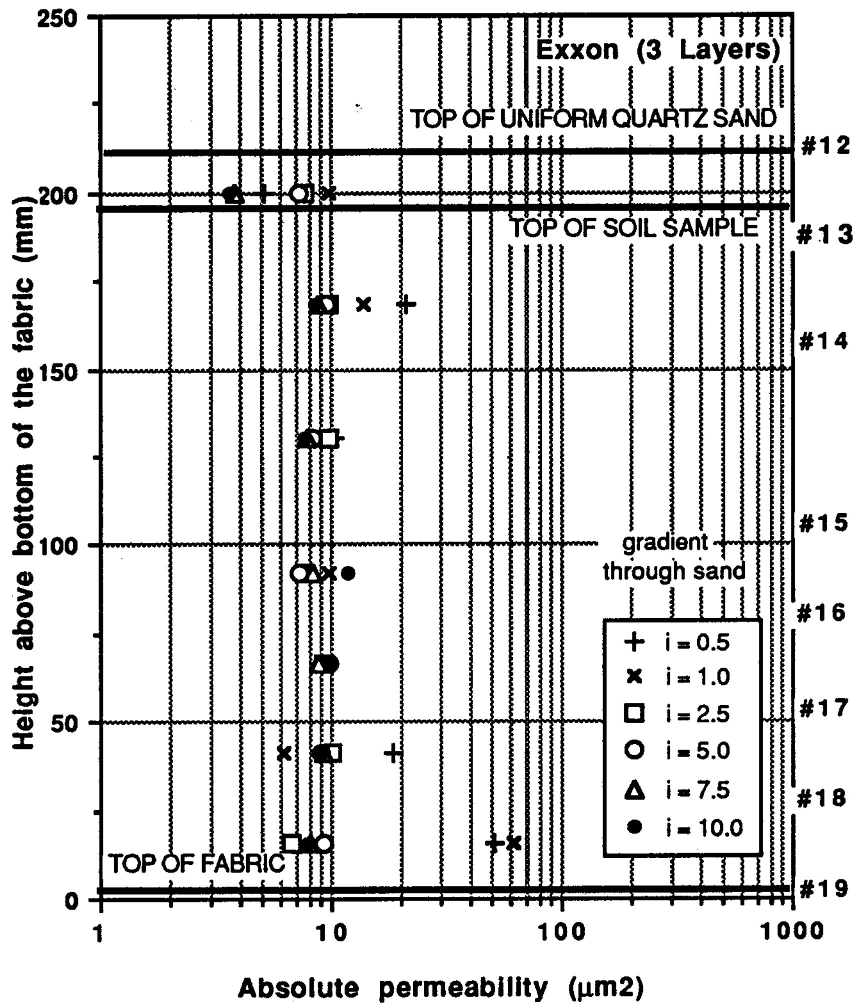

Figure 79: Absolute Permeability of the Sand - Geotextile System for Exxon in High Confining Stress Filtration Test

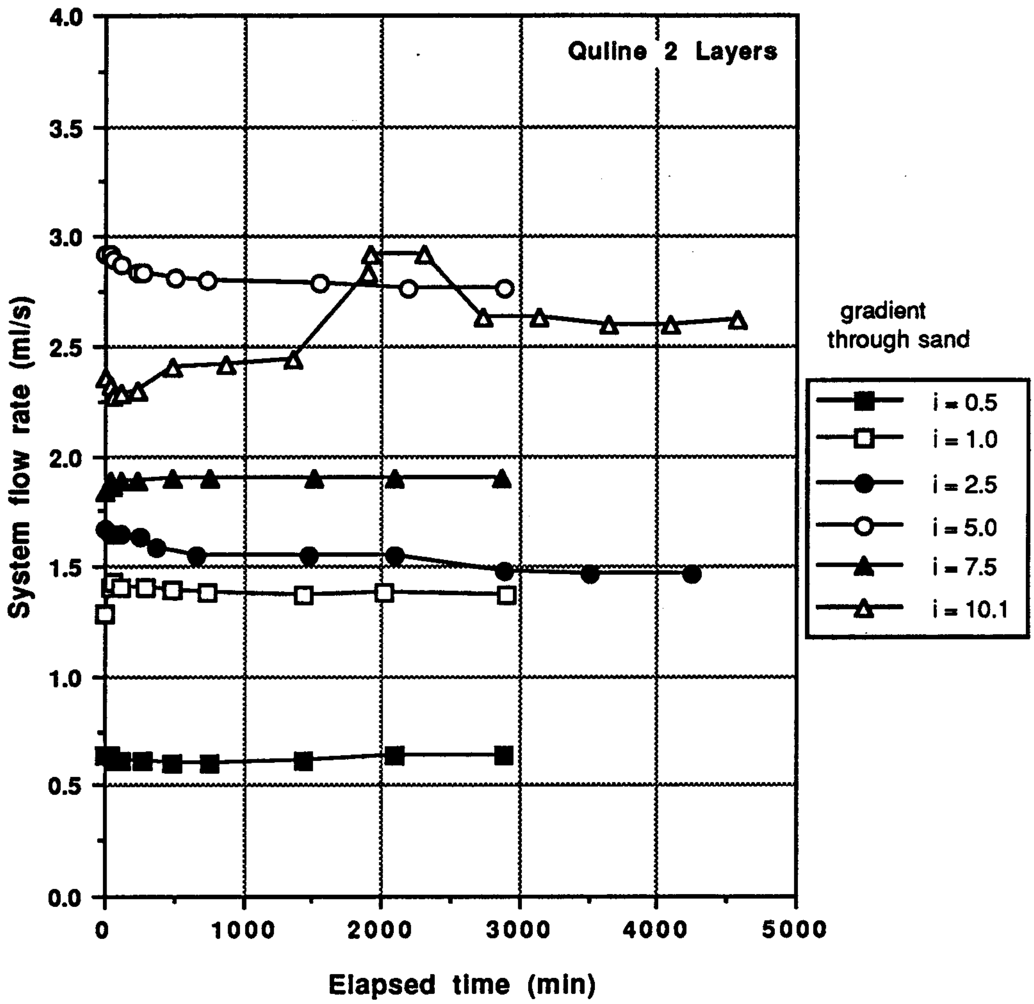

Figure 80 : Flow Rate for Quline in High Confining Stress Filtration Test

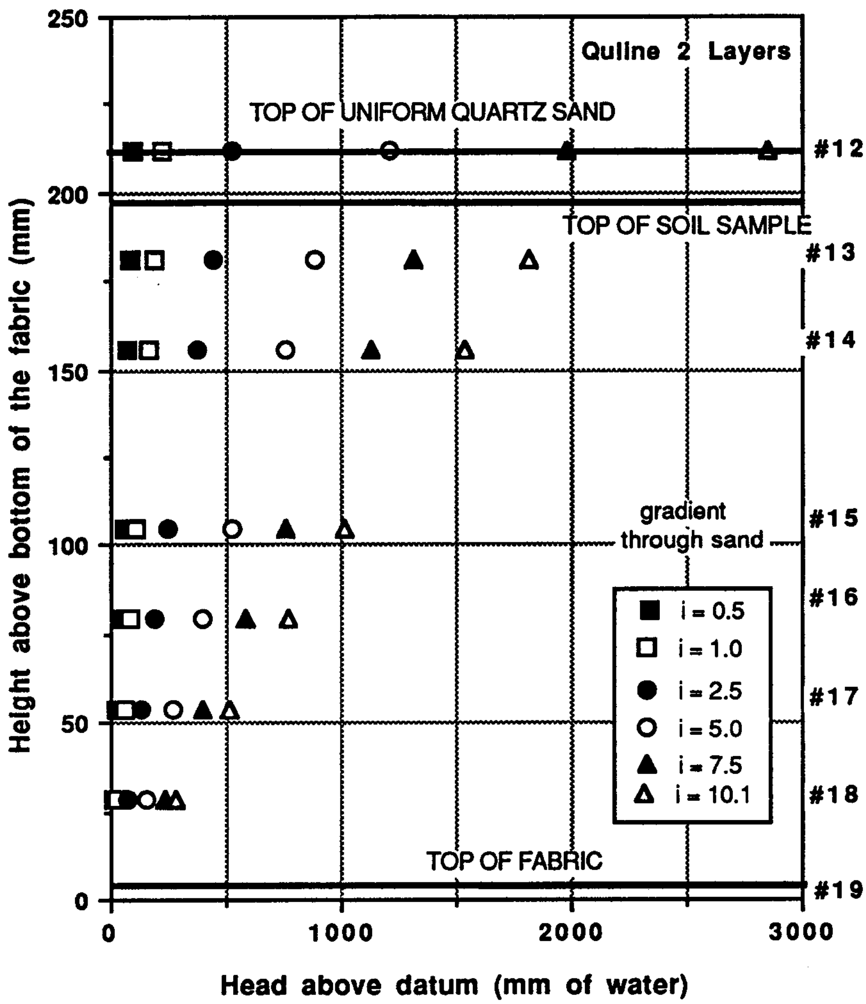

Figure 81 : Head Loss in the Sand - Geotextile System for Quline in High Confining Stress Filtration Test

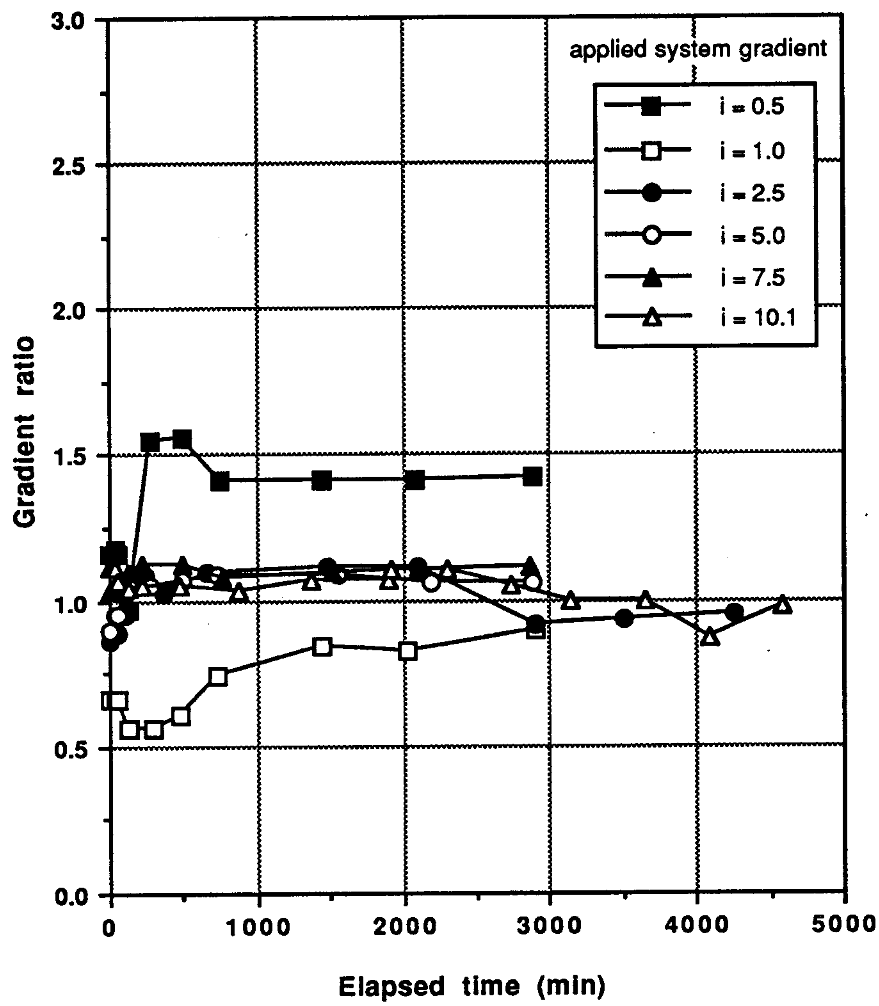

Figure 82: Gradient Ratio for Quline in High Confining Stress Filtration Test

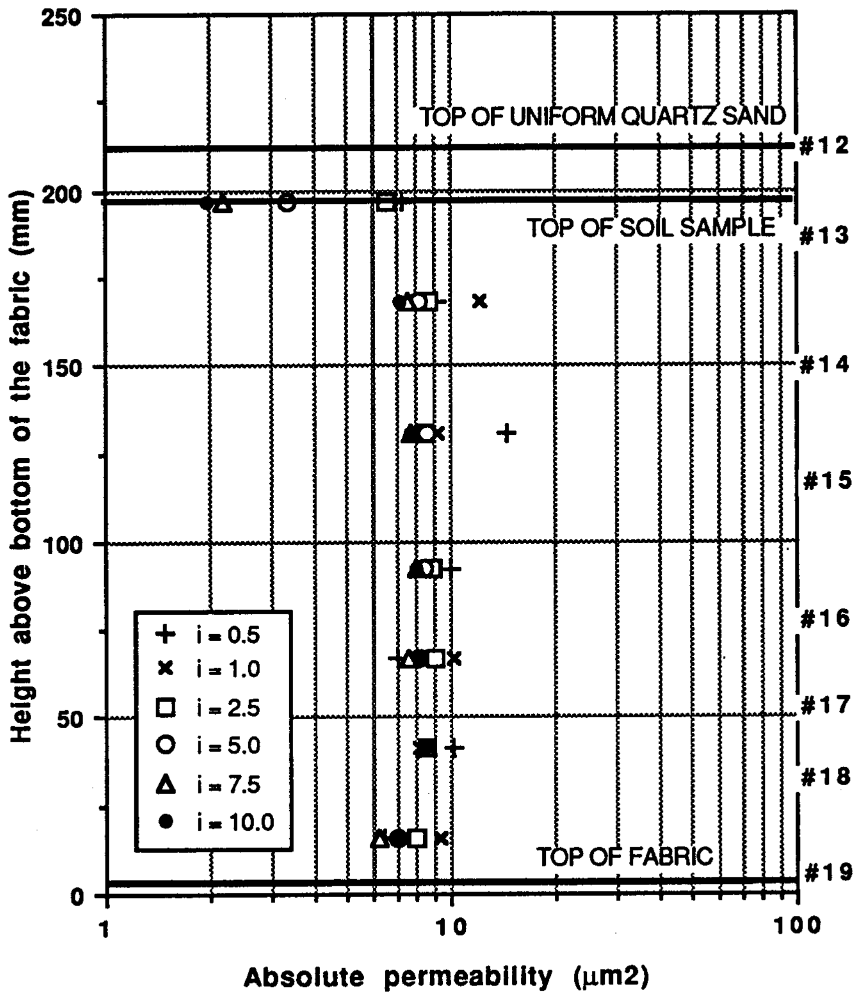

Figure 83 : Absolute Permeability of the Sand - Geotextile System for Quline in High Confining Stress Filtration Test

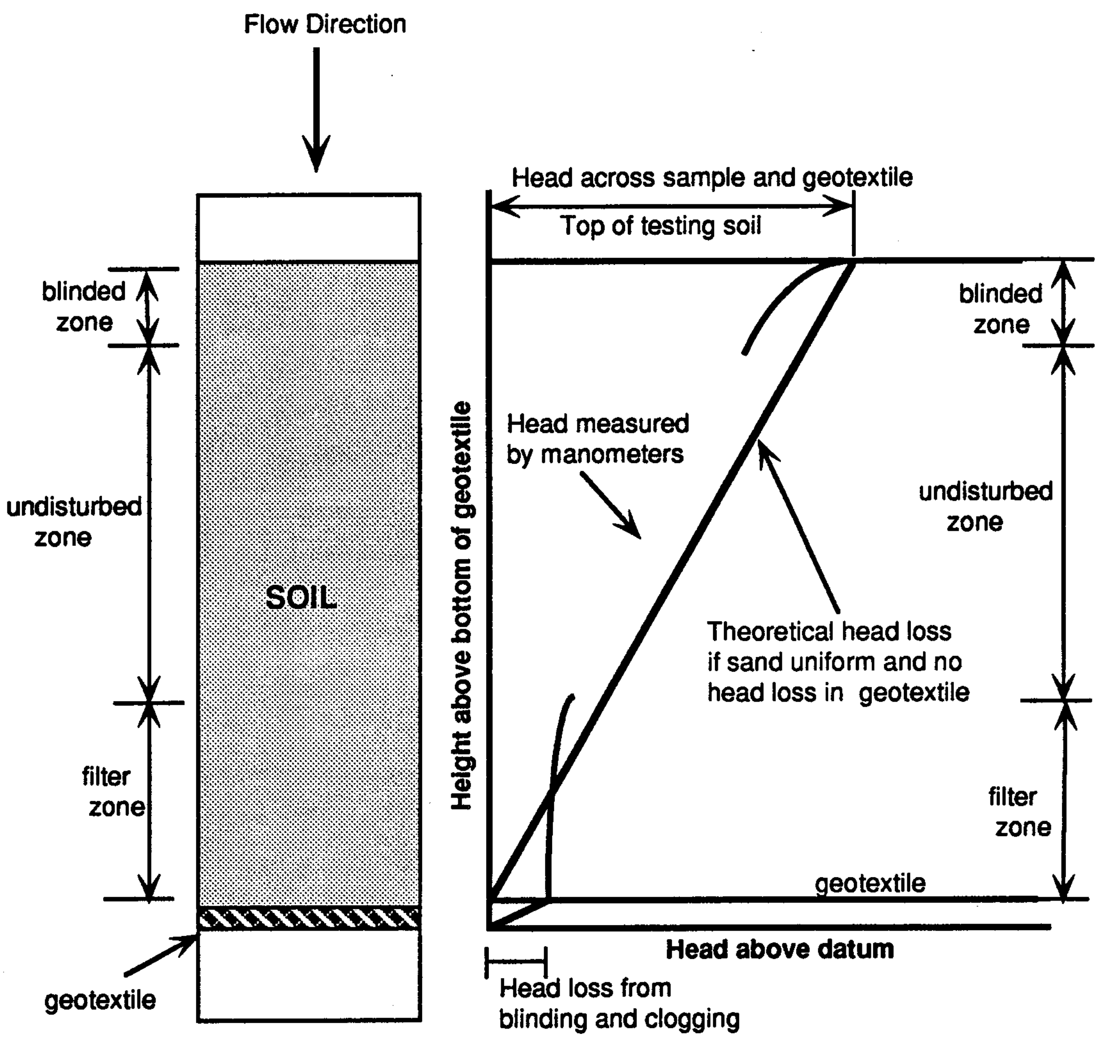

Figure 84 : Head Loss Through Soil-Geotextile System
(Scott, 1980)

