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LABORATORY TESTING OF ENVELOPE MATERIALS FOR PIPE DRAINS

by

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A Thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of

Master of Science

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Dedicated to my wonderful wife and children

To my mother and brothers to whom

I shall be forever indebted

ABSTRACT

Soils which were known to have caused sedimentation problems in drain pipes were used in the investigations. Different envelope combinations such as soil-fabric, soil- gravel and soil-sand-fabric were evaluated. Nine 100 mm diameter, 250 mm high permeameters were used to determine the functioning of envelope materials and to improve the criteria for testing of envelope materials. To obtain a clear indication of success/failure of an envelope, a wide range of hydraulic gradients and different thicknesses of soils and envelopes were used. The most effective thicknesses were, 5 cm of soil with fabrics and 2.5 cm of soil plus 7.5 cm of gravel for gravel envelopes.

All the fabrics were successful in retaining the soil particles. No clogging was observed and higher flow rates were measured in fabrics having 2 to 3 mm thicknesses with openings O_{95} finer than 100 µm.

SCS criteria (1988) with the following modifications: $D_{100} < 19$ mm and $D_{15} > 0.3$ mm for gravel; and $D_{100} < 9.5$ mm for crushed rock mixed with sand are suggested. The performance of envelopes meeting these criteria were successful.

The laboratory tests show that the use of a fabric with river sand as an envelope has a very good potential for successful field operation. There was no laboratory evidence to reject the functioning of this concept.

RESUME

Pour cette étude, des sols reconnus pour avoir déjà causé des problèmes de sédimentation dans les drains souterrains ont été sélectionnés. Différentes combinaisons sol/géotextile, sol/gravier et sol/sable/géotextile ont été évaluées. Neuf perméamètres, de 100 mm de diamètre par 250 mm de haut, ont été utilisés pour évaluer le fonctionnement d'enveloppes filtrantes pour les drains souterrains et pour améliorer les critères de tests des enveloppes utilisées à cette fin. Afin d'obtenir des indications claires sur les performances d'une enveloppe, les tests ont été faits pour une large gamme de gradients hydrauliques, d'épaisseurs de géotextiles et de couches de sol. Il ressort de l'étude que les meilleurs combinaisons sont: une couche de sol de 5cm avec une enveloppe géotextile, et une couche de 2.5 cm de sol avec une couche de 7.5 cm de gravier pour les enveloppes en gravier.

Toutes les enveloppes en géotextile examinées ont réussi à retenir les particules de sol. On n'a observé aucun blocage des pores des enveloppes. On a mesuré des débits plus élevés à travers des enveloppes ayant une épaisseur de 2 à 3 mm et des pores O_{95} inférieurs à 100 microns.

Les tests en laboratoire montre que les chances de succès des géotextiles utilisés en combinaison avec du sable de rivière dans des installations de drainage au champ sont très bonnes. Les expériences en laboratoire n'ont rien révélé qui puissent contrevenir à l'utilisation de géotextiles comme enveloppe de drains souterrains.

Le critère du SCS (1988) pourrait être modifié comme suit: $D_{100} < 19$ mm et $D_{15} > 0.3$ mm pour le gravier; et $D_{100} < 9.5$mm pour de la roche concassée mélangée avec du sable. Les enveloppes rencontrant ces critères ont bien fonctionné.

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I wish to convey my sincere thanks to the International Waterlogging and Salinity Research Institute (IWASRI) and the Netherlands Research Assistance Project (NRAP) who generously funded this project, and provided a scholarship to finance my Master's degree studies.

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Shafiq ur Rehman
December 1995

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LIST OF ABBREVIATIONS

Institutions

ASTM	American Society for Testing and Materials
CRBC	Chashma Right Bank Canal Project
FDP	Fourth Drainage Project
FES	Fordwah Eastern Sadiqia Project
IWASRI	International Waterlogging and Salinity Research Institute, Lahore, Pakistan.
NRAP	Netherlands Research Assistance Project, Wageningen, The Netherlands.
SCARP	Salinity Control and Reclamation Project, WAPDA, Lahore.
SCS	Soil Conservation Service
SMO	SCARP Monitoring Organization, Lahore, Pakistan

USBR	United States Bureau Reclamation
WAPDA	Water and Power Development Authority, Lahore, Pakistan

Other Abbreviations

AOS	Apparent opening size of fabrics as the result of dry sieving
ATA	After test analyses
DIK	Dera Ismail Khan
SAR	Sodium absorption ratio

LIST OF SYMBOLS

Symbols	Description	Dimensions
A	- Cross sectional area	L^2
C_c	- Coefficient of curvature	-
C_u	- Coefficient of uniformity	-
D	- Diameter of a granular envelope particle	L
d	- Diameter of a base soil particle	L
d_{10}, D_{10}	- Grain size diameter for which 10% of the soil particles are smaller	L
d_{15}, D_{15}	- Grain size diameter for which 15% of the soil particles are smaller	L
d_{30}	- Grain size diameter for which 30% of the soil particles are smaller	L

Symbols	Description	Dimensions
d_{50}, D_{50}	- Grain size diameter for which 50% of the soil particles are smaller	L
d_{60}, D_{60}	- Grain size diameter for which 60% of the soil particles are smaller	L
d_{85}	- Grain size diameter for which 85 % of the soil particles are smaller	L
d_{90}, D_{90}	- Grain size diameter for which 90 % of the soil particles are smaller	L
D_{100}	- Grain size diameter for which 100 % of the soil particles are smaller	L
i	- Hydraulic gradient	-
K	- Hydraulic conductivity at temperature T	LT^{-1}
M_1	- Mass of the fraction that passed through the geotextile	M
M_2	- Mass of the fraction that is retained on and within the geotextile	M
O_{50}	- Pore size diameter for which 50 percent of the pores have a smaller diameter	L
O_{90}	- Pore size diameter for which 90 percent of the pores have a smaller diameter	L
T	- Temperature	^0C
L	- Thickness of an envelope specimen	L
t_g	- Mean envelope thickness	L
t	- Time	T
V	- Volume	T
η_t	- Dynamic viscosity of water at temperature T	$ML^{-1}T^{-1}$

Symbols	Description	Dimensions
η_{20}	- Dynamic viscosity of water at 20 °C	$ML^{-1}T^{-1}$
μ	- Mass per unit area of a geotextile	ML^{-2}
μ_s	- Mass of a geotextile specimen	M
Ψ	- Permittivity	T^{-1}
μm	- micron	L

CHAPTER 1

INTRODUCTION

Prior to the start of large scale irrigation projects, the water table was deep in almost the entire area of the Indus plain in Pakistan and it was in dynamic equilibrium (Rehman 1975). The rise and fall in the water table was more or less seasonal, depending on the magnitude of the net annual recharge and discharge. The gradual expansion of irrigated areas and the associated seepage provided an additional source of water table recharge. In zones where the water table is near the soil surface, the excess of water content in the soil reduces the root aeration of the plants, consequently crop yields are reduced. Capillary rise from the shallow water tables and evaporation during the fallow season causes accumulation of salts at or near the soil surface. Also, poor water management and inadequate drainage facilities further accelerate the pace of deterioration.