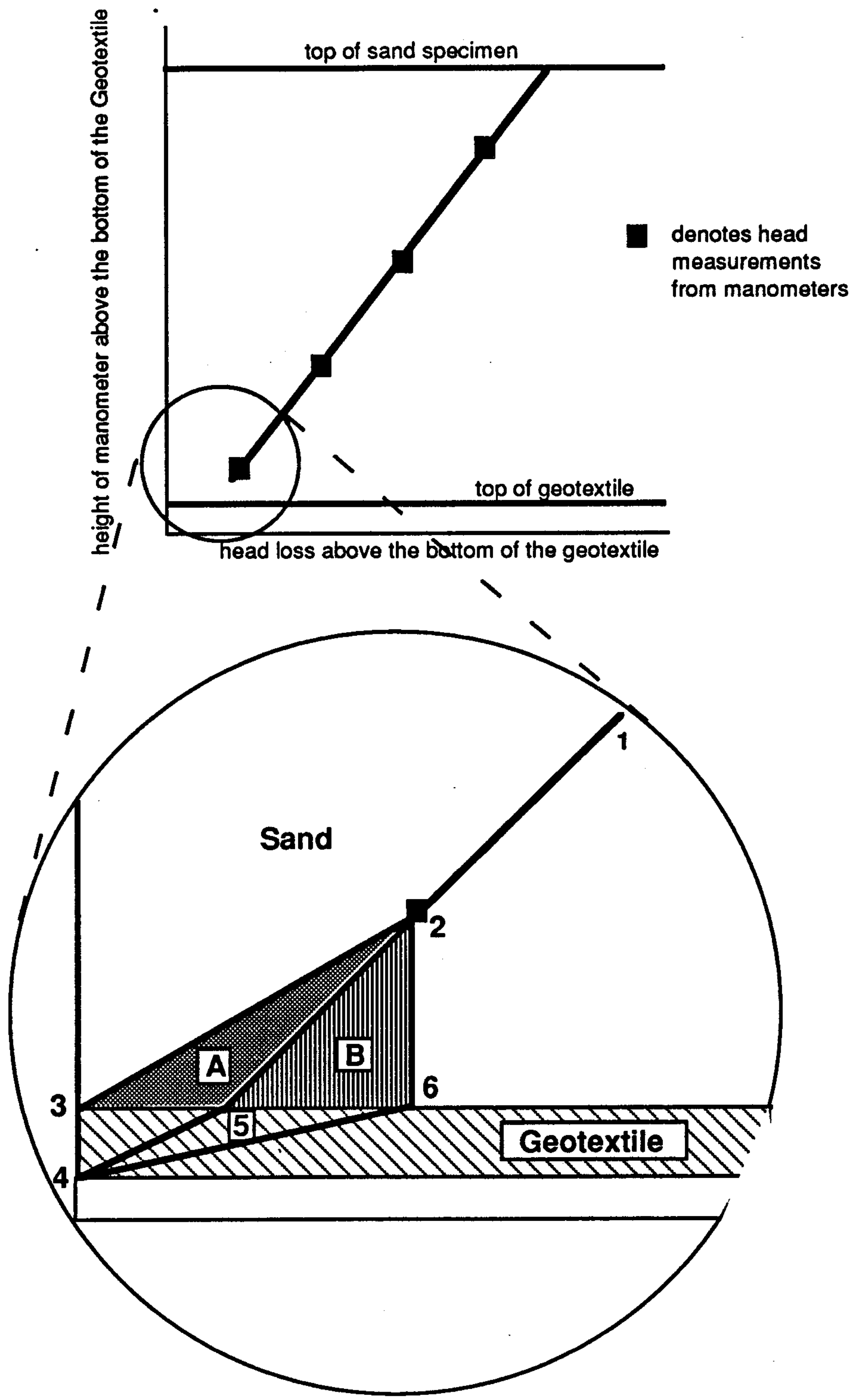

Figure 85 : Determination of the Head Loss Across the Geotextile in Filtration Tests

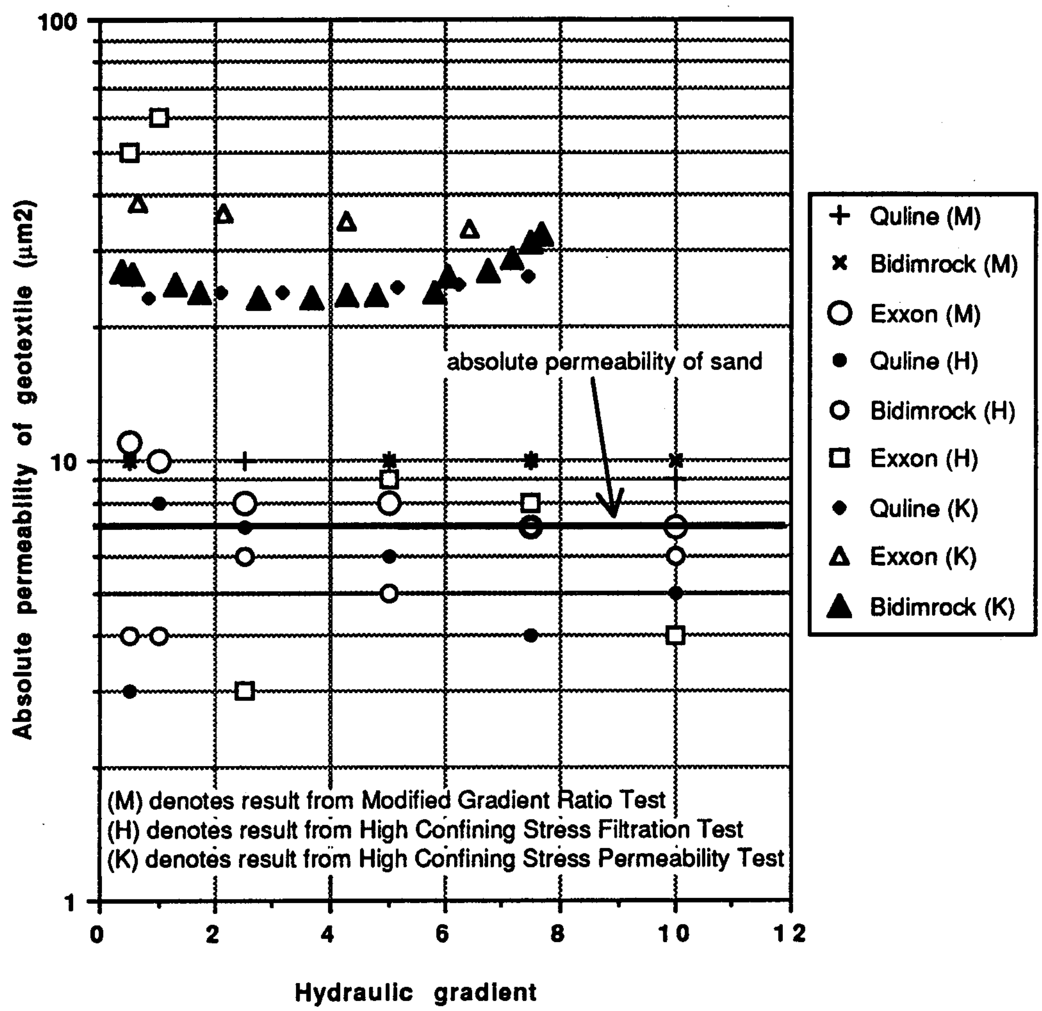

Figure 86 : Effect of Hydraulic Gradient on the Absolute Permeability of Geotextiles

APPENDIX A

Effect of Hydraulic Gradient and Time on the Hydraulic Conductivity of the Sand-Geotextile System in the Gradient Ratio Test