It has been estimated that Pakistan is losing culturable land at an alarming rate of 20,000 to 40,000 ha per year due to waterlogging and salinity problems, (Water And Power Development Authority, WAPDA, 1992). Pakistan possesses a suitable climate, good soils and the biggest gravity flow irrigation network in the world from a single river, the Indus. The irrigation systems convey over 123.35 billions m^3/year MAF (Millions of acre feet) of water to irrigate an area of about 14 million ha. On the average, the crop yields are far lower than those attained by many other countries.

The importance of pipe drainage has increased dramatically in the last decade in Pakistan. The first sub-surface drainage project was the East Khairpur Tile Drainage Project (EKTD), covering an area of 14500 ha. The soils below 1 m depth have silt and fine sand textured layers. This project was completed in 1986. The second project, Mardan Salinity Control and Reclamation Project was completed in 1991, having an area of 30,000 hectares and a soil texture generally varying between very fine sandy loam, silt loam and silty clay loam at drain depth. The third project, Chashma Right Bank Canal (CRBC) Project at Dera Ismail Khan, having an area of 61,000 ha was completed in 1993. Soils ranged from fine sand to coarse sand at drain depth. The Fourth Drainage Project (FDP), near Faisalabad having an area of 55,000 ha was completed in December 1994. Soils range from moderately coarse to moderately fine texture. Other subsurface drainage projects are under execution, the most important are: the Khushab SCARP 24,000 ha (soils: alluvial deposits moderately coarse to moderate fine texture), Fordwah Eastern Sadiqia (FES), 70,800 ha (the majority of soils fall in the category of sandy loam) and Swabi SCARP close to the Mardan Scarp project. In general, the soils of the above mentioned projects within the strata of subsurface drain pipe placement are very unstable when saturated; therefore, they require envelopes around the drain pipes. The location of subsurface pipe drainage projects is shown in Figure 1.1.

Means of preventing soil particles from entering into subsurface drains have been sought since the beginning of the pipe subsurface drainage. Abundant research has been done and practical experience has been gained in various countries during the period of 1960 - 1993. It is now possible by examining the soil physical/hydrological properties and existing flow conditions through the soil, to predict the needs for drain envelopes, to select appropriate materials and to provide guide lines for the design of envelopes (Stuyt and Willardson, 1993)[1].

The problems experienced at the FDP with gravel envelopes (based on

[1] Personal communication on draft section of a new Monograph.

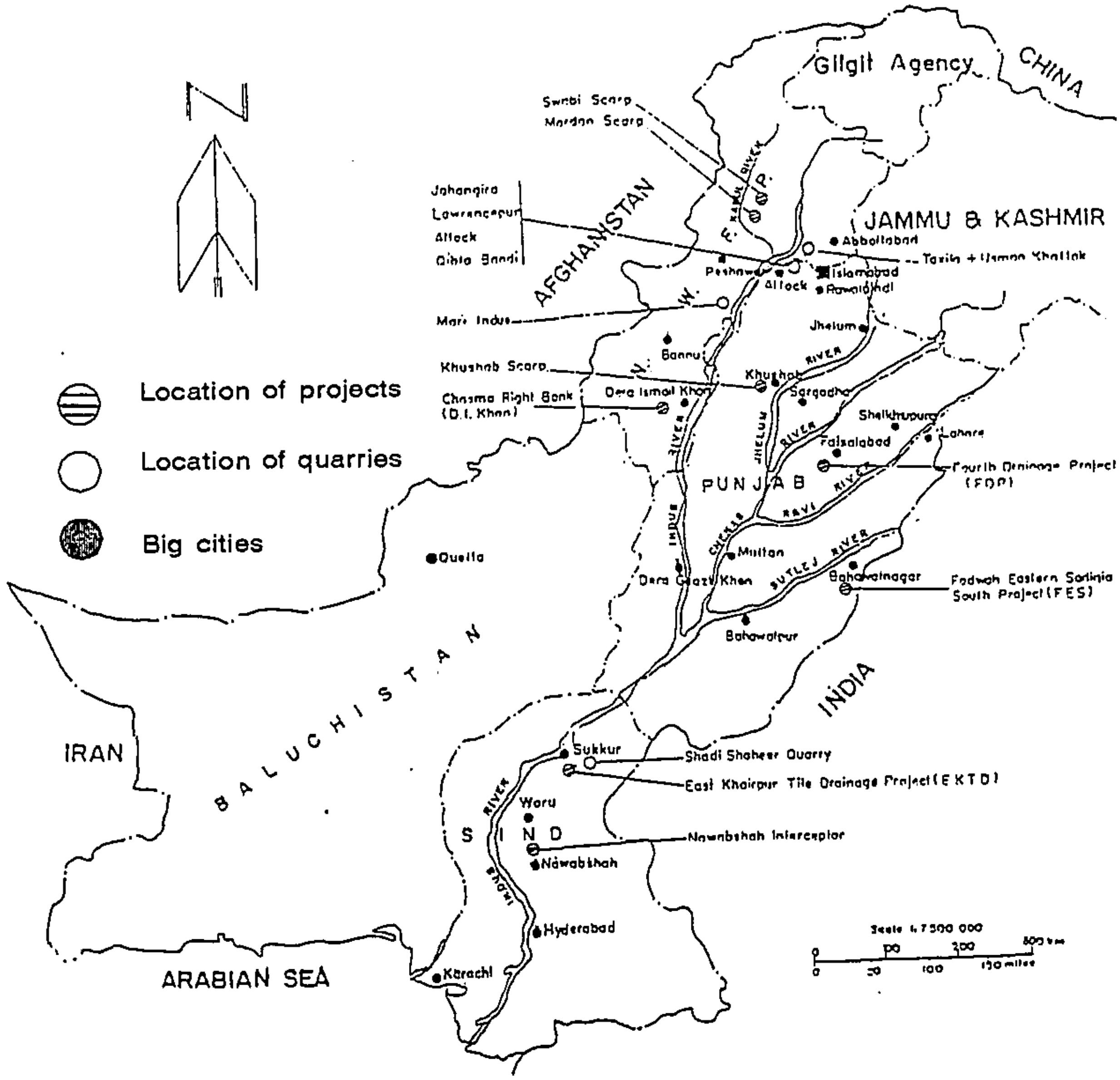

Figure 1.1 **Location of subsurface drainage projects and gravel sources**

USBR design) received immediate attention of the authorities involved in subsurface drainage design. Typical problems encountered were discontinuous flow of gravel in the trencher box, rapid pipe sedimentation and excessive development of sinkholes. It was observed in most of the installed subsurface drains that a major problem was caused by the deposition of solid particles in the pipes, which reduced the capacity of the drainage system (Bhatti and

Vlotman, 1990). The design of the envelope material was based on research and experience gained under different conditions in foreign countries. The failure of the gravel envelope in the FDP showed the need of additional research to improve drain envelope design and selection criteria based on Pakistani conditions. Due to the difficulties in the installation of gravel envelopes, synthetics alone and combinations of synthetic envelopes and sand envelopes (dual envelopes) were tested and suitable envelope materials for the Pakistani conditions were chosen.