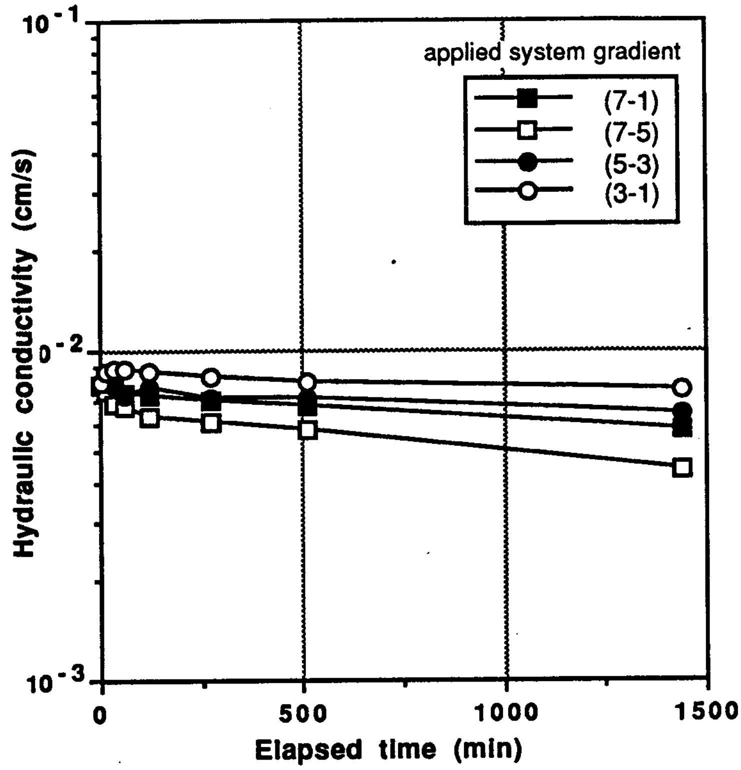

Figure A1: Hydraulic Conductivity for Armtec in Gradient Ratio Test, i = 1.0

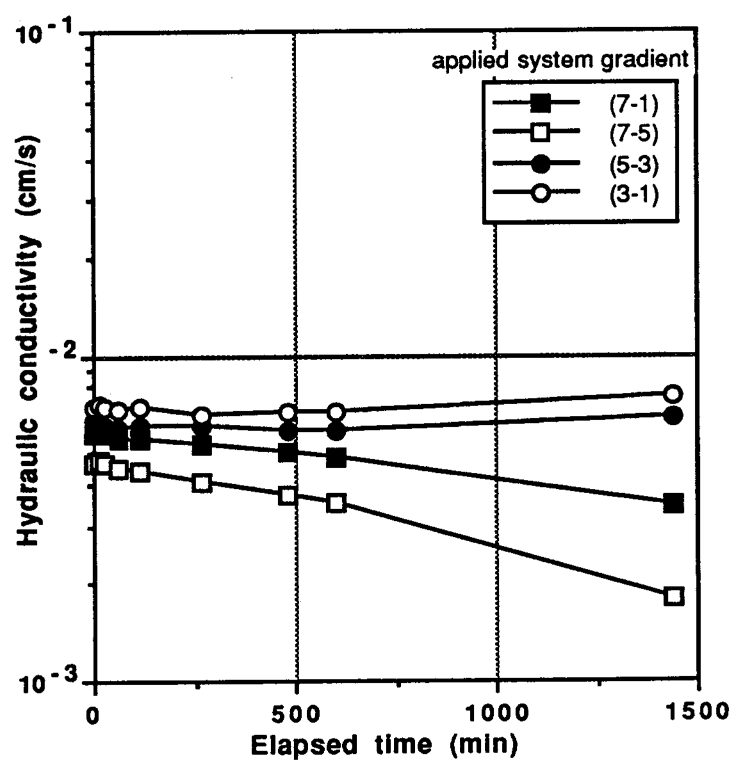

Figure A-2: Hydraulic Conductivity for Armtec in Gradient Ratio Test, i = 2.5

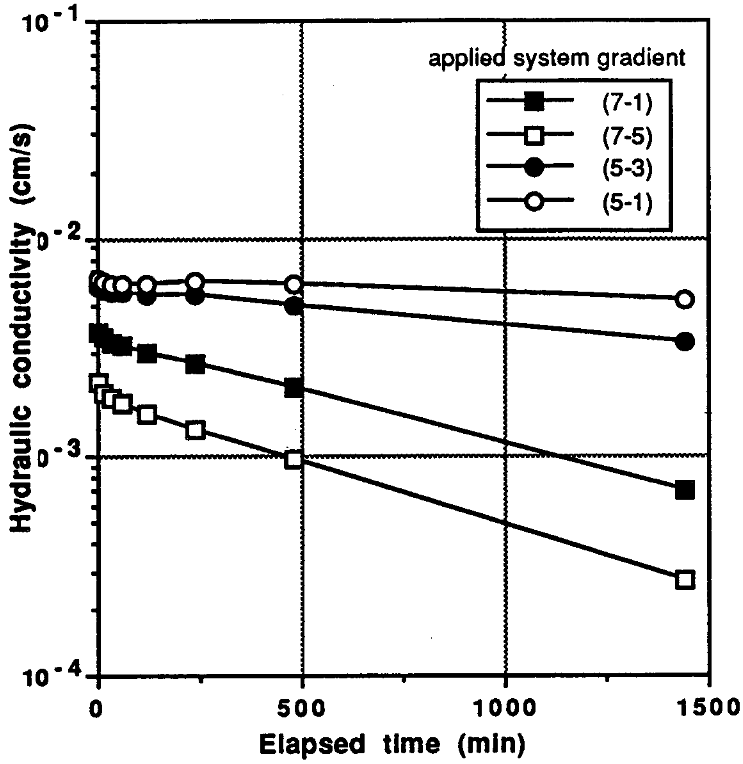

Figure A-3: Hydraulic Conductivity for Armtec in Gradient Ratio Test, i = 5.0

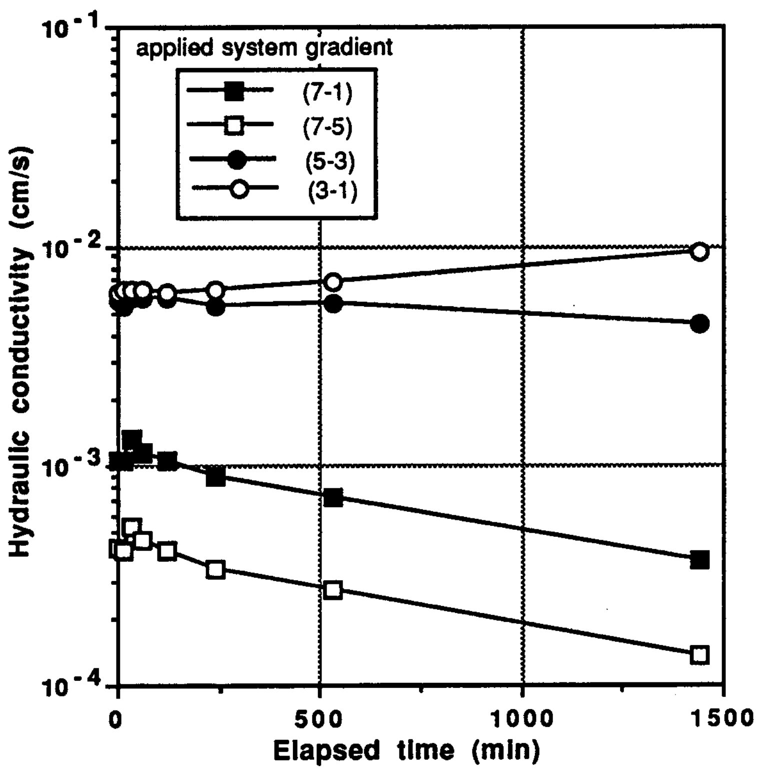

Figure A-4: Hydraulic Conductivity for Armtec in Gradient Ratio Test, i = 7.5

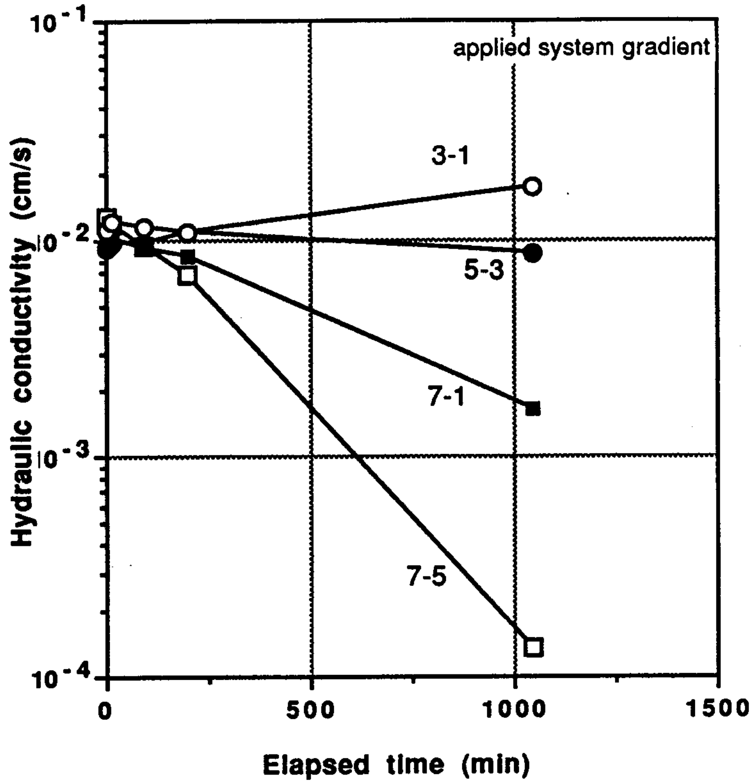

Figure A-5: Hydraulic Conductivity for Bidim in Gradient Ratio Test, i = 0.7

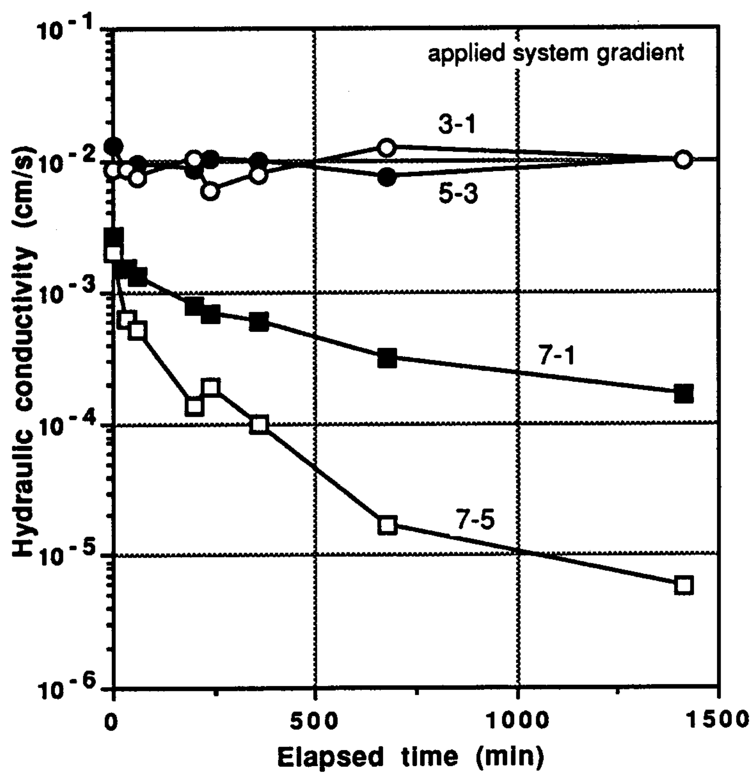

Figure A-6: Hydraulic Conductivity for Bidim in Gradient Ratio Test, i = 2.5

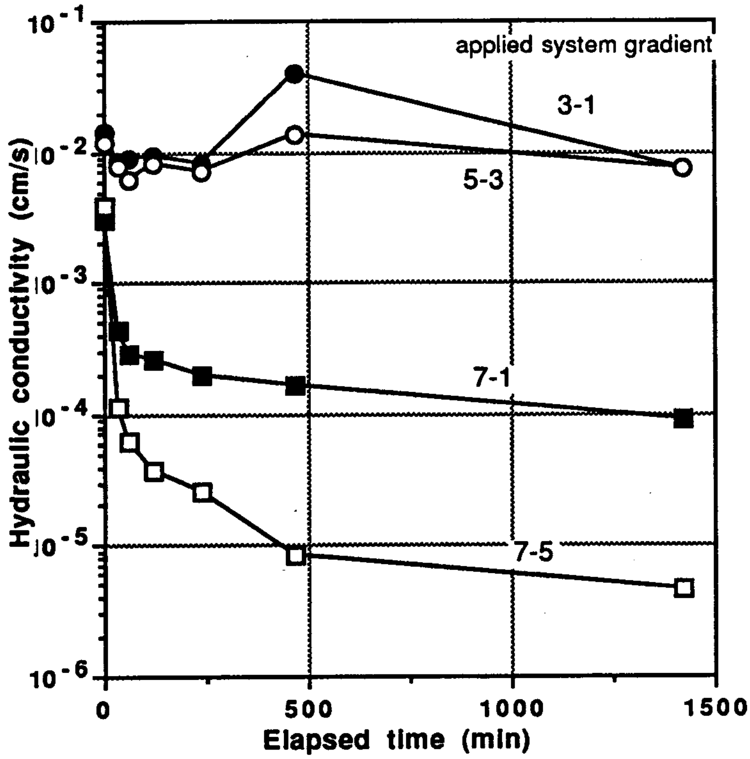

Figure A-7: Hydraulic Conductivity for Bidim in Gradient Ratio Test, i = 5.0

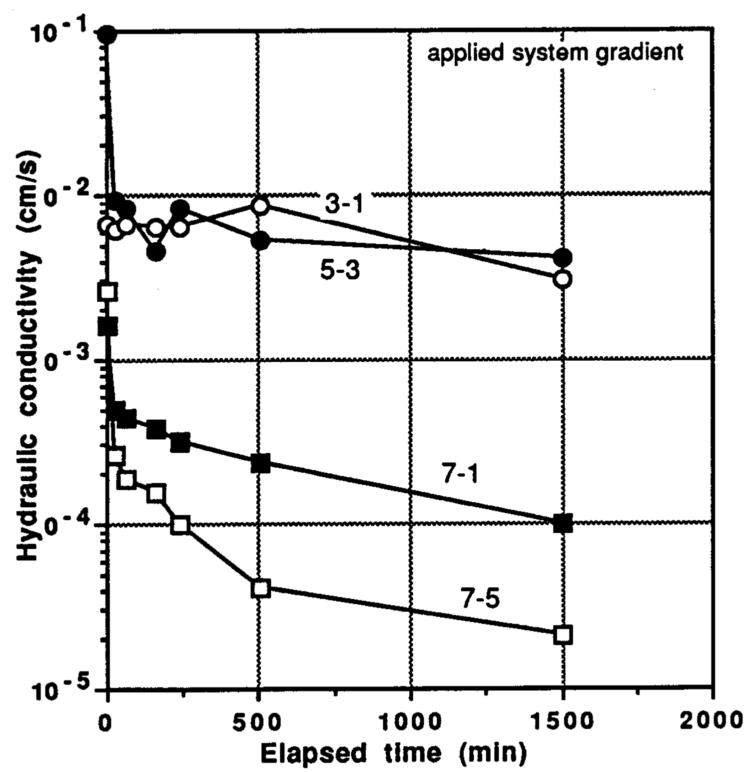

Figure A-8: Hydraulic Conductivity for Bidim in Gradient Ratio Test, i = 7.3

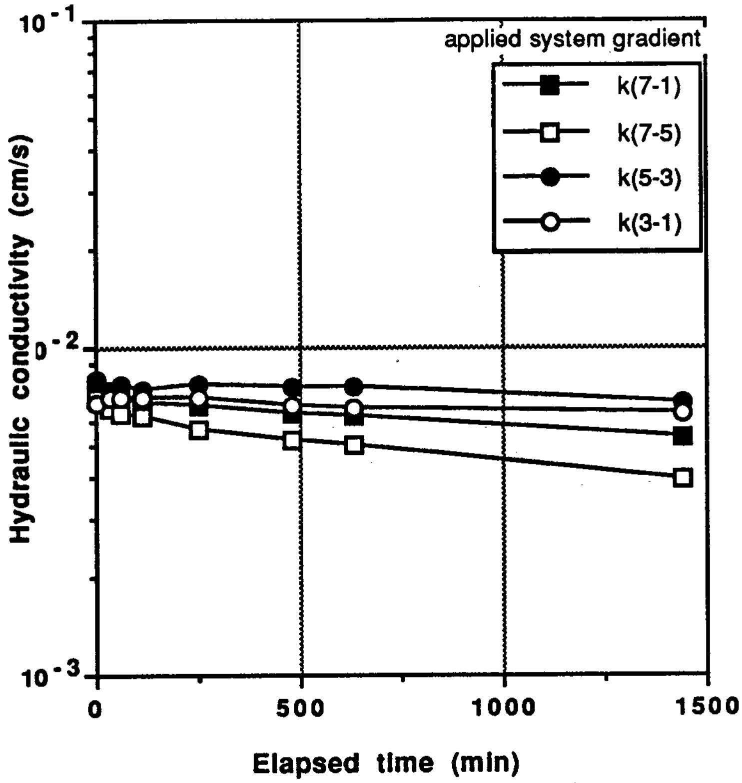

Figure A-9: Hydraulic Conductivity for Polyfelt in Gradient Ratio Test, i = 1.0

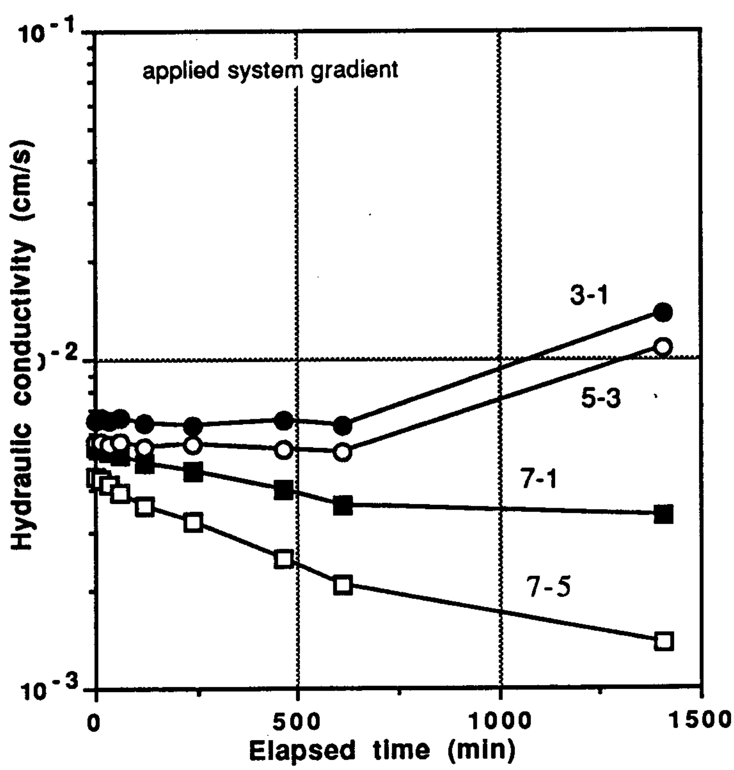

Figure A-10: Hydraulic Conductivity for Polyfelt in Gradient Ratio Test, i = 2.5

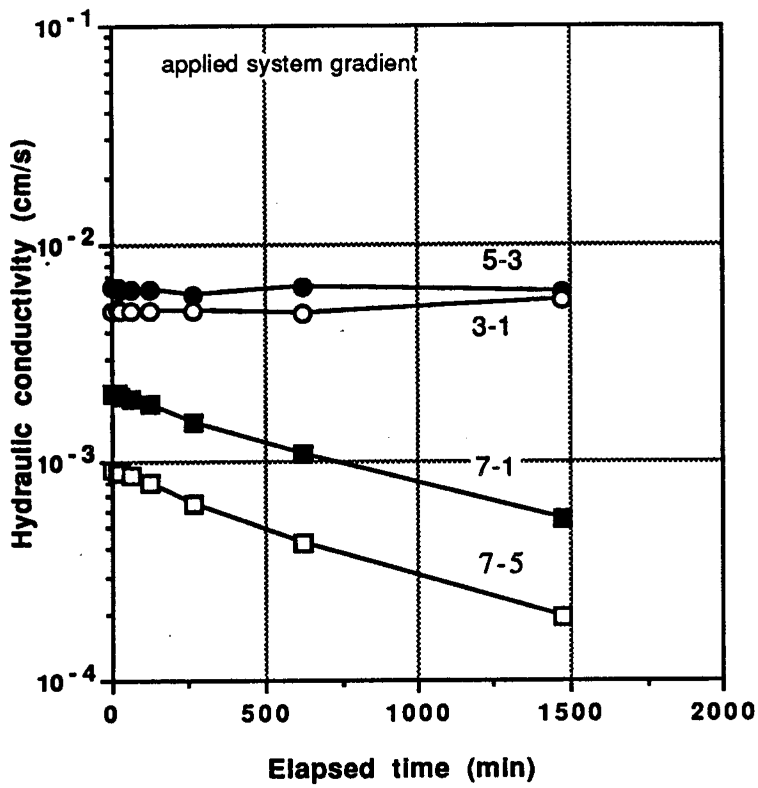

Figure A-11: Hydraulic Conductivity for Polyfelt in Gradient Ratio Test, i = 5.0

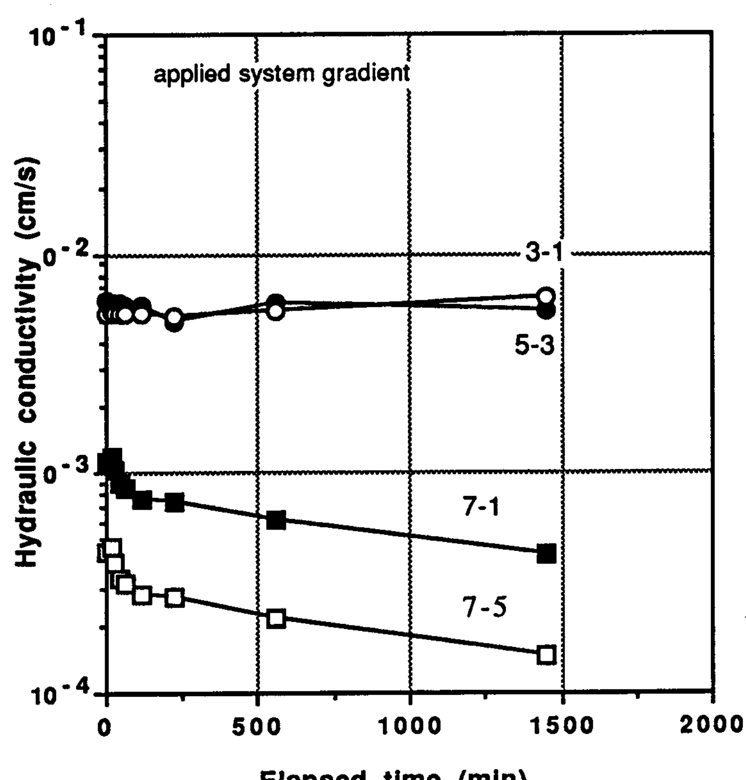

Figure A-12: Hydraulic Conductivity for Polyfelt in Gradient Ratio Test, i = 7.5

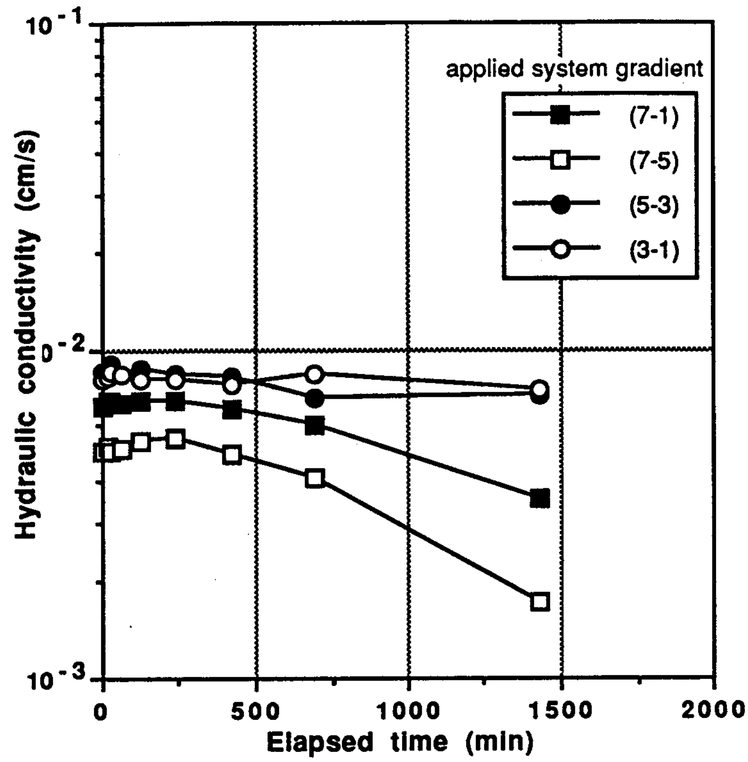

Figure A-13: Hydraulic Conductivityfor Trevira in Gradient Ratio Test, i = 1.0

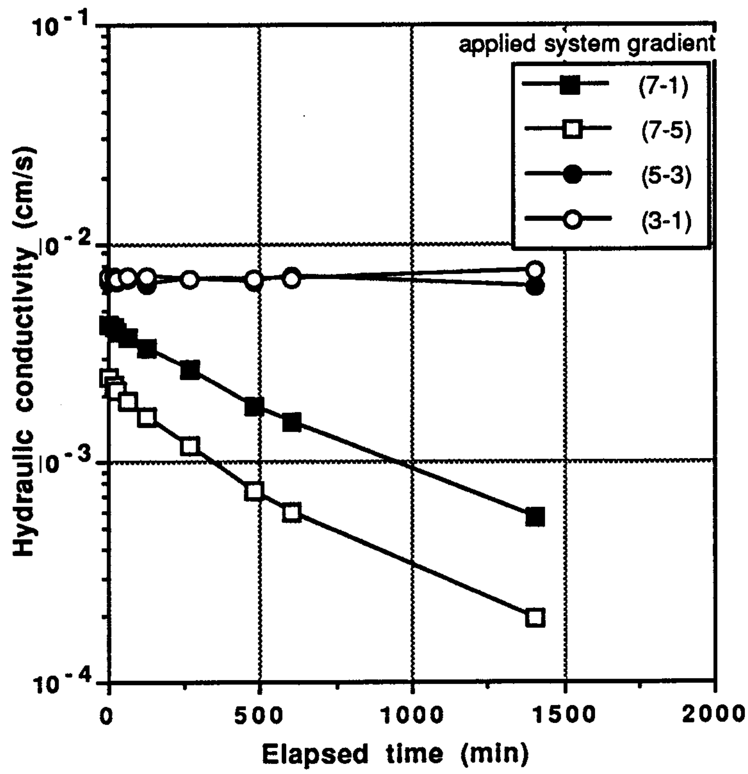

Figure A-14: Hydraulic Conductivity for Trevira in Gradient Ratio Test, i = 2.6

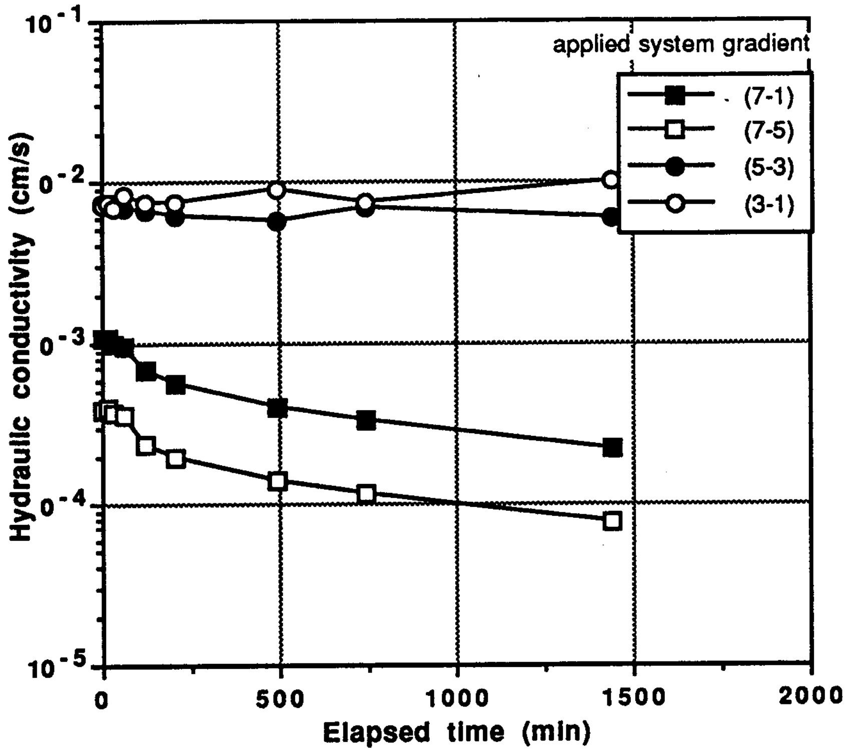

Figure A-15: Hydraulic Conductivity for Trevira in Gradient Ratio Test, i = 5.1

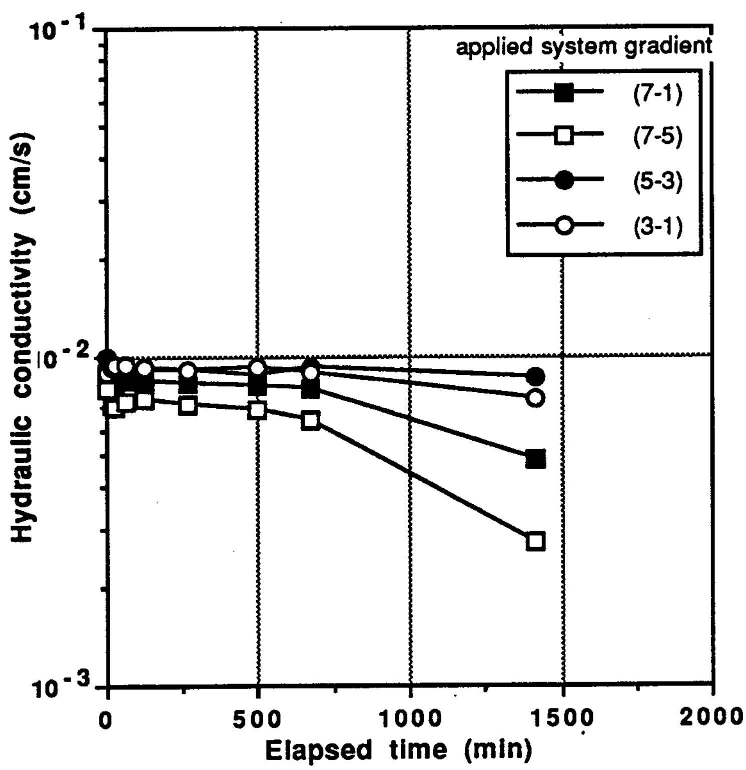

Figure A-16: Hydraulic Conductivity for Bidimrock in Gradient Ratio Test, i = 1.0