At the present time in most of the developed countries, synthetic fabric envelope materials with polyester and polypropylene fibres are used widely rather than organic envelope materials, such as straw, coconut fibres and cotton that were used in the earlier years. In some West-European countries voluminous fabric envelopes are preferred while in other countries thin sheet envelopes are used (Deirickx 1990). Synthetic envelopes are promising alternatives to gravel, because they can easily be wrapped around drain pipes and do not decay once the drain pipes are installed. Fabric envelopes have been used in Pakistan. At the Mardan SCARP project many laterals with synthetic fabrics were laid with a trenchless plow. 200,000 m of collector pipes with 250 and 300 mm diameter were installed by trencher machine using Texel F200 polyester fabric. At the Nawab Shah Interceptor Drain of the Left Bank Outfall Drain in the Sindh, several synthetic fabrics have been installed in 1990. In the same project, fabric with sand was also tried but monitoring results are not yet available.

The International Waterlogging and Salinity Research Institute (IWASRI) and the Netherlands Research Assistance Project (NRAP) are actively involved in drain envelope studies in Pakistan. Research was initiated to improve envelope design procedures. For the last five years IWASRI/NRAP has made serious effort to develop standards for the selection of suitable and economical envelopes for subsurface drainage. The filtration performance of the envelopes were measured in permeameters designed by Dierickx and built at Scarp Monitoring Organization (SMO) under the supervision IWASRI and NRAP.

To select the best soil-envelope combination, several granular and synthetic fabric envelopes combined with and without sand, have been tested in the laboratory. The soils used in these tests were brought from various projects. Some of the tests have given positive indications of success/failure, whereas others were not conclusive. To ascertain the effectiveness of these envelopes, some more severe test conditions were performed on various combinations of soil and envelope (gravel sample) thickness, hydraulic gradient was suddenly increased or decreased during the experiment. To simulate this condition a surging method was introduced to evaluate envelopes performance, where pressure head is changed abruptly from minimum to maximum and from maximum to minimum. A clear indication of success/failure on most of the tests were obtained, when high hydraulic gradients were applied and when the materials were exposed to abrupt changes in head. "Failure", when envelope didn't retained the soil particles and a whole soil passage occurred through the top plate.

1.1 Objectives

This study aims to evaluate the filtration performance of different envelope materials used with problem soils obtained from various drainage projects located within Pakistan.

1. To present a summary of the permeameter test results.
2. To evaluate the results.
3. To improve the methodology of the testing procedures.

CHAPTER 2

LITERATURE REVIEW

2.1 Envelopes

Drainage envelopes can be divided into:

* Granular envelopes (sand, gravel, or crushed rock)
* Organic envelopes
* Synthetic envelopes
* Dual envelopes

Graded gravel and sand materials have historically been used as the "ideal" envelope material around subsurface drains in arid and semi-arid areas (Dierickx 1990, Lennoz-Gratin 1992). Such materials meet the requirements of a good envelope in addition to long durability, structural support of the pipe and high permeability; but these materials in some areas are expensive and sometimes unavailable. Extensive research has been carried out over the decades to develop, an ideal and low cost envelope (Dierickx 1990).

Organic materials, such as peat, flax straw, flax textile corn cobs, and wheat straw have been used. In the early 1970's coconut fibres were introduced as drain envelope materials in Europe and Asia (Dierickx 1990).

Synthetic envelopes have progressively become more widely used throughout the world (Dierickx, 1987). The replacement of concrete and clay drain pipes by corrugated plastic pipes has enhanced the use of synthetic envelopes. Synthetic fabrics can be conveniently installed on corrugated plastic drain pipes at the factory or in the field. Geotextiles are available as woven products (monofilament, multifilament, or a combination) and as non woven products (needle-punched, heat-bonded and chemical-bonded). Similarly, knitted geotextiles or geoknitted materials are produced by interloping one or more yarns, fibres, filaments or other elements.

Dual envelopes are known to have been used in Pakistan and the United States, but no published results on the performance of dual envelopes has been found. This type of envelope is the combination of synthetic fabric and pit run sand or gravel, and has been found very convenient in silty soils.

2.1.1 Functions of envelopes

The following are the basic functions of the envelope materials:

* To create a more pervious zone surrounding the drain pipe, reducing the entrance resistance and improving the performance of the drainage system.
* To prevent significant soil invasion into the drain pipes. Siltation is one of the major problems that makes a drainage system ineffective.

Granular envelopes such as coarse sand and gravel can have additional functions such as:

* To provide bedding for the drain pipe, in order to mechanically stabilize the trench and maintain the pipe elevation.
* To protect corrugated plastic drain pipes from local crushes due to collapsing of the trench wall, or stones or lumps of earth falling onto the pipe in the trench.

Dierickx 1990 reported that envelope materials are intended to protect drain pipes against soil particle invasion (mechanical function) and to facilitate water inflow by creating a more permeable zone around the pipe (hydraulic function).

2.1.1.1 Hydraulic function.

Drain pipes are not completely permeable but have water entry openings on 1 to 2% of the total pipe surface. Seepage paths converge towards these openings causing an additional flow resistance due to the change in direction of the flow path, which is known as the "entrance resistance" of drain pipes. Changes in the drain pipe envelope will affect the converging flow and, consequently, the entrance resistance. Permeability as well as thickness of drain pipe surroundings influence the entrance resistance (Nieuwenhuis and Wesseling 1979; Dierickx 1980).

2.1.1.2 Mechanical function:

Since it is almost impossible to make perforations (like pin-hole pipe) in such a way that they prevent drain pipe siltation, envelopes are used. Drain pipes installed in stable well structured, heavy clay soils do not require envelopes to protect them against siltation but they may need an envelope to improve the hydraulic function. Drain pipes installed in cohesionless sandy soils do need envelopes to prevent siltation, while the hydraulic functions become less important in case of highly pervious soils. A drainage envelope should prevent fine soil particles from passing through it.

2.1.2 Envelope characterization

Granular envelopes are characterized by their particle size distributions. Synthetic envelopes are characterized by their pore size distributions. The most important characterization parameters are the permeability and the pore sizes. The water permeability of granular materials and geotextiles can be determined. For many geotextiles the test conditions are such that laminar flow conditions can hardly be obtained. The flow may be turbulent or in the transition between laminar and turbulent (Willardson and Ahmad 1988). The water permeability can then be characterized by a discharge under a given head loss. The coarser the envelope the more permeable it is.

Suitable synthetic envelopes should be highly permeable and should, without any risk of harmful blocking or clogging, prevent soil particles from entering the drain pipe. "Blocking" is the decrease in permeability as a result of pore obstruction by soil particles when the envelope is brought into contact with the soil. "Clogging" is the reduction in permeability of the envelope with time as a result of the deposit of clay and silt particles, organic dust or chemical deposits. In addition, the envelope must resist chemical and biological attack to perform adequately for many years.