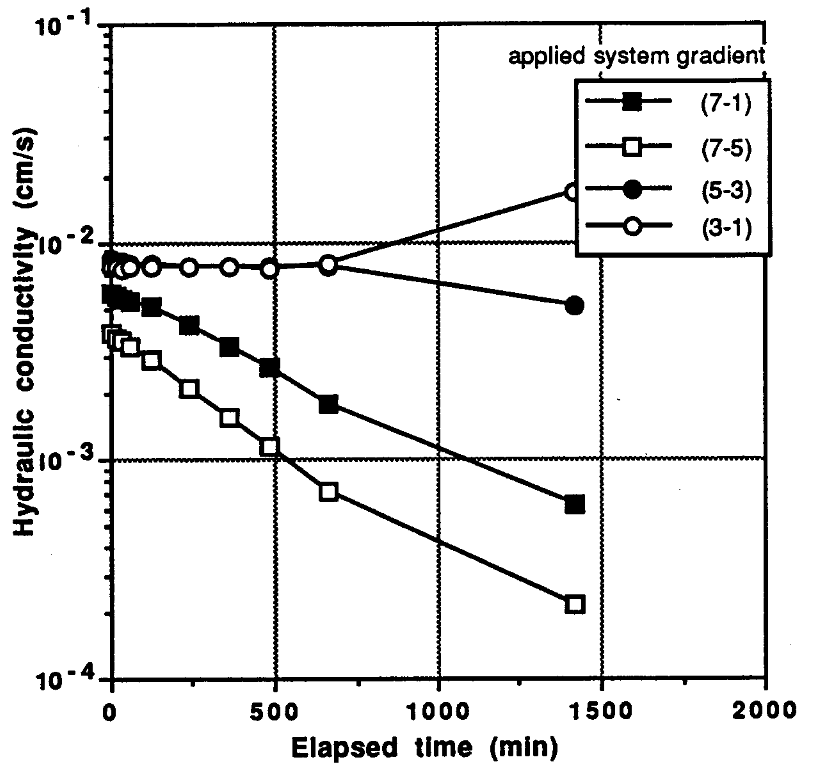

Figure A-17: Hydraulic Conductivity for Bidimrock in Gradient Ratio Test, i = 2.5

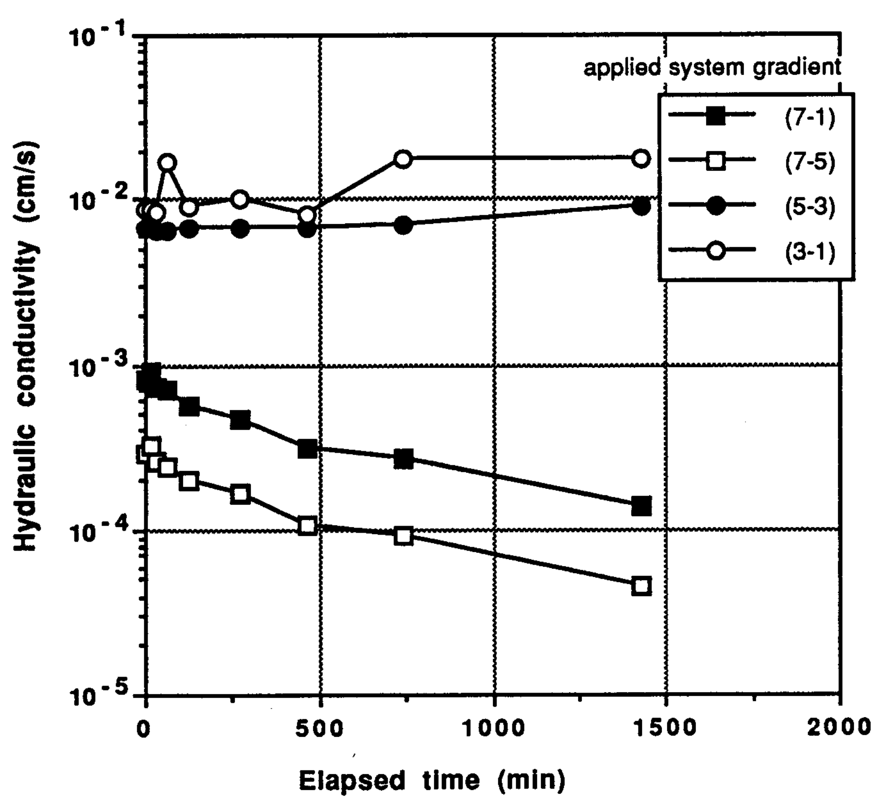

Figure A-18: Hydraulic Conductivity for Bidimrock in Gradient Ratio Test, i = 5.0

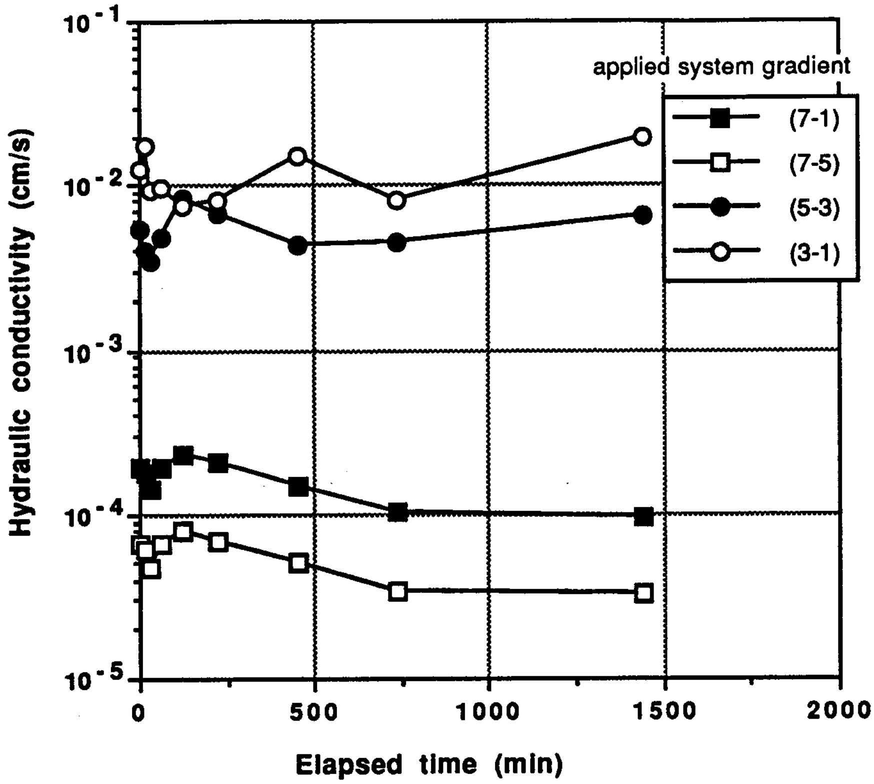

Figure A-19: Hydraulic Conductivity for Bidimrock in Gradient Ratio Test, i = 7.8