2.1.3 Soil texture effect on envelopes

The rate of pipe sedimentation was found to be largely and significantly determined by soil structure stability, installation practices and properties of envelopes. Soils containing a large amount of clay particles can be very cohesive and do not separate easily into single particles; hence drain pipes in non sodic soils with more than 30% clay do not require envelopes because there is no siltation. This condition is not applied for sodic soils with sodium absorption ratios, SAR, greater than 8. If the SAR of the soil exceeds 8, an envelope may be required if the clay content is less than 40% (Metzger et. al., 1992).

Soils with large amount of sand particles do not have any cohesion and exist in single soil particles only; drain pipes installed in cohesionless sandy soils do require envelopes (Willardson 1974).

Sedimentation in drain pipes is a major factor affecting the performance of drainage systems in areas with fine sand and silty soils. Envelopes, granular and fabric, when properly selected are the most effective method of reducing sedimentation of pipes. Zanten (1986) gives the upper and lower limit for these so called problem soils: d_{50} varies between 0.05 and 0.15 mm (or d_{90} varies between 80 and 600 µm), where d_{50} and d_{90} are the particle size at which 50% and 90% by weight passes a sieve, respectively. Al-Rawi and Daham (1990) state that soil particles can move towards the drain pipes in the coarse textured soil rather than in fine textured soil.

Dierickx (1990) reported that in cohesive soils the need for envelope materials depends on soil structural stability, which may not only be related to the physical soil texture. It also depends on the chemical soil composition, the ability of the cohesive soil to withstand flow pressure and the physical soil conditions. Soil bulk density influences the functioning of the envelopes.

2.1.4 Entrance resistance

Several researchers have evaluated the performance of subsurface drainage materials by studying the entrance resistance. The total resistance to seepage to subsurface drains is composed of four components: vertical, horizontal, radial and entry resistance. The first two would depend on the porous medium (i.e. the bulk soil) while the last two depend on both the soil and the type of drain and envelope. The presence of corrugations on a drain increases the entry resistance as the stream lines experience additional seepage path distance as they converge towards the opening between the corrugations.

A large percentage of the entrance resistance occurs in the immediate vicinity of the openings (Broughton et. al. 1976). The entrance resistance of a naked drain pipe can be reduced considerably, so that it becomes close to an ideal drains, by the use of envelope material (Broughton et al., 1976, Skandar 1984). Envelopes around the pipe decrease the exit hydraulic gradient and entrance resistance and equipotential lines become circular and concentric to the pipe (Lennoz-Gratin, 1989).

The entrance resistance for all type of envelopes varies with hydraulic head above drains, it is maximum at low hydraulic head and minimum at high head. Ultimately it becomes constant at higher heads. The entrance resistance was computed for gravel, geotextile and plastic netting for three years in the field. The study shows that it decreased with time. In the case of gravel envelopes, entrance resistance decreases, and it shows a better performance (Singh et al., 1992). According to Dierickx et al., 1992, the maximal decrease in entrance resistance is obtained at an envelope thickness of about 5 mm. A larger thickness does not result in a further decrease in the entrance resistance although it reduces the radial flow resistance since a more permeable envelope material replaces the less permeable soil.

2.2 Granular envelopes

In designing granular envelopes, a distinction is made between a filter design and a surround design; the first one being designed for retaining the base soil material, the latter one just to create a highly permeable surround. Widely used criteria have been established by the US Bureau of Reclamation (USBR), the US Soil Conservation Service (SCS) and the UK Road Research Laboratory (RRL). The general procedure for designing a gravel envelope for a given soil is to make a mechanical analysis of both the soil and the proposed envelope material, compare the two particle size distribution curves, and then decide by some set of criteria, whether the envelope material is satisfactory.

The first criteria proposed by Terzaghi (US Corps of Engineers, 1941) for what he termed as a filter: 1. The particle diameter of the 15% size of the filter material (D_{15}) should be at least 4 times as large as the diameter of the 15% size of the base material (d_{15}). This will make the filter at least 10 times more pervious than the base soil. 2. The 15% size of the filter material should not be more than 4 times as large as the 85% size of the base material. This will prevent the fine particles of the base material from washing through the filter material pores.

The Soil Conservation Service (1988) has recommended for a naturally graded pit-run material as drain envelope, or a mixture of medium or coarse sand with fine and medium gravel, that the maximum size should not be more than 38 mm, no more than 30 percent of the material should be smaller than the 250 µm (#60 sieve) and not more than 5 percent should be smaller than 75 µm (#200 sieve). They also suggest the following additional criteria (SCS 1971). D_{15} size smaller than 7 times the d_{85} size but not smaller than 0.6 mm. D_{15} size larger than 4 times the d_{15} size. Where, D_{15} and d_{85} are the particle size at which 15% and 85% by weight passes a sieve, respectively.

Figure 2.1 s. ws the particle size distribution curves for two typical problem soils in Pak. tan. The Curves labelled FDP upper and FDP lower are the acceptable limits of the Fourth Drainage Project (FDP), Faisalabd for a suitable envelope sands-gravel and crushed rock, based on the gradation curves of the soil. A drain envelope made from crushed rock with an "acceptable" gradation curve (FDP upper and Lower limits in Figure 2.1) did not function properly. The drains filled with sediments in a very short time. In an effort to solve the problem empirically, a natural material called Qibla sand was mixed with crushed rock. The mixture produced an envelope that successfully protected the drains from sediment inflow. The D_{15} size of the new envelope mixture was approximately 0.3 mm and D_{100} size smaller than 19 mm