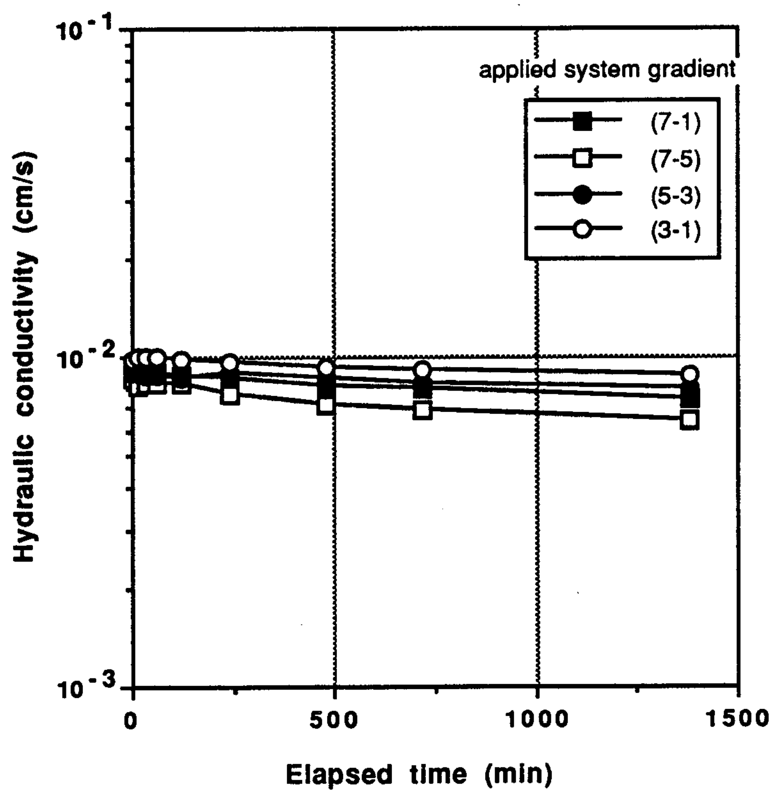

Figure A-20: Hydraulic Conductivity for Exxon in Gradient Ratio Test, i = 1.0

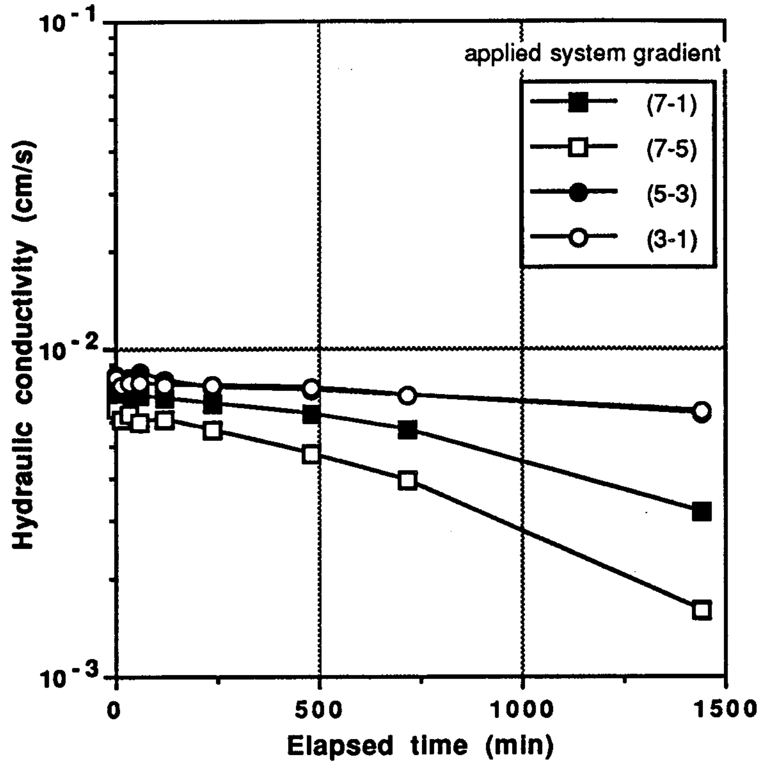

Figure A-21: Hydraulic Conductivity for Exxon in Gradient Ratio Test, i = 2.5

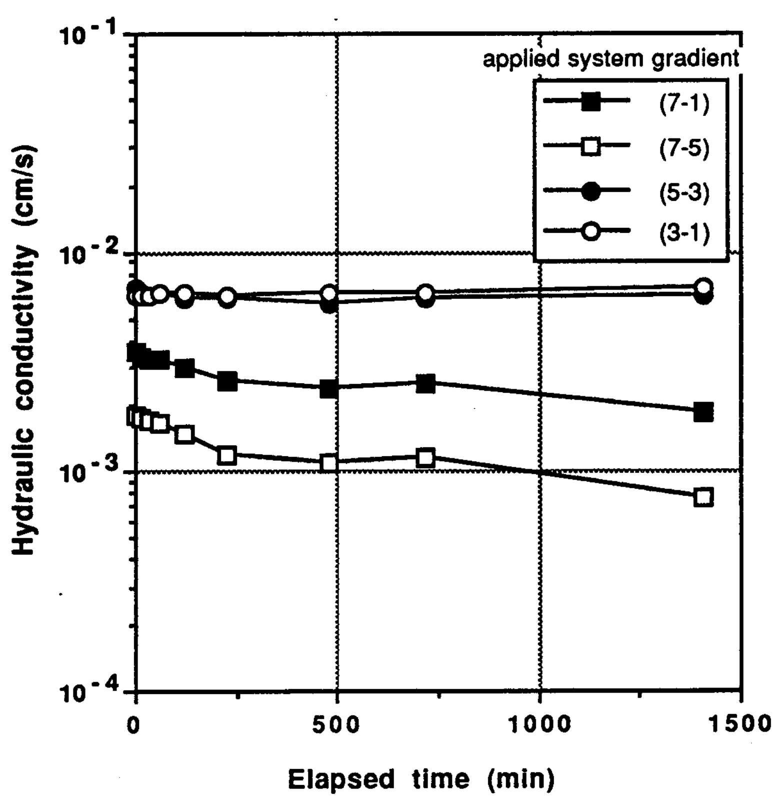

Figure A-22: Hydraulic Conductivity for Exxon in Gradient Ratio Test, i = 5.0

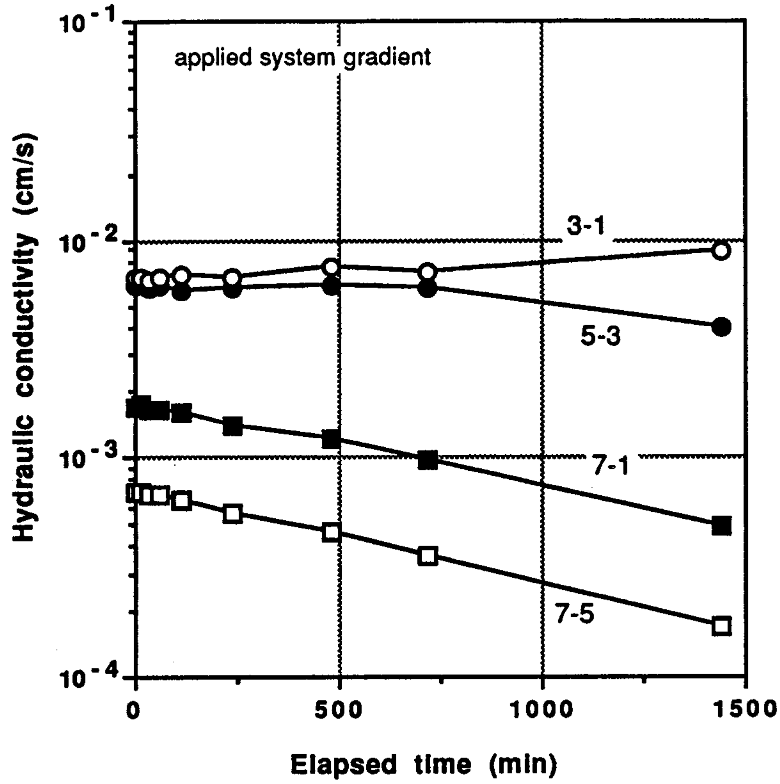

Figure A-23: Hydraulic Conductivity for Exxon in Gradient Ratio Test, i = 7.5

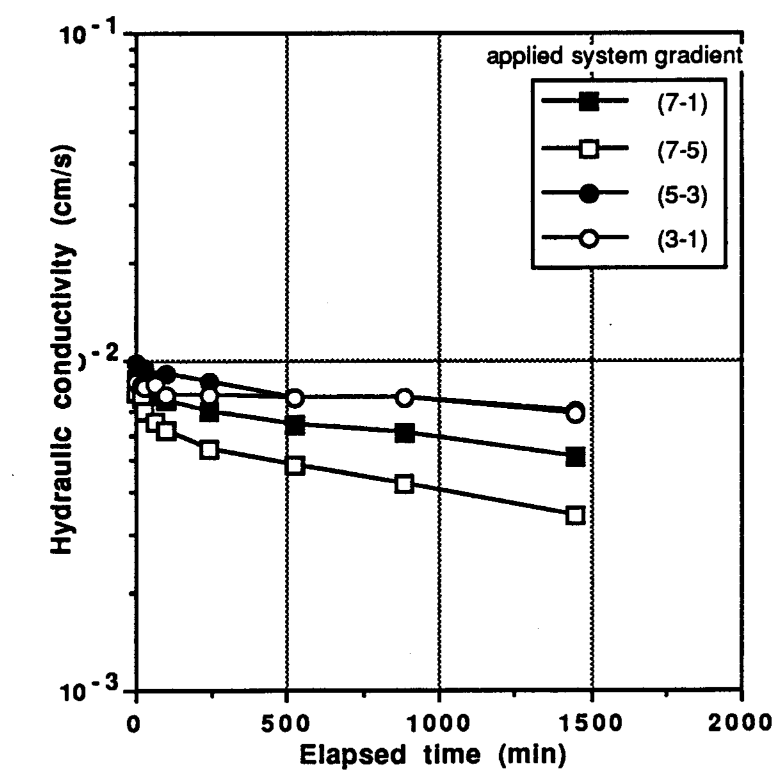

Figure A-24: Hydraulic Conductivity for Quline in Gradient Ratio Test, i = 1.0

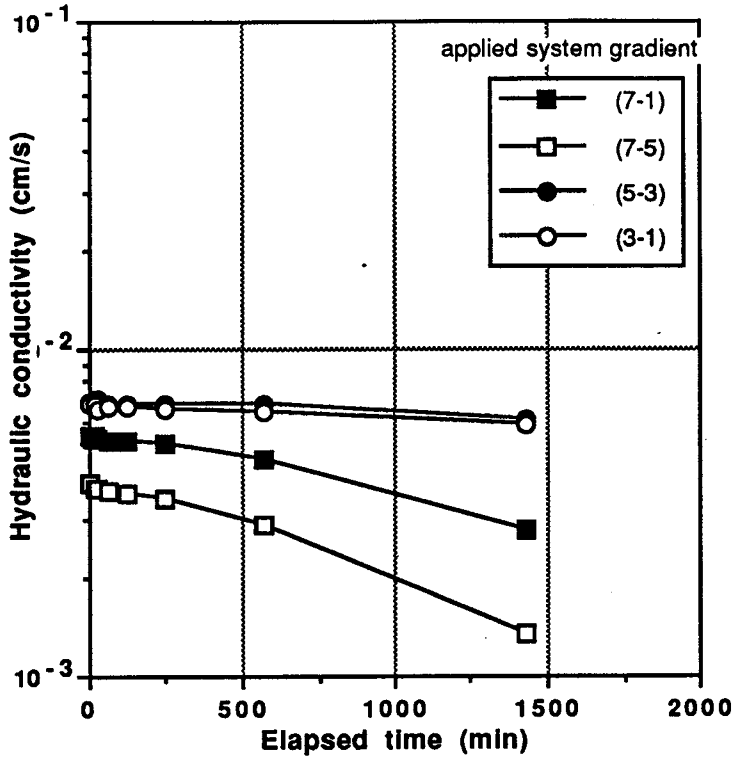

Figure A-25: Hydraulic Conductivity for Quline in Gradient Ratio Test, i = 2.5

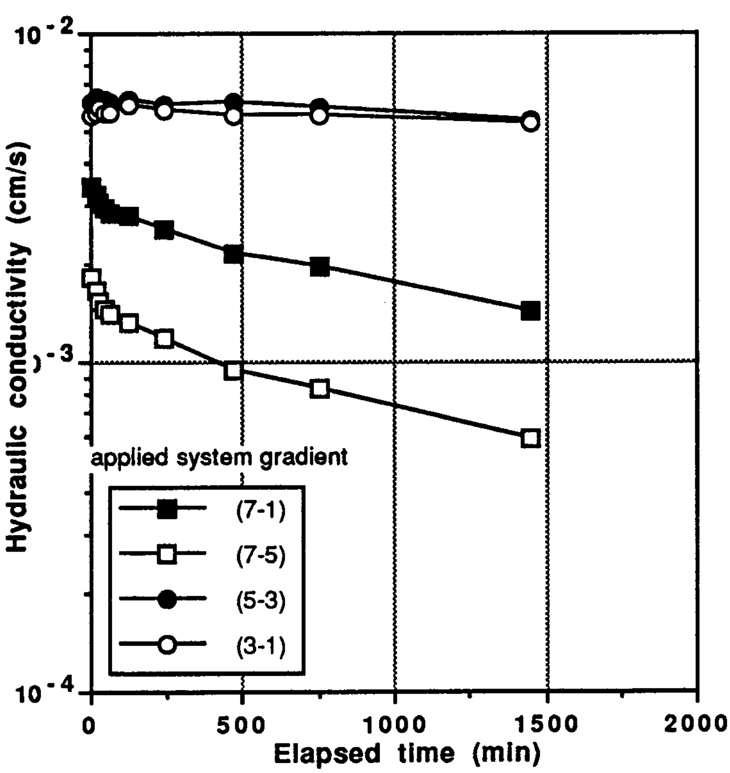

Figure A-26: Hydraulic Conductivity for Quline in Gradient Ratio Test, i = 5.0

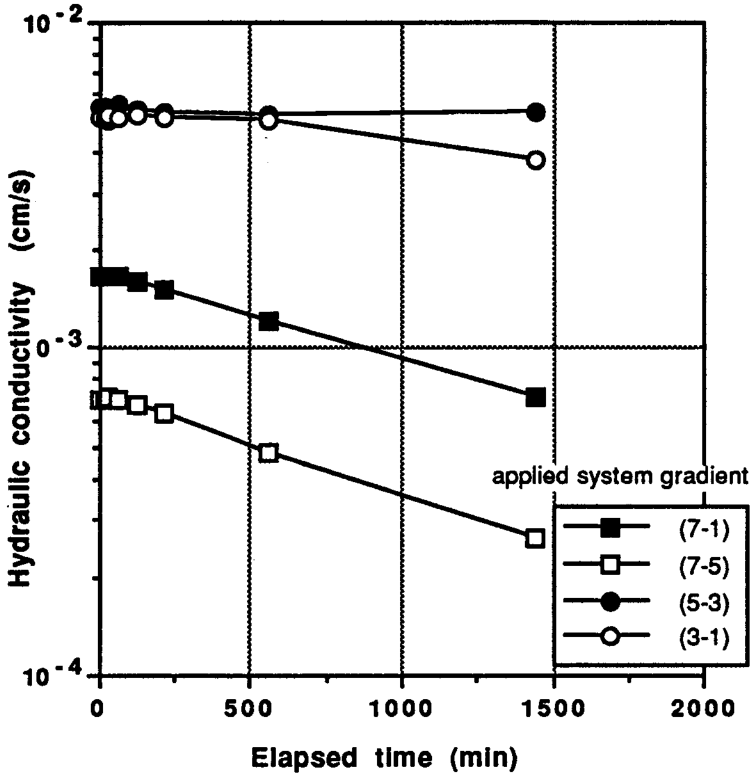

Figure A-27: Hydraulic Conductivity for Quline in Gradient Ratio Test, i = 7.5

APPENDIX B

Effect of Hydraulic Gradient and Time on the Hydraulic Conductivity of the Sand-Geotextile System in the Modified Gradient Ratio Test

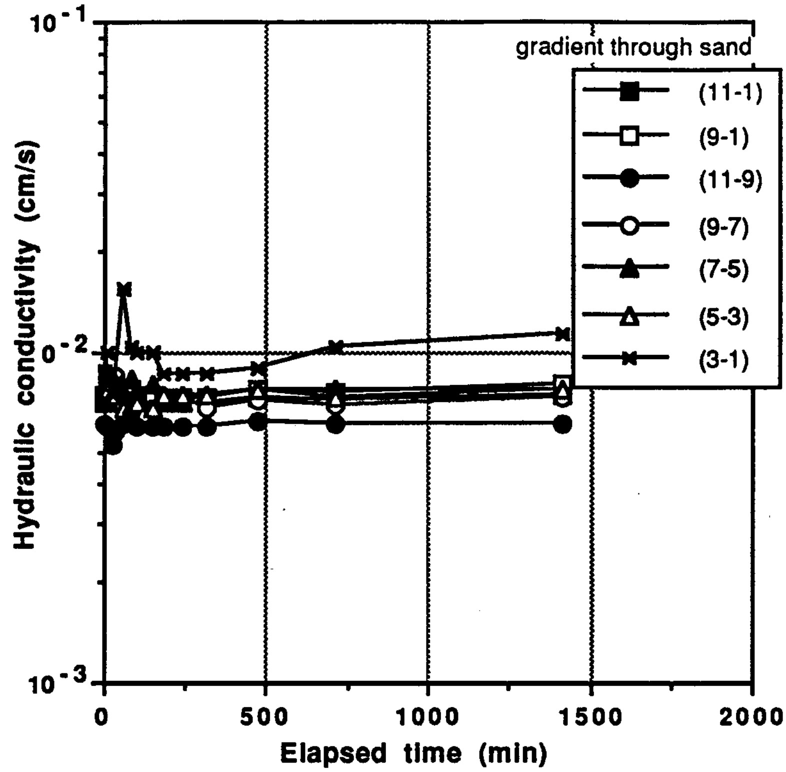

Figure B-1: Hydraulic Conductivity for Bidimrock in Modified Gradient Ratio Test, i = 0.5

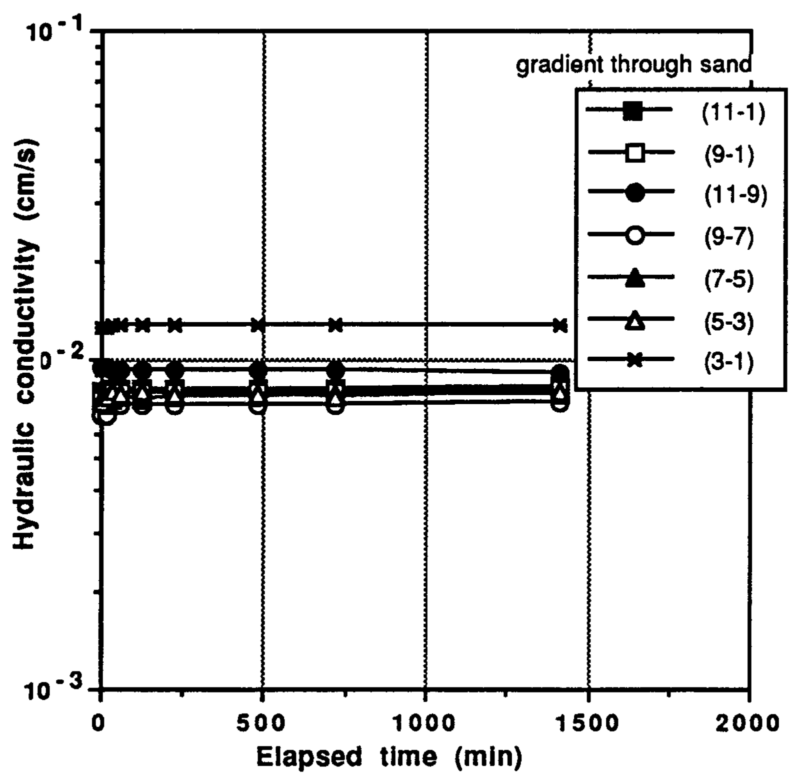

Figure B-2: Hydraulic Conductivity for Bidimrock in Modified Gradient Ratio Test, i = 1.0

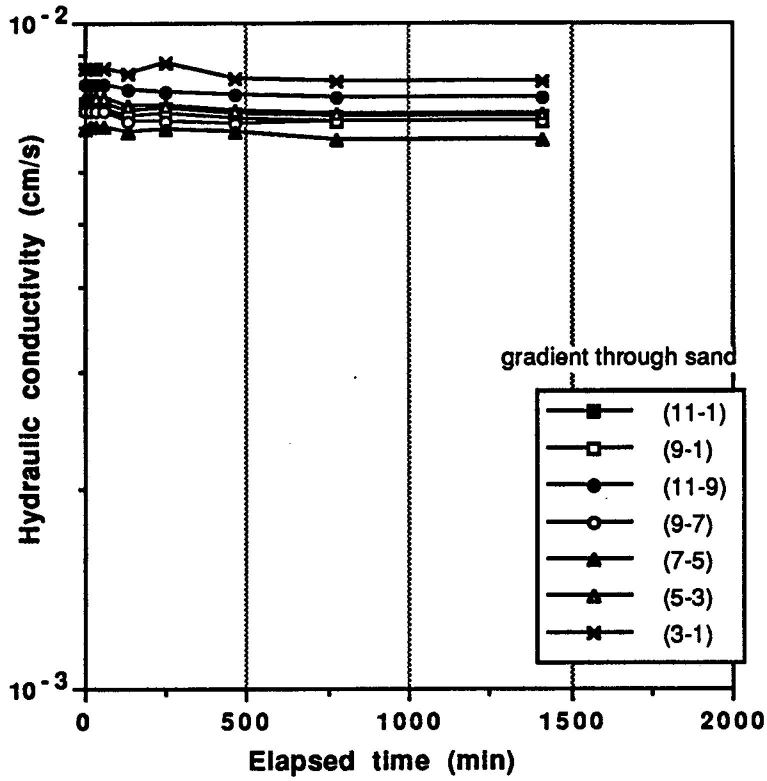

Figure B-3: Hydraulic Conductivity for Bidimrock in Modified Gradient Ratio Test, i = 2.5

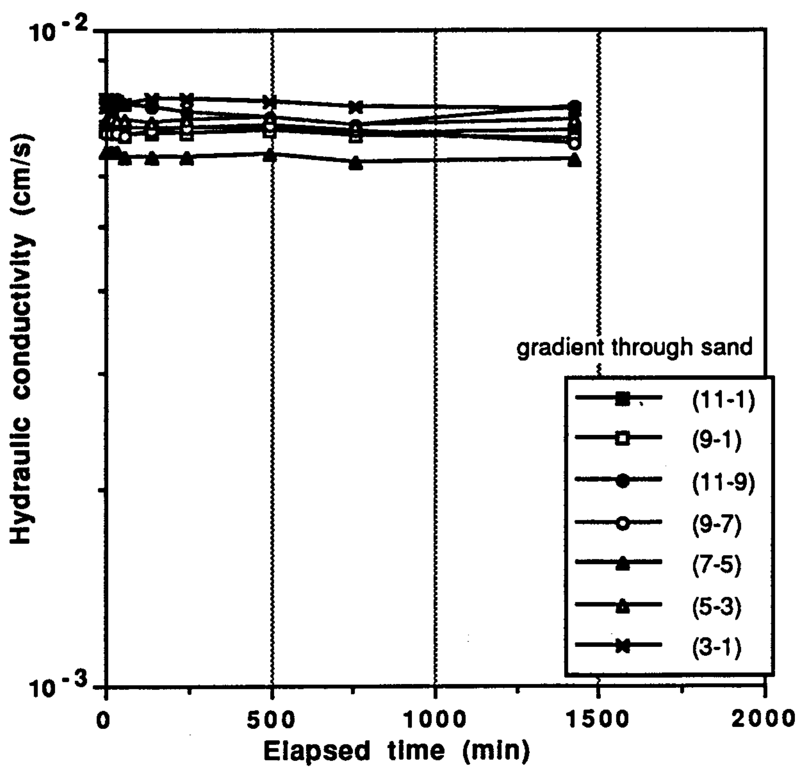

Figure B-4: Hydraulic Conductivity for Bidimrock in Modified Gradient Ratio Test, i = 5.0

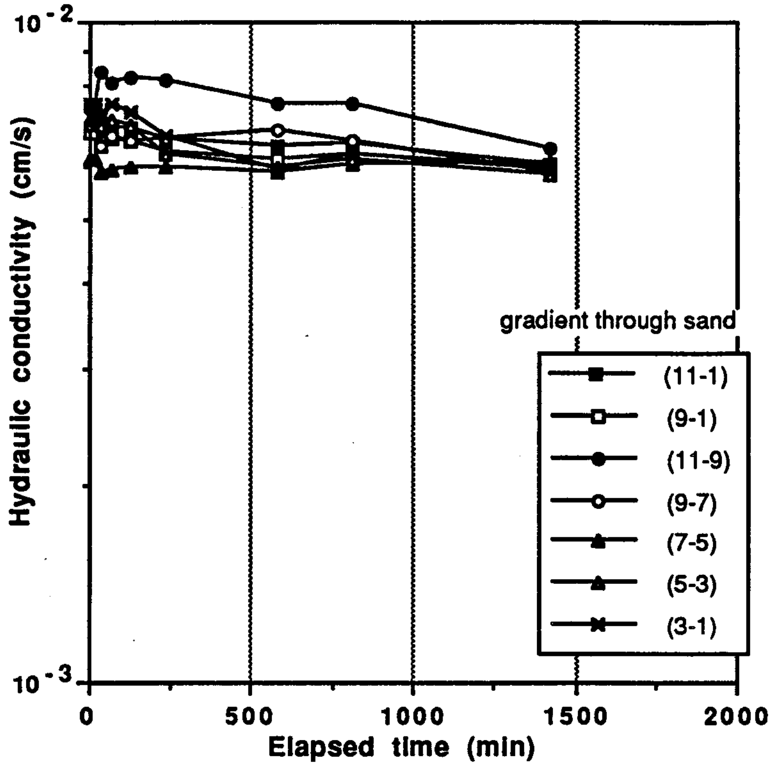

Figure B-5: Hydraulic Conductivity for Bidimrock in Modified Gradient Ratio Test, i = 7.5

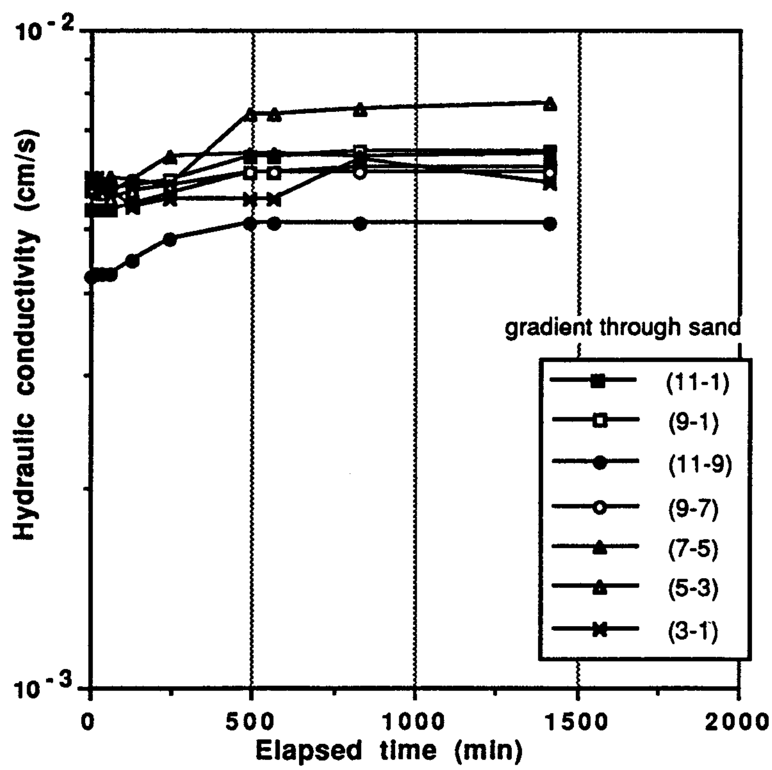

Figure B-6: Hydraulic Conductivity for Bidimrock in Modified Gradient Ratio Test, i = 10

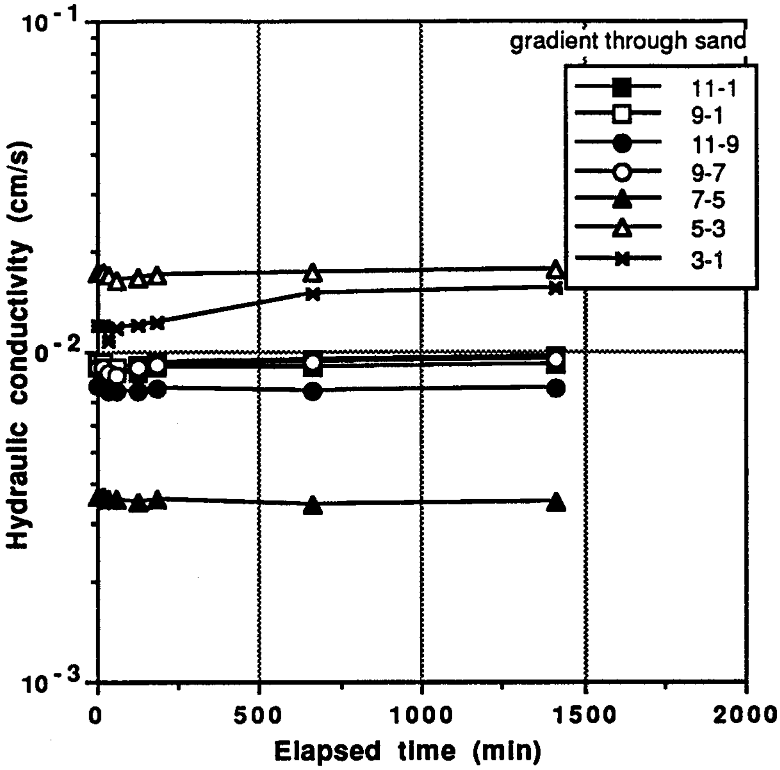

Figure B-7: Hydraulic Conductivity for Exxon in Modified Gradient Ratio Test, i = 0.5

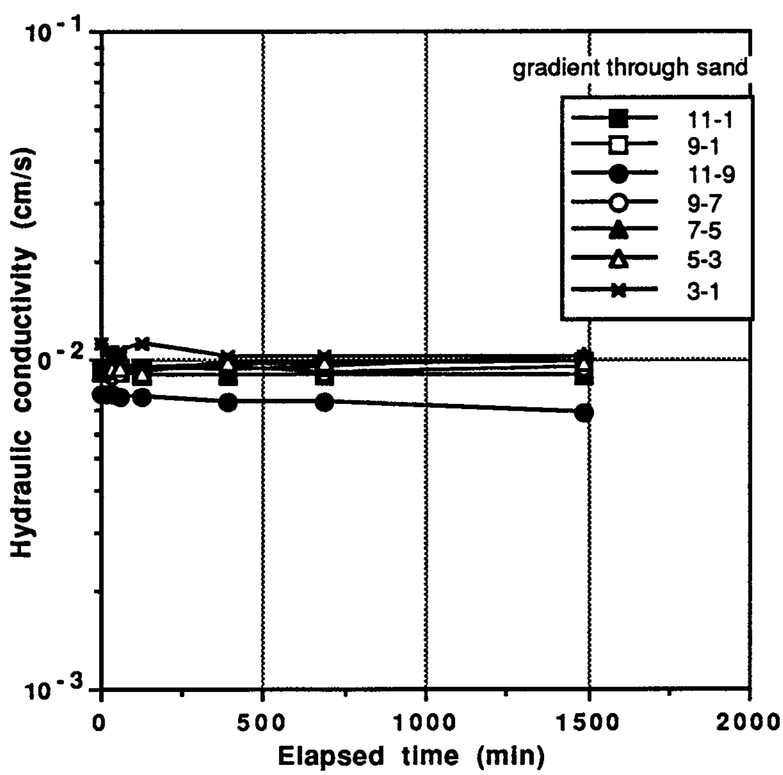

Figure B-8: Hydraulic Conductivity for Exxon in Modified Gradient Ratio Test, i = 1.0