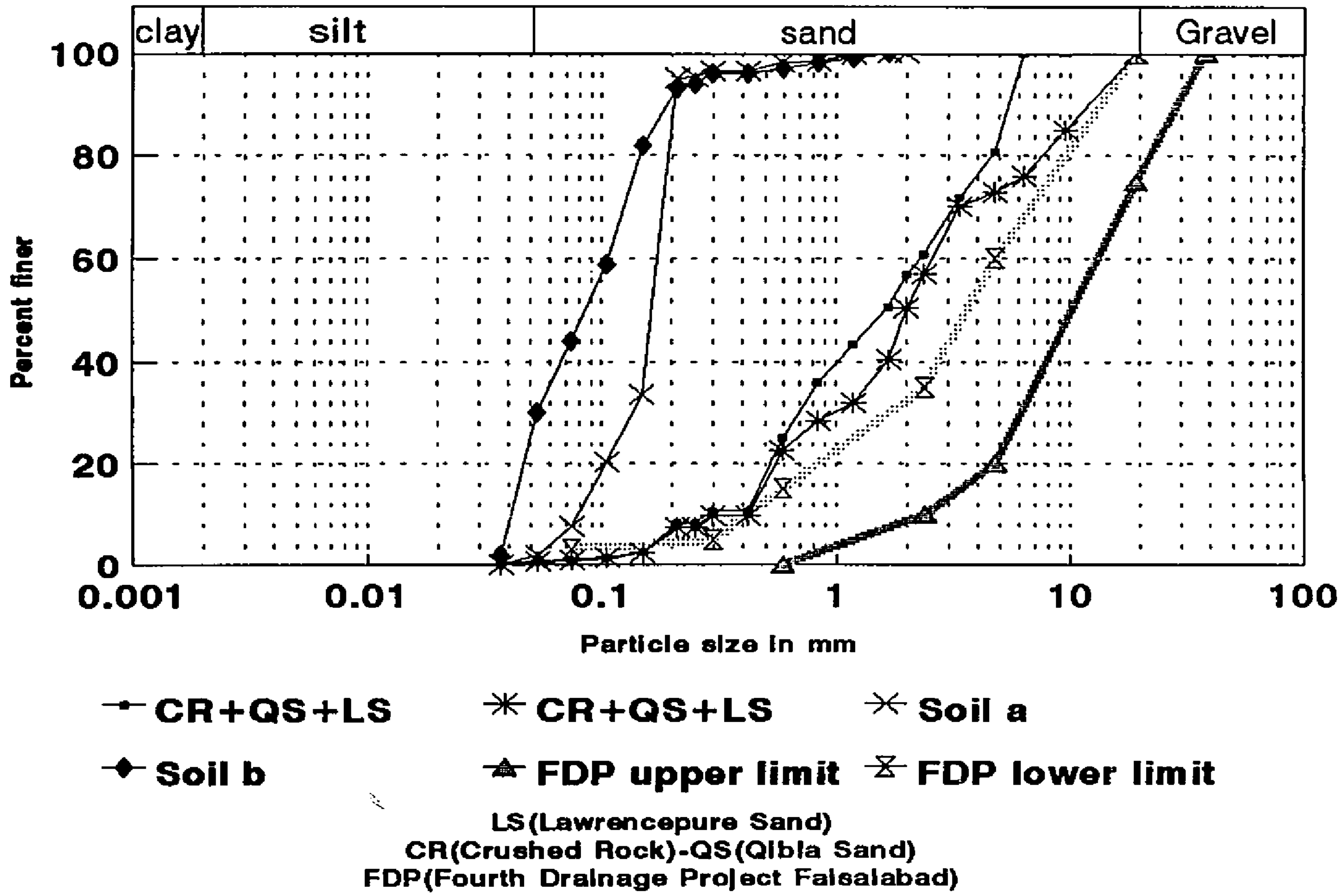

Figure 2.1 Particle size distribution of crushed rock mixed with two types of sand Also, curves of FDP envelope mixed with sand and pit-run gravel.

(Vlotman et. al., 1992).

According to Shered et al., 1984, sand and gravelly sands having D_{15} equal or smaller than 0.5 mm are good filter for fine grained clay and uniform sand. Envelopes must contribute to the prevention of soil failure to ensure the stability of the drainage system. High hydraulic gradients should be avoided (Dierickx 1987).

Bhatti and Vlotman (1990) reviewed drain envelope design criteria for the FDP project and performed the field tests. They found that USBR (1978) specification are suitable for envelopes which improve flow characteristics around the pipe but seem less suited for envelopes that are expected to function as a filter.

Broughton[1] (1987) mentioned that during the inspection of the siltation problem at some locations along the drain lines at Mardan SCARP, Pakistan, the envelope was found to be too course. The oblong nature of some of the gravel and the use of screens of one inch square opening resulted in some pieces of gravel 3 inch long and one inch diameter passing into the envelope materials. These large pieces of gravel could segregate from the fine gravel in the gravel hopper during transport, or on the conveyor belts leading to the gravel hopper and drain pipe.

2.3. Synthetic fabric envelopes

In certain region of the world materials known as geotextiles are widely

[1] Personal communication in a letter to Mr. G. Thompson on Mardan SCARP.

used as pre-wrapped synthetic drain envelopes. Fabric envelopes are made of polyester, polypropylene, polystyrene and nylon. They may be woven, non woven or knitted. Woven fabrics are produced by interlocking and needle or non-needle punching, at right angles, two or more sets of fibers. Similarly, knitted fabrics are produced by interloping one, or more, yarns. Nonwoven fabrics are in the form of manufactured sheets, webs or batts of directionally or randomly oriented fibres bonded together.

The most widely accepted types of envelope materials used in agricultural drainage are the non-woven needle-punched, the spun-bonded and the knitted sock fabrics (Zeijts, 1992). These materials are generally divided in two types:

- Voluminous envelope, a felt-like material having a thickness of 3 - 10 mm, which is mostly used in Europe (Dierickx,1987)
- Thin envelope, a sheet like material of less than 1 mm in thickness and mostly used in the United States and Canada.

The ability of a geotextile to retain soil particles is usually expressed as the ratio of a characteristic pore size of the geotextile to a characteristic particle size of the soil. This ratio is called the retention criterion, also known as bridging factor or filter criterion (Stuyt and Willardson[2] 1993).

A widely used criterion for synthetic envelopes is the O_{90}/d_{90} ratio, where O_{90} is the pore size of the geotextile at which 90% of the pores have a smaller diameter (by dry sieving test method), and the d_{90} the particle size of the soil at which 90% of the particles by weight have a smaller diameter. However the ratio O_{50}/d_{50} has also been used with bridge factors ranging from 3 to 21 for dry sandy soil (Willardson and Walker, 1979). Davies et al. (1978) suggests an

[2] Personal communication on draft section of a new Monograph.

O_{50}/d_{50} of 5. Dierickx and Sluys (1990) concluded that the particle retention capability of thin geotextiles is satisfactory if O_{90}/d_{90} is < 2.5. For thicker geotextiles, with a thickness of at least 5 mm, he found a ratio of $O_{90}/d_{90} < 5$ to be acceptable. Leonoz-Gratin (1987) reported that in the case of fine textured soils, envelope materials need specific characteristics in order to be functional. These characteristics are a small pore size (less than 80 µm) and a rough surface to assist arching between soil particles and geotextile fibres.

In Canada and in Europe, thin synthetic geotextiles have been successfully used for filtration and soil stabilization since about 1973 (Martinek 1986). A few authors extracted such geotextiles from the ground (of 2 to 15 years old) and have reported favourably on their continued good performance as drain envelopes (Bonnell et al., 1992). But, still the long term durability of synthetic envelopes as drain pipe filters is questioned by some persons. The principal question the designer faces when choosing synthetic envelope: which type of synthetic envelope performs better, a thin one or a coarse voluminous envelope? There is no general acceptability of synthetic envelopes. According to Stuyt (1992) in sandy soils (silty and loamy), thin envelopes retention capability was worse than that of "voluminous" ones. He also reported that pipes sedimentation rates was higher in low structural stable soils.