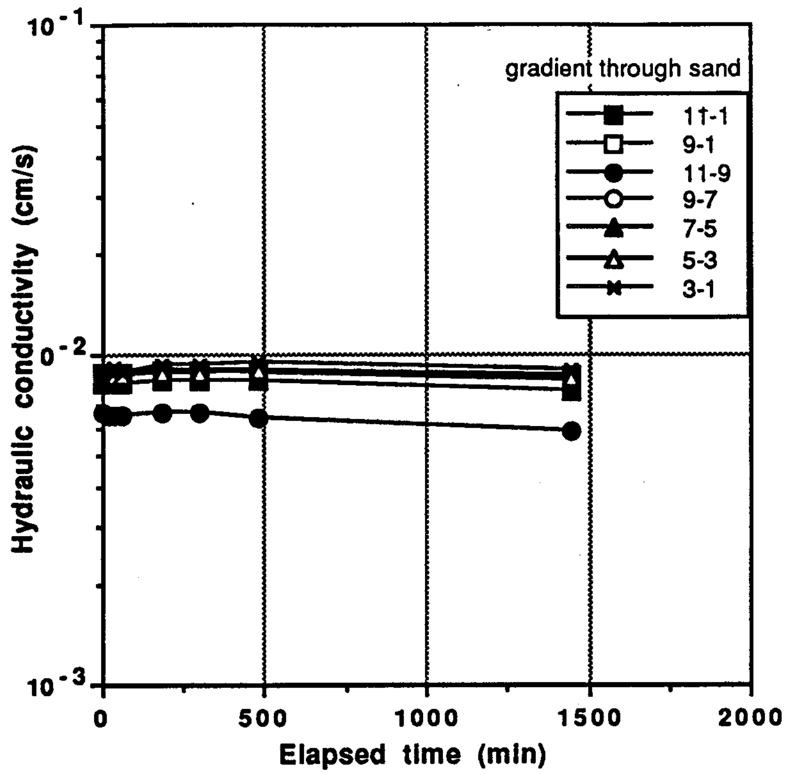

Figure B-9: Hydraulic Conductivity for Exxon in Modified Gradient Ratio Test, i = 2.5

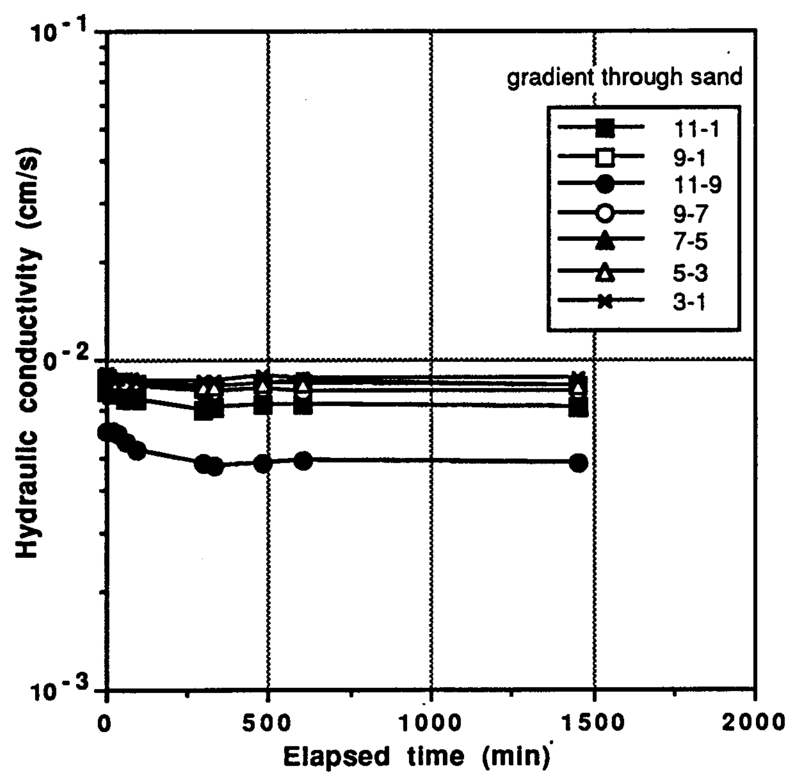

Figure B-10: Hydraulic Conductivity for Exxon in Modified Gradient Ratio Test, i = 5.0

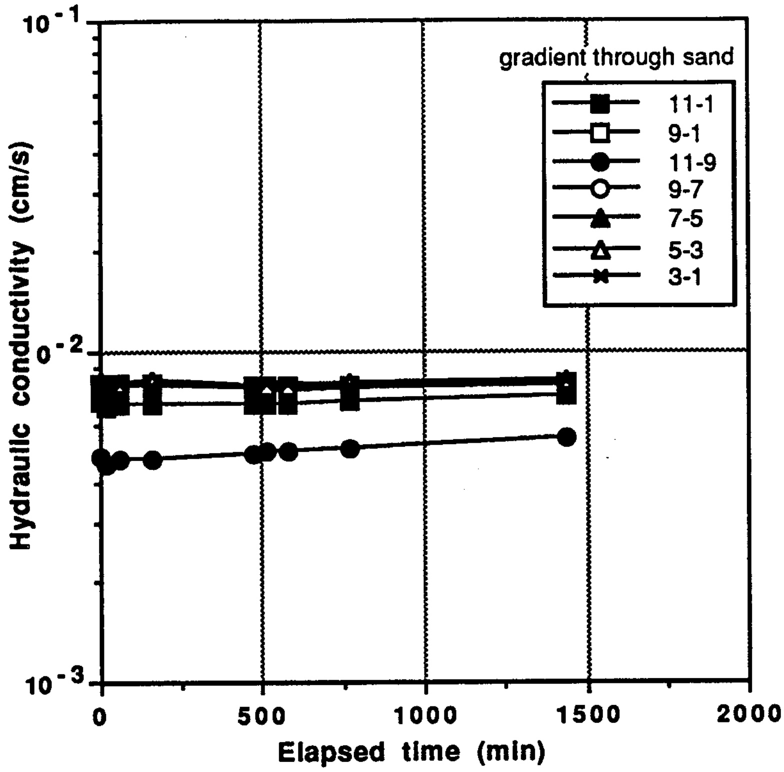

Figure B-11: Hydraulic Conductivity for Exxon in Modified Gradient Ratio Test, i = 7.5

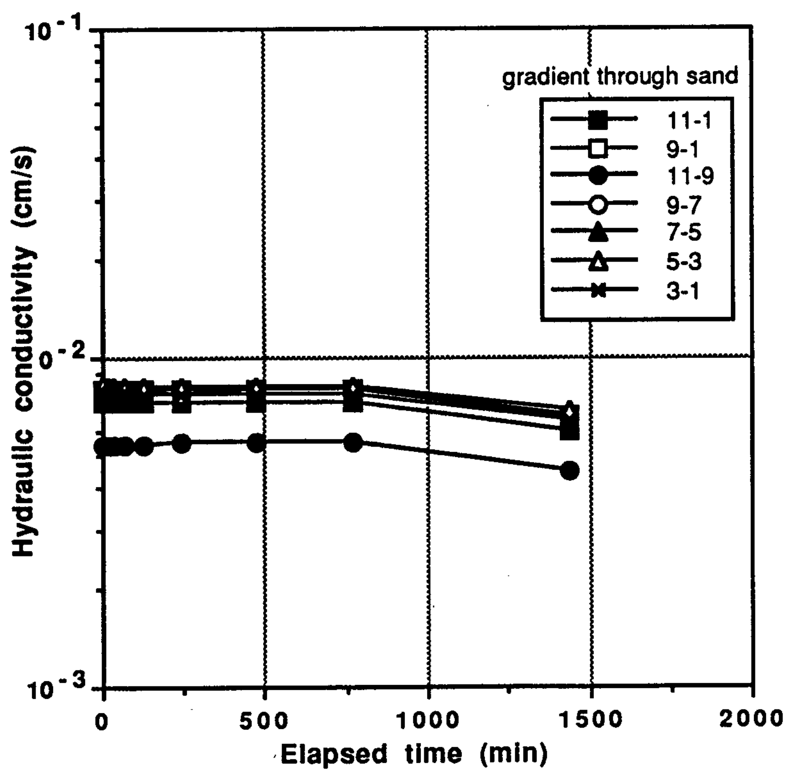

Figure B-12: Hydraulic Conductivity for Exxon in Modified Gradient Ratio Test, i = 10.0

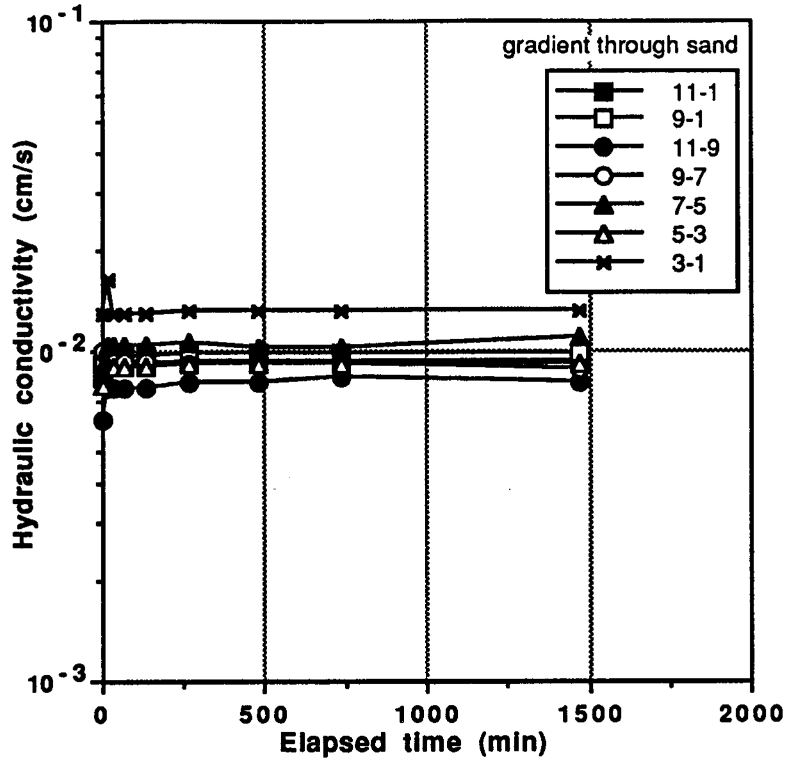

Figure B-13: Hydraulic Conductivity for Quline in Modified Gradient Ratio Test, i = 0.5

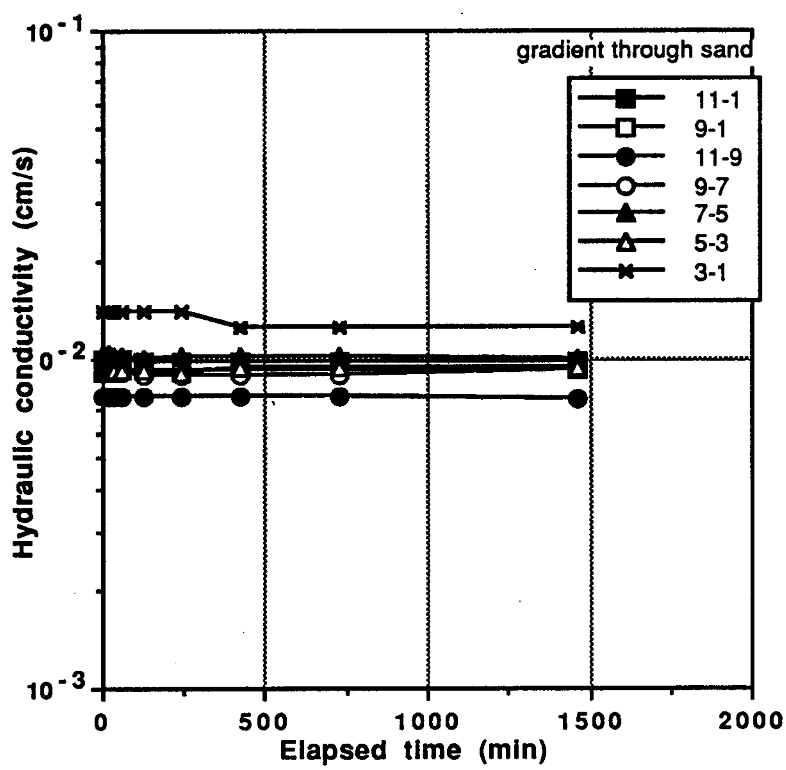

Figure B-14: Hydraulic Conductivity for Quline in Modified Gradient Ratio Test, i = 1.0

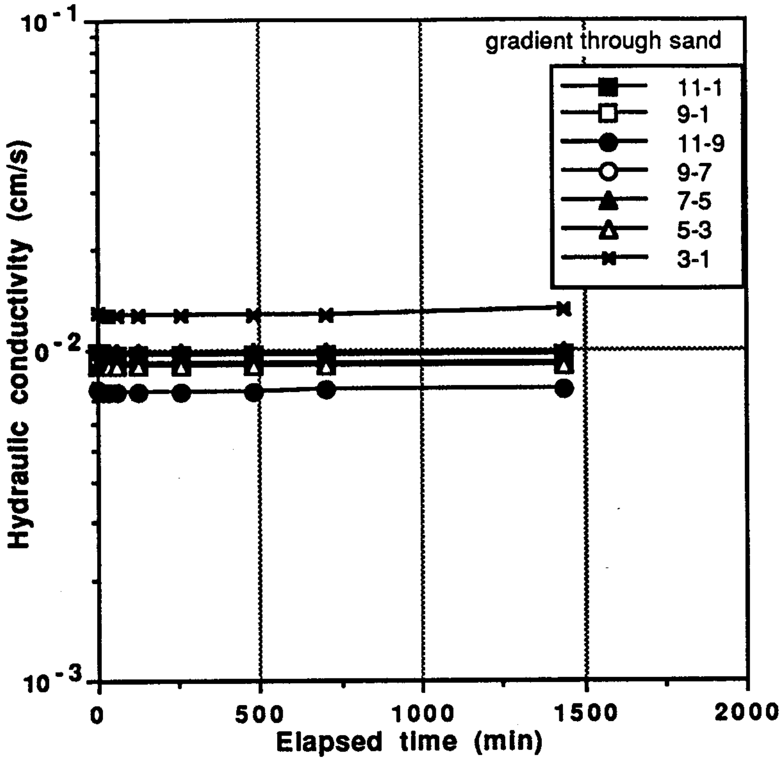

Figure B-15: Hydraulic Conductivity for Quline in Modified Gradient Ratio Test, i = 2.5

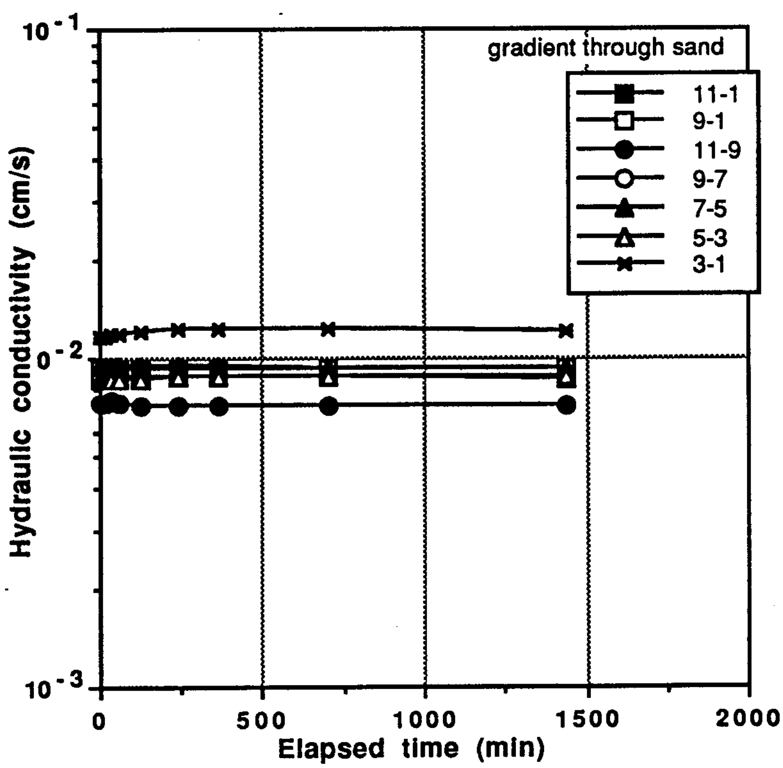

Figure B-16: Hydraulic Conductivity for Quline in Modified Gradient Ratio Test, i = 5.0

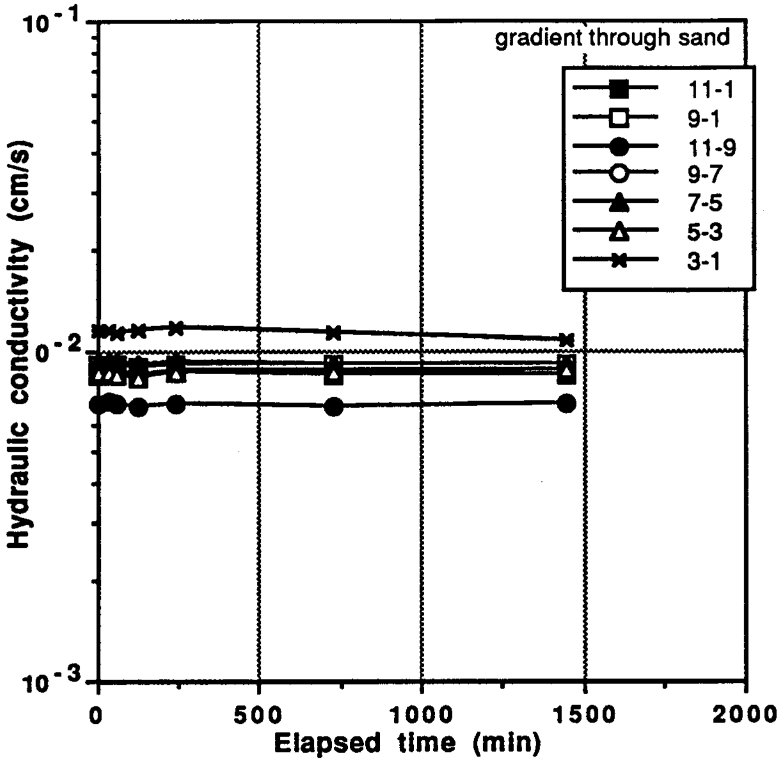

Figure B-17: Hydraulic Conductivity for Quline in Modified Gradient Ratio Test, i = 7.5