In analyzing water flow through synthetic envelopes, Dierickx et al. (1992), assume that for voluminous envelopes, the flow lines approach the soil-envelope interface radially, hence the concentration of the flow lines towards the perforations will occur in the more permeable drain pipe envelope. Using thin envelopes, the convergence of the flow lines towards the perforations starts already in the soil, and due to the differences in permeability between soil and envelope, flow lines at the interface are refracted to further converge on the perforations. According to Bonnell, 1984, initial soil contact with the envelope was found to be a critical factor. The reason postulated for this was, that without the initial contact of the soil with envelope, any chance for an infrastructure to be formed was lost.

Bolduc et al., 1987, found that the thicker envelope materials can give a uniform velocity field close to the drain tube with the result of locally lowering the dynamic forces on soil particles. The thicker the envelope material the greater will be the flow area offered to water flowing in its plane. This flow area is many time greater than the area of the slots in the drainage tube.

Zeijts (1992), in his evaluation of the Dutch experience, reported that even though the performance of voluminous envelopes with respect to pipe sedimentation was observed to be good (good hydraulic performance and less sensitive to clogging), thin envelopes were more effective in preventing sedimentation in the drains. Rollin et al.(1987) field study indicates that thin synthetic envelope materials installed in silty soils were successful in preventing soil from entering drain pipes while maintaining good drainage rates. They observed no sediment clogging of the drainage systems three years after installation.

Stuyt (1992) took core samples of soils surrounding drain pipes wrapped with fabric filter materials installed in weakly cohesive soils. Most of the drains were observed to have "clogged" soil near them, that is fine particles (≤ 30 μm) moved towards the drains and filled the pores among the larger particles. He concluded that the filter materials around the drains appeared to have little or no effect on this process. The result of this soil clogging was that hydraulic conductivities were greatly reduced in the soil in the vicinity of the drains, and water flow was slowed considerably. In a similar study Bonnell et. al. (1992) performed field and laboratory tests of nine fabrics materials at two locations in Canada. These had been in place in fields from 4 to 15 years.

Upon excavation, it was noticed that fine soil particles have been removed from a zone of soil with immediate contact with the fabric from 2 to 4 mm in thickness. This thickness had a highly permeable soil zone due to abundant macropores. Also, the fabric was visually differ from the virgin samples from manufacturers in colour only. They also found that the soil adjacent to the fabric contained more clay sized particles as compared to 150 mm away from the fabric. None-the-less drainage rates from these drains exceeded the design rate of 9 mm/day and the farmers were very satisfied with the drainage.

Zaslavsky (1978) favours coarse voluminous envelopes. According to him, particles finer than the envelope pores move into it, while the larger ones don't. This process continues until the soil stabilizes. Simultaneously, an inverted natural soil filter will be formed outside the envelope. If the envelope is thin with large pores the erosive process may cause silting up before the soil stabilizes and if it has small pores, then all fine particles may be retained and severe clogging may occur. Whereas with a thick and coarse envelope fine particles are retained at random places in the envelope and the probability of the envelope clogging is reduced.

Hermsmeier (1976) compared the performance of gravel with several types of fabric envelope materials. Laboratory tests were performed in a tank filled with soil, while at the field, drain pipe with wrapped fabric envelope and drain pipes with three-inch gravel envelope thickness were laid in the soil. The drainage rates from the fabric envelopes ranged from 60 to 80 percent of the drainage rate of gravel envelope. But the drainage rates from the fabric wrapped drains were adequate for most drainage conditions. The filtering ability of fabric envelopes was not as good as for the gravel envelope. Satisfactory performance of fabric and gravel were noticed in a field with sandy soil during a four-year test period.

2.4 Dual envelopes

In Pakistan the drainage envelope materials most predominantly used is gravel (river run and crushed rock), which does not always result in effective protection of the drain pipe against sedimentation (Vlotman et al. 1992). Problems experienced with the gravel envelopes were: discontinued flow of gravel in the trencher box, rapid sedimentation into the pipes and excessive development of sink holes (Bhatti and Vlotman, 1990). Because of these disadvantages, fabric envelopes are increasingly replacing gravel envelopes (Dierickx, 1993). The life of the fabric envelopes is not yet known. A promising alternative for a long-life effective envelope is a combination of fabric with sand cover. Such an envelope can be more economical than gravel and less problem for quality control, while giving good performance. The consultants of the FES project, Pakistan, have decided to use fabric envelopes or fabric with sand combination (Honey field and Sial, 1992). Use of sand will increase the drain entry area and will provide a good bedding for pipe support.

Although no design criteria are available for combinations of sand and fabric envelopes, these have been successful in practice. In highway drainage, the practice of lining a narrow shallow trench with a fabric and then backfilling the trench with single sized gravel (9.5 mm) is an acceptable solution for some pavement drainage works (Koerner, 1994). Similarly Broughton[3] (1995) is of the opinion to try to use pit run gravel and coarse sand to increase the seepage entry area by putting sand or gravel on the top and sides of the fabric wrapped drain pipe. This will guarantee placement of the pipe on grade and the trench will be less wide as compared to gravel around the pipe.

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[3] Broughton R.S., 1995, a draft paper on installation of drains.

In a laboratory study, Lennoz-Gratin, (1987) found in sandy soil that all the fabric envelope materials commercially available are suitable because there is almost no change in the hydraulic conductivity at the soil /envelope interface and the risk of envelope clogging is always slight. In the case of fine textured soils (silts), envelope materials need specific characteristics to be efficient and safe. These characteristics are a small pore size (less than 80 µm) and a rough surface to allow arching between soil particles and geotextiles fibres. By having pit run sand between the fabric and the silt, a much better filtration and seepage flow situation exists.

It is accepted that many large subsurface drainage development projects are forthcoming in the arid and semi-arid regions of the world. The immense costs involved in such projects necessitates a firm confidence in geotextiles as functional synthetic drain envelopes, before they will be chosen over the relatively costly yet accepted method of bulk gravel envelopes. This research project was initiated in an effort to improve the engineers confidence in recommending the use of synthetic envelopes on subsurface drainage systems.

2.5 Background of laboratory testing procedures

Field tests of large numbers of envelope materials for subsurface pipe drainage is time consuming and expensive. Permeameter testing is recommended to eliminate envelope soil-combinations that are obviously unacceptable. Many types of analogue models and testing procedures have been designed to simulate mineral envelope clogging in laboratories all over the world (Table 2.1), but still there is no standard procedures to test the envelope-soil filtration characteristics.

Analogue modelling of water flow near subsurface drains was introduced in the Netherlands by Hooghoudt in the 1930's (Stuyt, 1992). Hooghoudt built a concrete tank 25m long by 5m wide to verify his mathematical solutions of the flow towards drains. Smaller analogue models appeared in the 1950's. These models were used to verify solutions for flow in the immediate vicinity of drains, considering radial flow resistance and due to convergent flow towards the perforations (Stuyt, 1992).

Research on the filtration behaviour of envelope materials is still continued in many locations of the world, but there is no consistency in similarity of testing procedures. Permeameters are being used in different shapes and sizes, soil and envelope (granular) are used in different thickness. Some researchers have used variable head conditions and some constant head conditions.