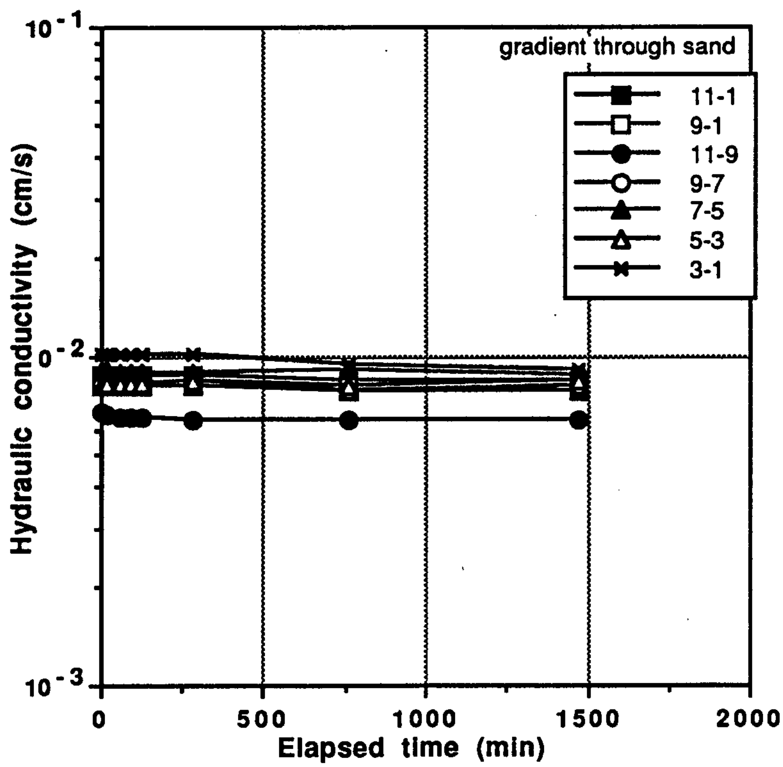

Figure B-18: Hydraulic Conductivity for Quline in Modified Gradient Ratio Test, i = 10

APPENDIX C

Effect of Hydraulic Gradient and Time on the Hydraulic Conductivity of the Sand-Geotextile System in the High Confining Stress Filtration Test

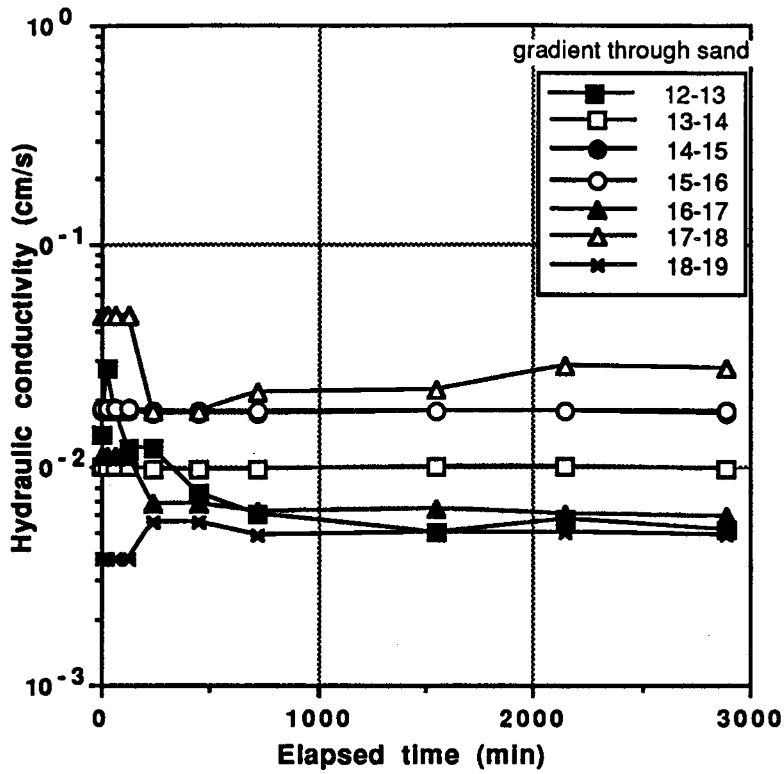

Figure C-1: Hydraulic Conductivity for Bidimrock in High Confining Stress Filtration Test, i = 0.5

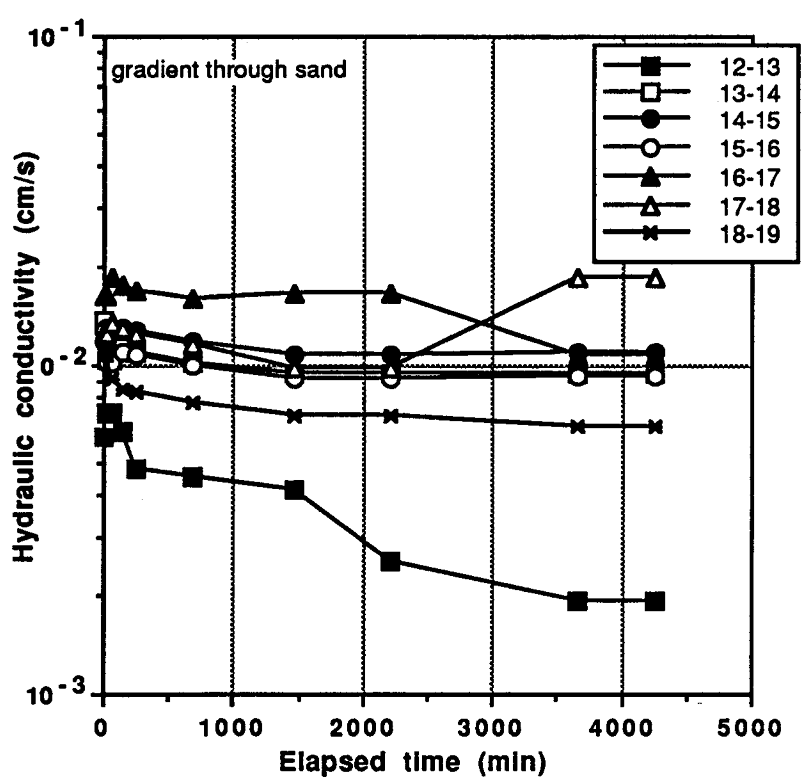

Figure C-2: Hydraulic Conductivity for Bidimrock in High Confining Stress Filtration Test, i = 1.0

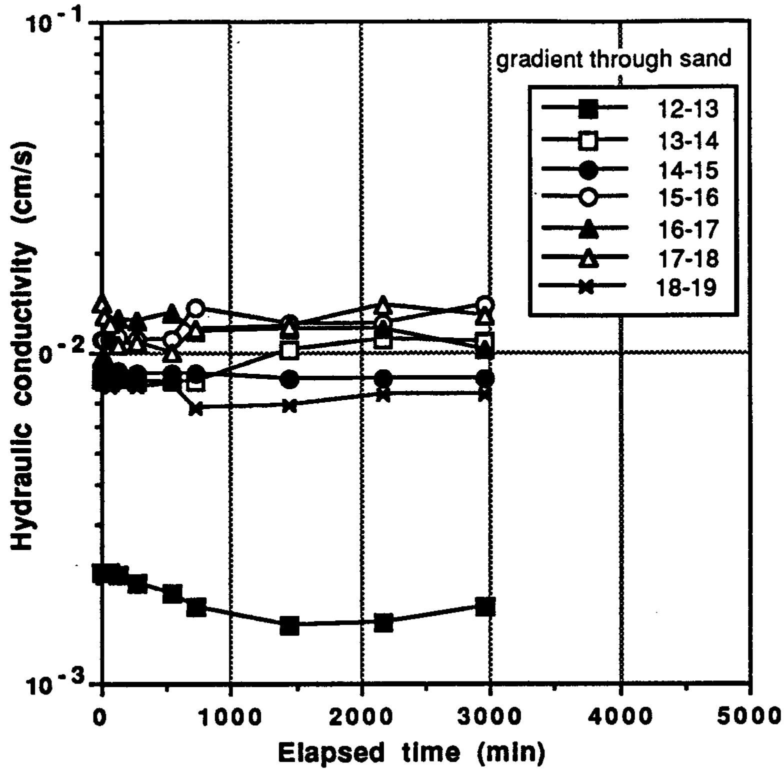

Figure C-3: Hydraulic Conductivity for Bidimrock in High Confining Stress Filtration Test, i = 2.5

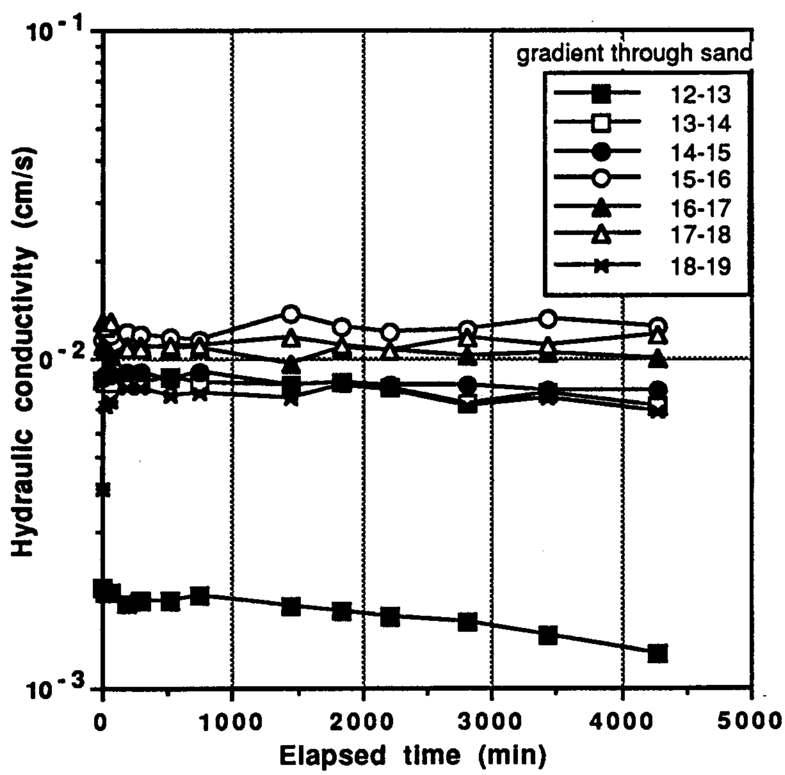

Figure C-4: Hydraulic Conductivity for Bidimrock in High Confining Stress Filtration Test, i = 5.0

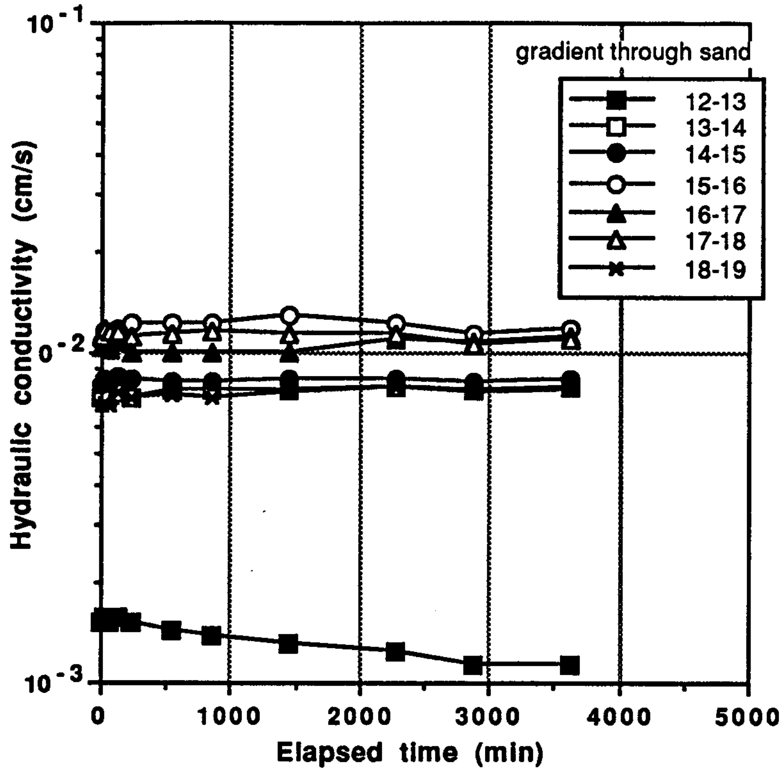

Figure C-5: Hydraulic Conductivity for Bidimrock in High Confining Stress Filtration Test, i = 7.5

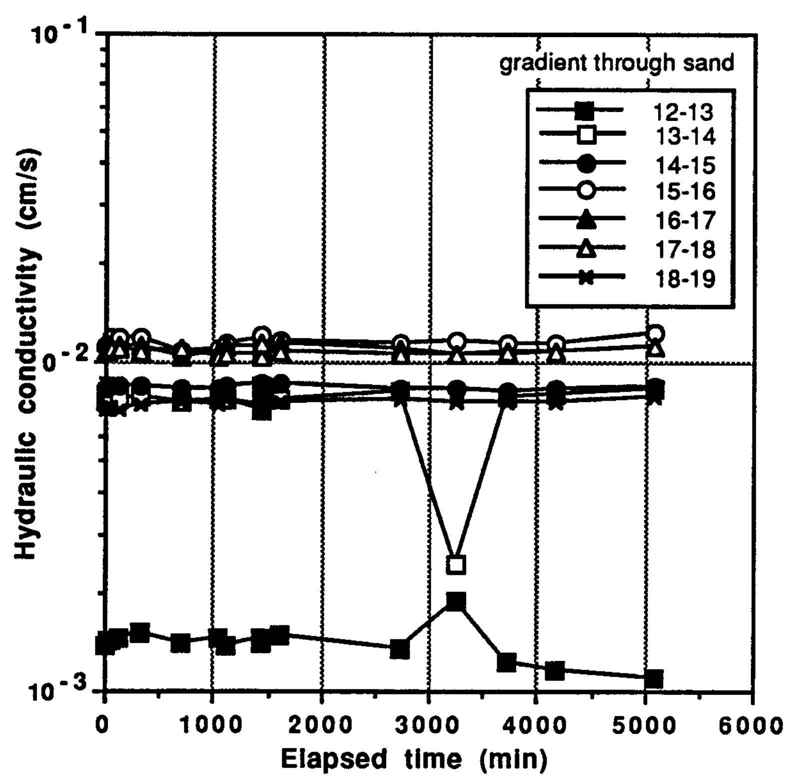

Figure C-6: Hydraulic Conductivity for Bidimrock in High Confining Stress Filtration Test, i = 10

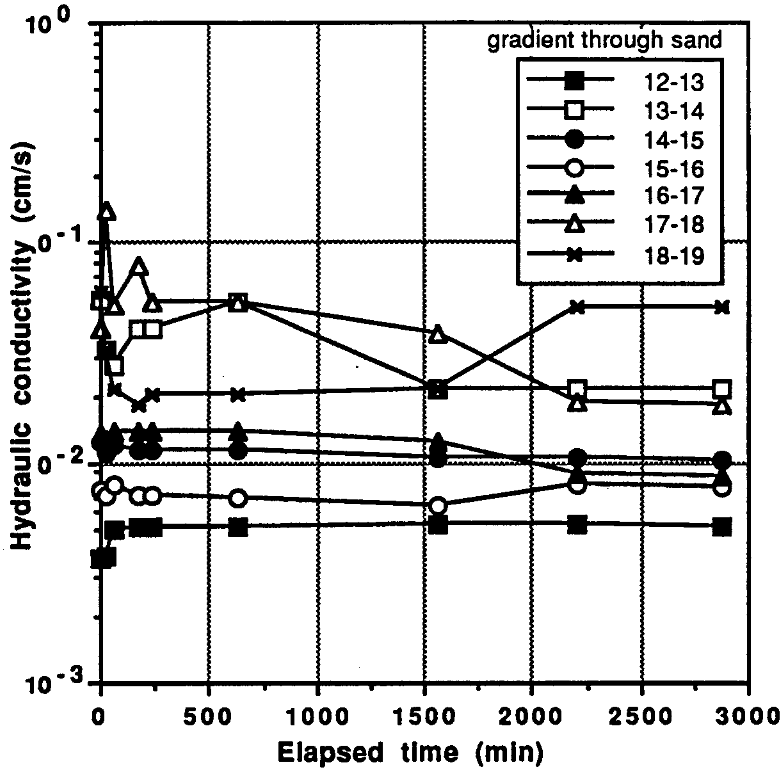

Figure C-7: Hydraulic Conductivity for Exxon in High Confining Stress Filtration Test, i = 0.5

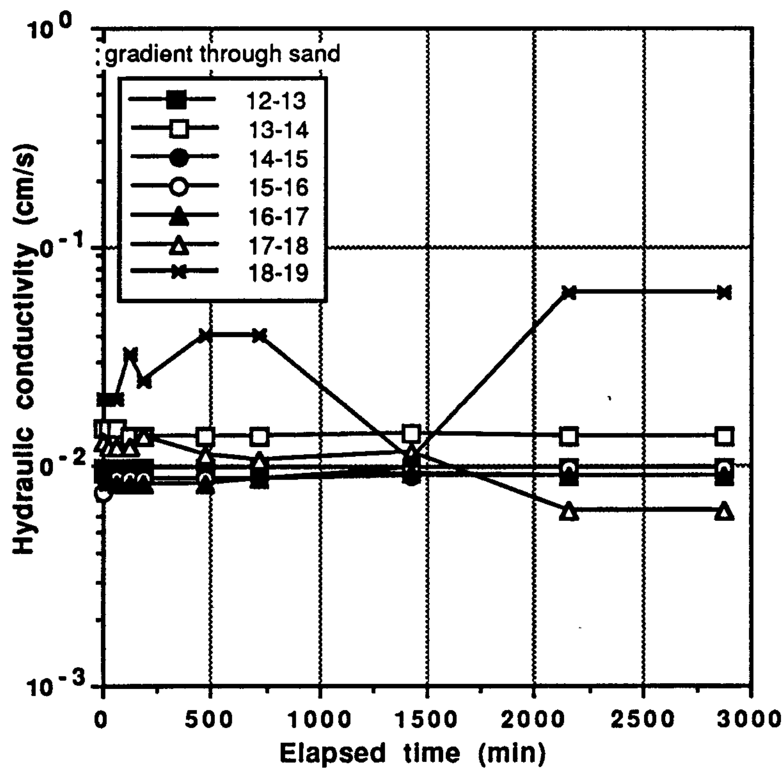

Figure C-8: Hydraulic Conductivity for Exxon in High Confining Stress Filtration Test, i = 1.0

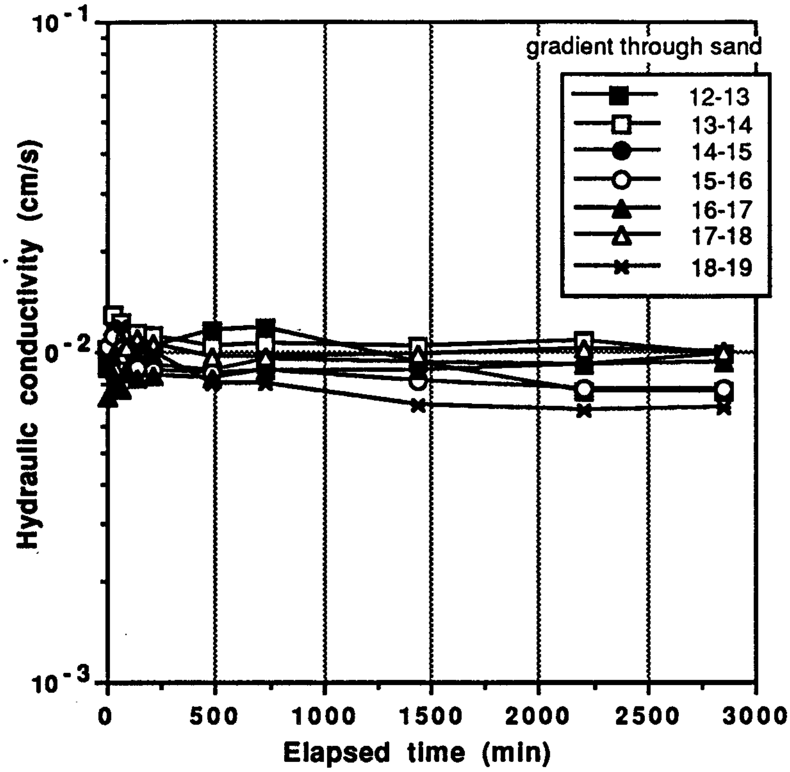

Figure C-9: Hydraulic Conductivity for Exxon in High Confining Stress Filtration Test, i = 2.5