At a joint seminar held by the International Union of Testing and Research Laboratories for Material and Structures, the International Colleges of Building Science and the International Geotextile Society (IGS), a major conference recommendation was that "researchers need to form an international data bank, monitor envelopes in use, develop suitable test procedures and identify factors which will provide indicators to the aging process (Bonnell et al. 1992)

In this study, the affect of using different soil and envelope materials are checked using a cylindrical permeameter manufactured at the Laboratory of Agricultural Water management, National Institute of Agricultural Engineering, Merelbeke, Belgium, already in use in Belgium, France, Holland, Pakistan, Egypt etc.

Table 2.1 Analogue models and testing procedures for envelope materials.

Names of researchers	Year of testing reported	Size of model (cm * cm)	Remarks
Broughton et. al.	1976	38 * 30	1.2 m constant head and flow in radial direction
Benz et al.	1976	10 * 48	
Hermsmeir et al.	1976	10 * 75	0.4 m constant head and flow in downward direction.
Willardson and Khan	1976	26.67 * 36.56	Flow in downward direction. Tested at higher gradient conditions.
Irwin	1979	280 long	A simple device using coffee cans. Suitable for field test.
Dierickx and Yunguolu	1982	20 * 10	Flow upward.
Stuyt et al.	1989	40 * 15	Variable head and
Shafiq and Vlotman	1992	20 * 10	several thicknesses.
Abdel-Dayem et al.	1992	20 * 10	
Shered	1984		Upward and direction flow.
Rollin et al.	1987		0.35 m of constant head.
Fourie and Bentley	1990	30 * 40	Flow in radial direction.
Kumbhare et al.	1992	100 * 60	

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3 METHODOLOGY AND MATERIALS

Preselection of fabric and granular envelopes can be based on some predetermined hydraulic/mechanical properties. The equipment available for determining some of these properties is described below.

3.1 Fabric materials

Seven fabric materials were selected for laboratory testing. Table 1 in Appendix-B shows the list of the fabric materials, the name of manufacturer and the supplier of the materials. Generally these materials can be divided into two major groups: thick (Voluminous) materials and thin (Sheet like) materials. Fabrics tested in this study, are non woven and needle punched geotextiles. Most of the materials have 0_{90} close to 100 µm and a few of them have O_{90} bigger than 200 µm. Some characteristics of the fabrics are given in Table 3.1.

Table 3.1 Some chacateristics of fabric tested materials.

Type of fabric	**Thickness mm**	**Mass g/m²**	**O_{90} µm**	**K m/day**
United	5.58	550	340	1134
Olympia 3	2.98	285	40	185
Nayyer	6.02	556	450	1360
Texel 909	2.72	320	84	231
Texel 912	2.90	250	75	174
TS-22	.85	90	130	153

The following tests were performed to determine the individual properties of the fabric envelope materials:

- thickness of the fabric;
- mass per unit area of the fabric;
- pore size distribution of fabric;
- hydraulic conductivity perpendicular to the plane of the fabric;

3.1.1 Thickness determination of fabric material

The thicknesses of the fabric materials were determined under 2 kPa loading according to ASTM D4439 standard by using an electronic thickness meter (Fig. 3.1). This apparatus is used to measure the thickness of all non-conductive materials such as fabric, paper, leather, plastic, etc. (Dierickx 1993). The portable apparatus is made of two units linked with an electric cable (Fig. 3.1). The first unit consists of a mechanical support with an electromagnetic sensor on which the fabric is placed. The second unit is an electronic meter with a numeric display and switches for measuring thickness between "0-5" and "5-10" mm. Thickness measurements between 0 and 10 mm are possible to an accuracy of 0.01 mm.

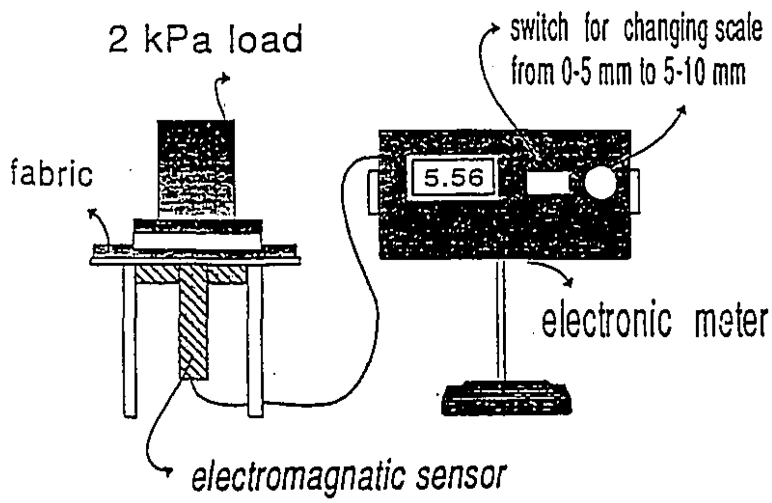


Figure 3.1 Apparatus for thickness measurement of fabrics

3.1.2 Mass per unit area of fabric material

The mass per unit area has been determined by weighing a small square, or circle of fabric material in accordance with ASTM D4439 standard and using the following formula:

$$\mu=\frac{\mu_s}{A} \qquad 3.1$$

where μ = mass per unit area, rounded to the nearest (g/m^2); μ_s = mass of the specimen (g); A = area of the specimen (cm^2);

3.1.3 Pore size distribution of fabric material

The pore size distribution of the fabric material was determined by dry sieving with sand fractions in accordance with ASTM D4751. The sand particle sizes ranged from 37 to 4760 µm. The mass of the total sand sample retained upon the fabric materials has been calculated by using the following formula:

$$M_2=50-M_1 \qquad 3.2$$

Where M_1 = particles which have passed through the fabric and caught in the receiving pan; M_2 = particles which have retained on and within the fabric; 50 = grams total mass of the particles used.

The percentage of particles retained on and within the fabric has been plotted against the mean size of the particles (Table 3.2) of each grade on semi logarithmic paper. A smooth curve was drawn through the points (Fig 3.2). The O_{90} (90% of the particles retained) value of the fabric was obtained from this particle size distribution curve.

Table 3.2 Sand fractions to determine the pore size distribution of geotextiles.

No .	Range of Particle Size (µm)	Mean Particle Size (µm)	No .	Range of Particle size (µm)	Mean Particle Size (µm)
1.	37 - 53	45.0	9.	420 - 500	460.0
2.	53 - 74	63.5	10.	500 - 840	670.0
3.	74 - 105	89.5	11.	840 - 1190	1015.0
4.	105 - 140	127.0	12.	1190 - 1680	1435.0
5.	149 - 210	179.5	13.	1680 - 2000	1840.0
6.	210 - 250	230.0	14.	2000 - 2380	2190.0
7.	250 - 297	273.5	15.	2380 - 3360	2870.0
8.	297 - 420	358.5	16.	3360 - 4760	4060.0

The sieving is carried out at a vibration frequency of 50 Hz with a vertical amplitude of 0.75mm.