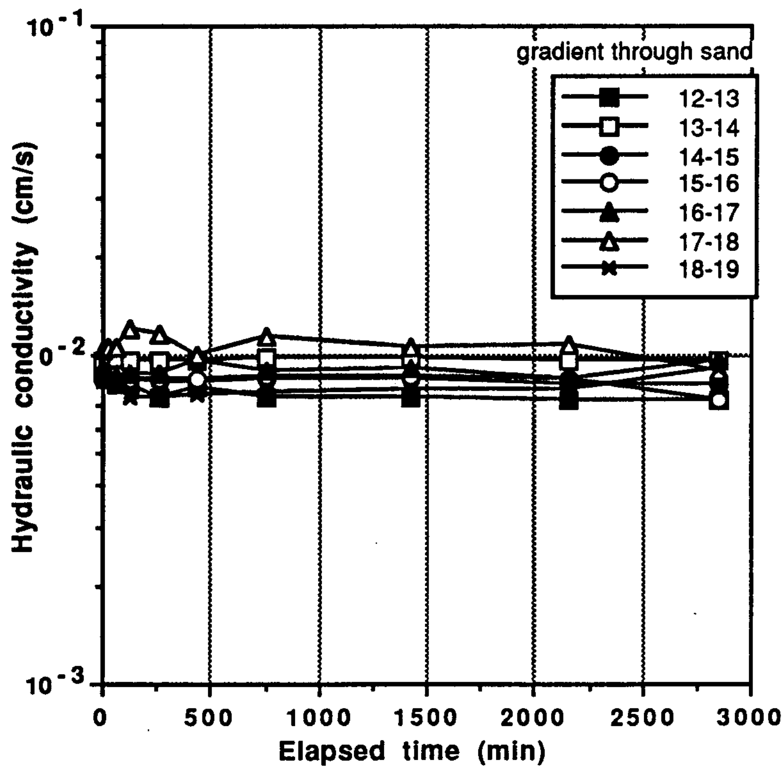

Figure C-10: Hydraulic Conductivity for Exxon in High Confining Stress Filtration Test, i = 5.0

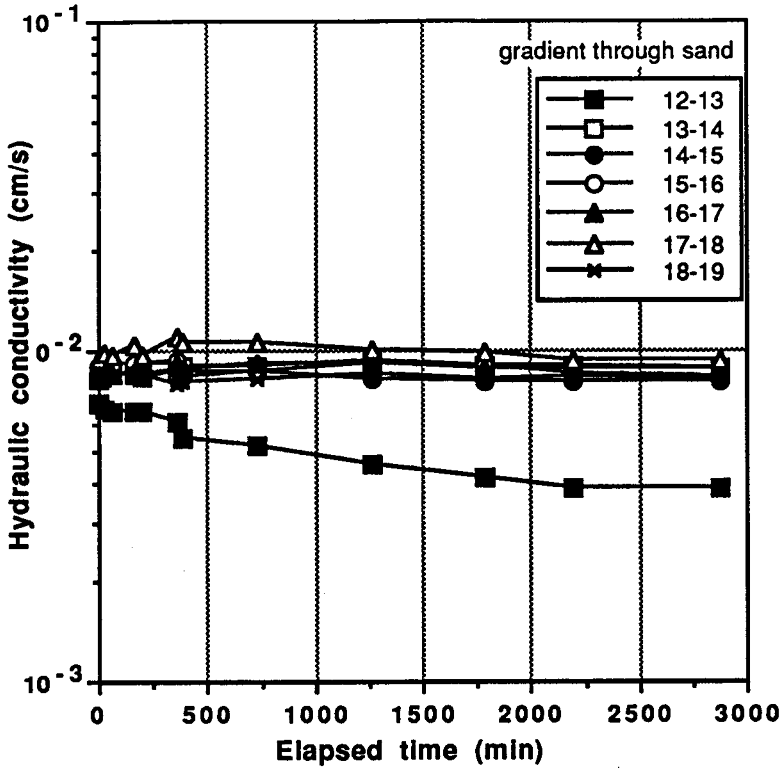

Figure C-11: Hydraulic Conductivity for Exxon in High Confining Stress Filtration Test, i = 7.5

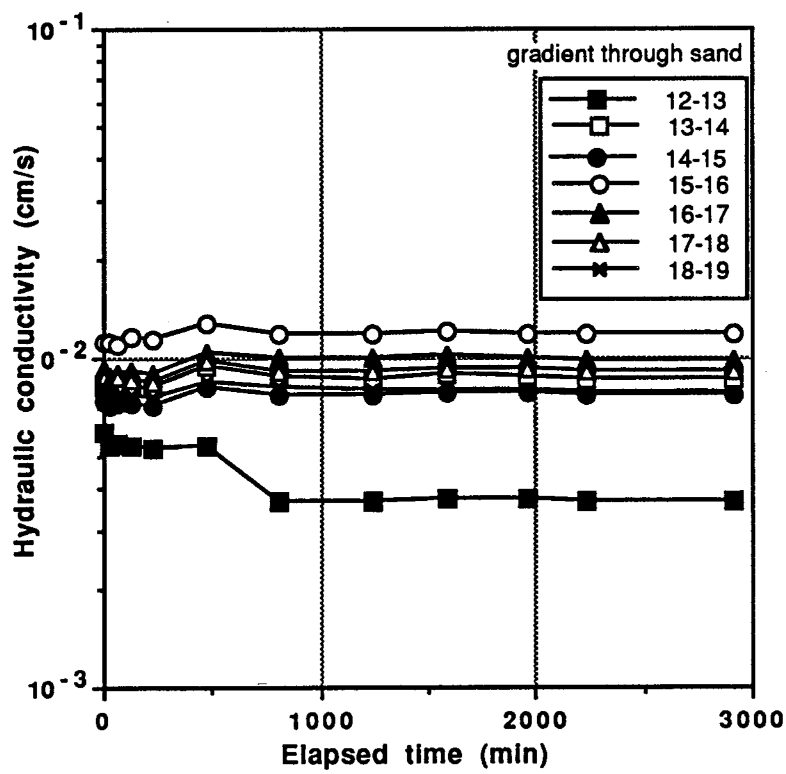

Figure C-12: Hydraulic Conductivity for Exxon in High Confining Stress Filtration Test, i = 10.0

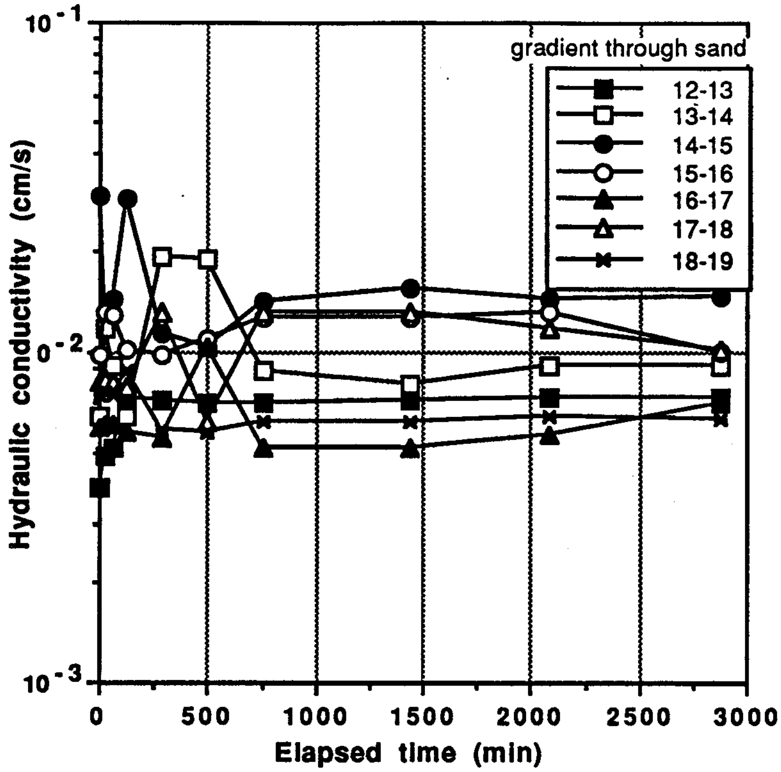

Figure C-13: Hydraulic Conductivity for Quline in High Confining Stress Filtration Test, i = 0.5

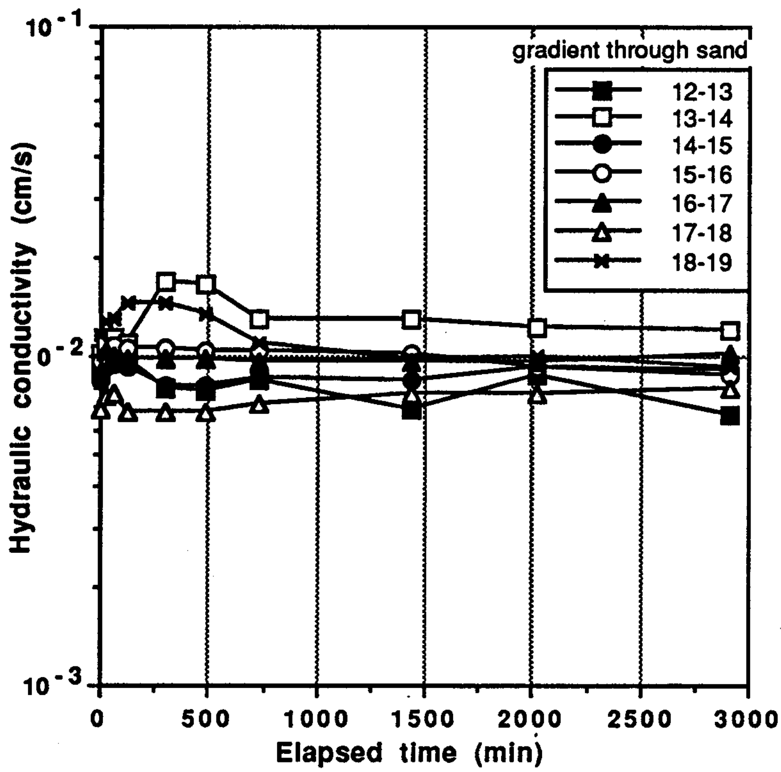

Figure C-14: Hydraulic Conductivity for Quline in High Confining Stress Filtration Test, i =1.0

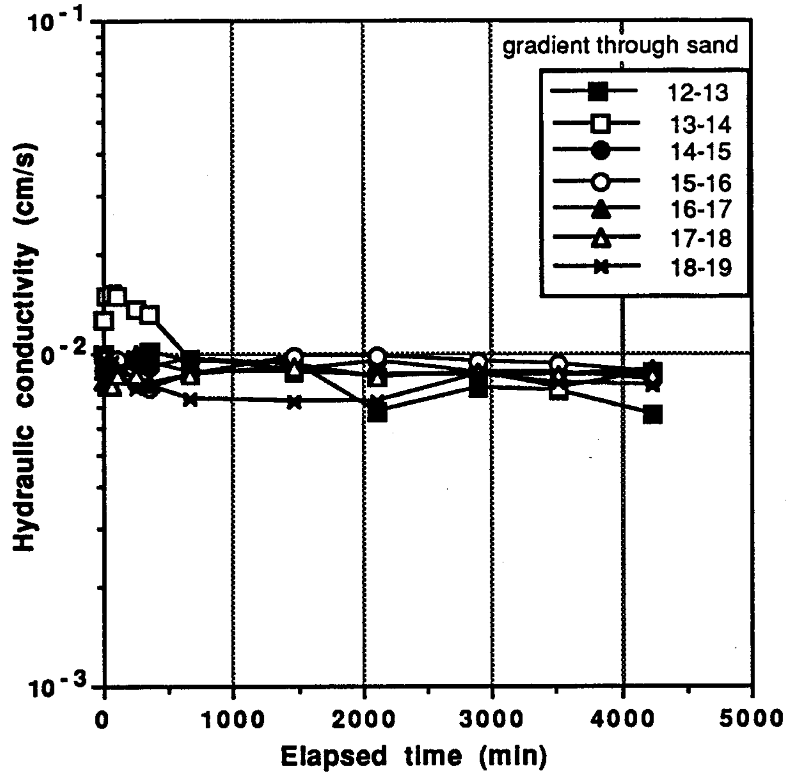

Figure C-15: Hydraulic Conductivity for Quline in High Confining Stress Filtration Test, i =2.5

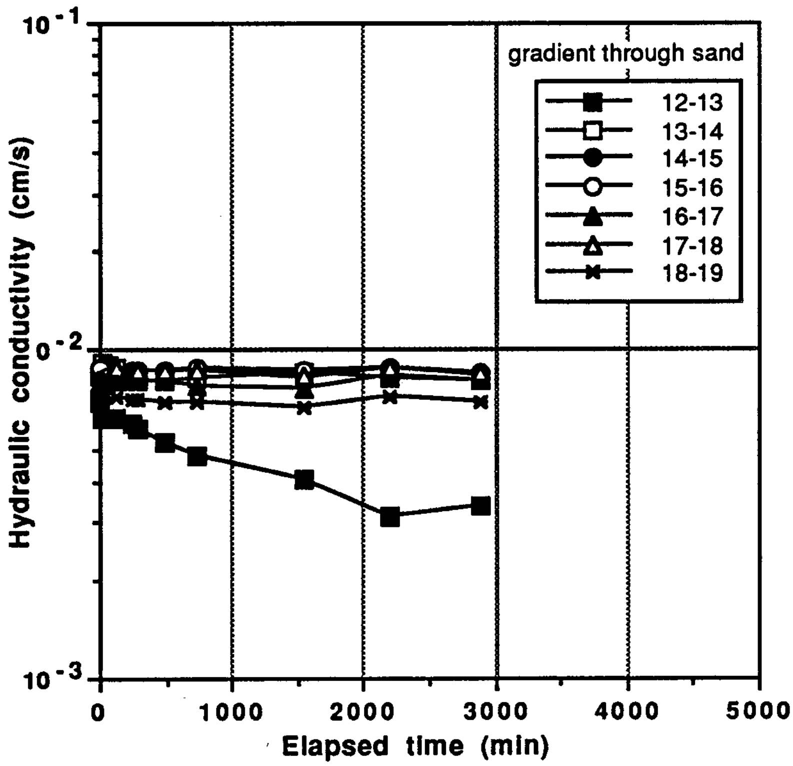

Figure C-16: Hydraulic Conductivity for Quline in High Confining Stress Filtration Test, i =5.0

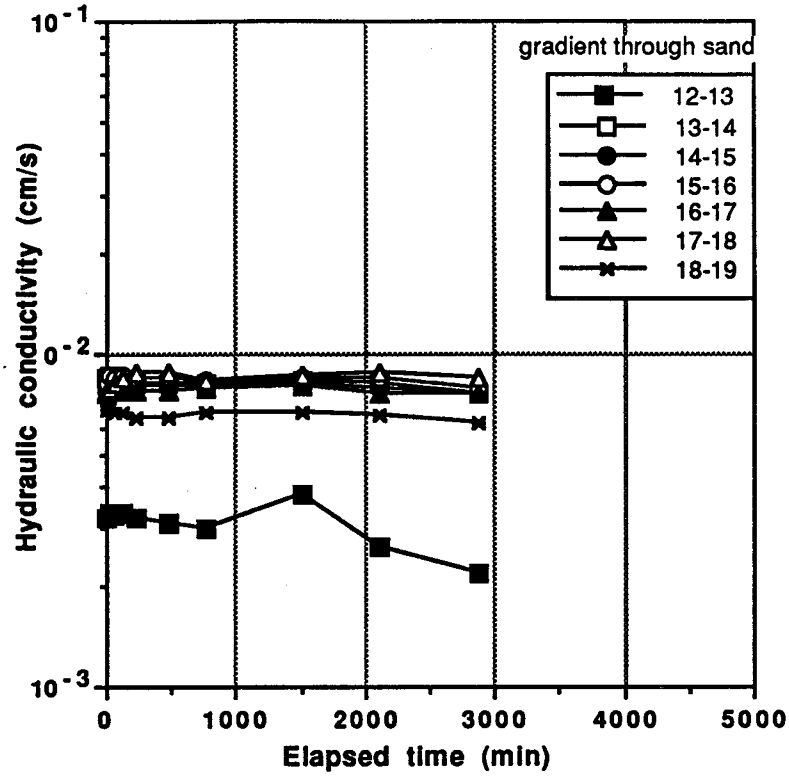

Figure C-17: Hydraulic Conductivity for Quline in High Confining Stress Filtration Test, i =7.5

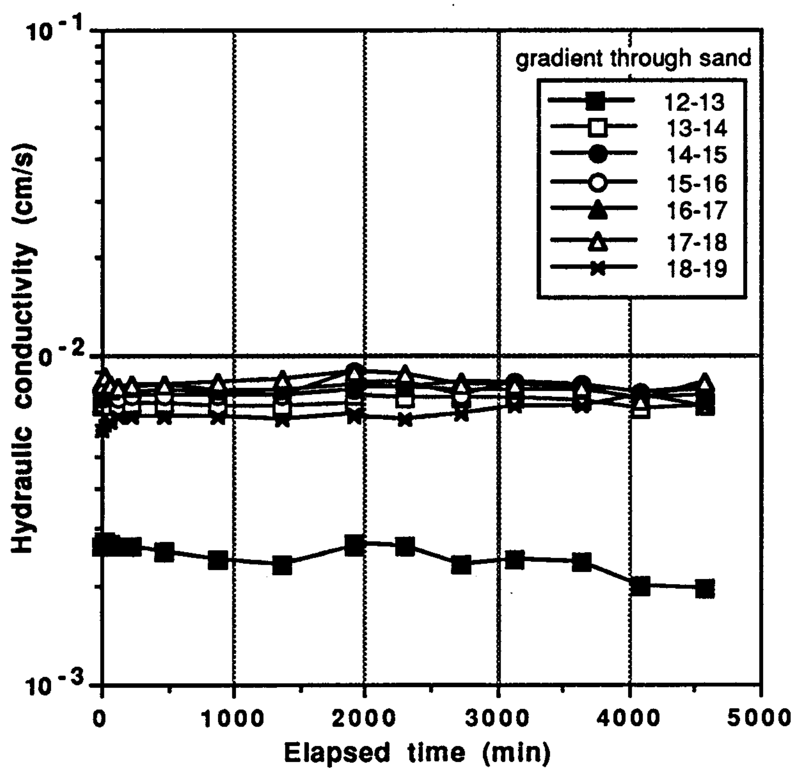

Figure C-18: Hydraulic Conductivity for Quline in High Confining Stress Filtration Test, i =10.1