3.1.4 Permeability normal to the plane

Various methods exist for determining the hydraulic conductivity (permittivity) of fabric materials according to ASTM D-4491. A constant head (30 cm) method was used to determine the permittivity across the fabric material under unloaded conditions (Dierickx 1993). A fabric specimen was installed between two flanges in a tube (Fig 3.3). One side of the tube was connected to a constant head reservoir and the other end connected to a moveable outlet. Manometers were installed close to both sides of the fabric, to determine the head loss across the material.

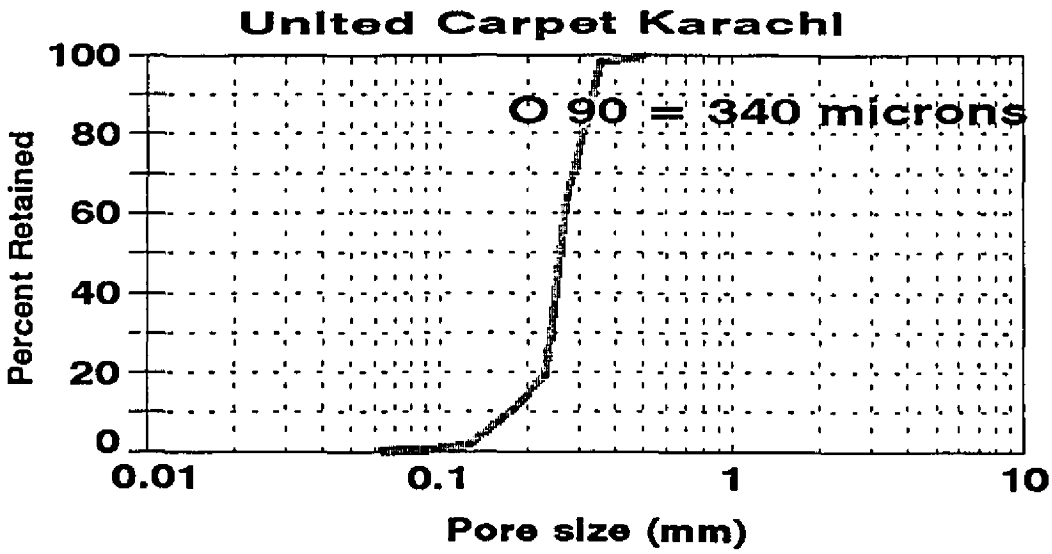


Figure 3.2 Pore size distribution curve of a fabric material

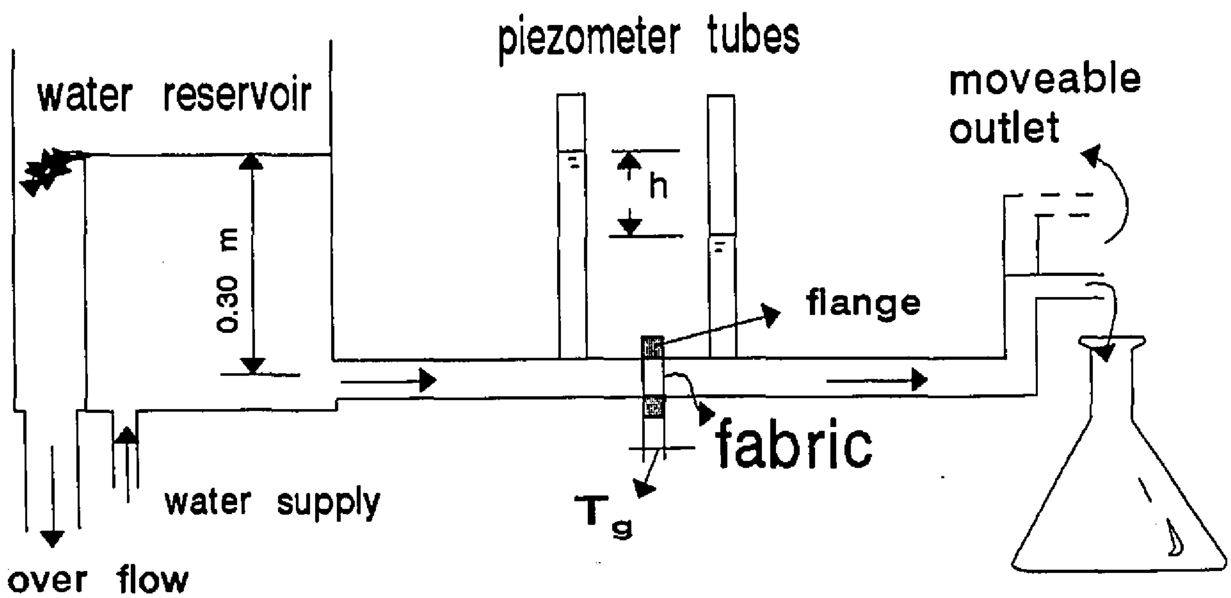


Figure 3.3 Scheme of the apparatus used to determine the permittivity of a fabric.

The permittivity (ψ) normal to the plane of a fabric envelope was determined using Darcy's law:

$$\Psi=\frac{Q}{A*i}(\frac{\eta_t}{\eta_{20}})=\frac{V}{A*t*i}(\frac{\eta_t}{\eta_{20}}) \qquad 3.3$$

Where: Q = discharge (L^3/t); A = cross section area of fabric material (L^2); V = volume of water collected (L^3); t = the time (t); i = h/t_g h = hydraulic head (L) and t_g = fabric thickness (L); η_t/η_{20} = temperature correction factor based on the ratio between the dynamic viscosity at the test temperature and that at 20 °C.

3.2 Granular envelope material.

The granular materials were taken from sources: crushed rock and river run as shown in Table 3.3. The location of quarries is shown in Figure 1.1.

Table 3.3 Locations of granular envelope materials tested in the laboratory.

Type of Material	Location of Quarry
Crushed Rock	Sargodah, Punjab
River run	Attock and Texla, Punjab
Sand (very coarse)	Qiblabandi, Punjab
Sand (coarse)	Lawrencepur, Punjab
Sand (coarse)	Sutlej river, Punjab
Sand (fine)	Sutlej river, Punjab

The following parameters of these materials were studied:

- sieve analysis;
- hydraulic conductivity;

3.2.1 Sieve analysis

Gravel envelopes designed for drainage projects, are generally based on a seven sieves analysis (ASTM standard). In this experiment 21-sieves (Table 3.4) were used because Vlotman et al.1992, found that gradation gaps may be missed by the standard seven sieve analysis (bold sieves in Table 3.4). Cumulative percentages of the amount passing or retained on each sieve were calculated and plotted on a semi-logarithmic graph (Figure 2.1). The coefficients of uniformity and curvature were determined from these curves.

Table 3.4 ASTM standard sieve numbers and corresponding size in mm.

No.	ASTM Sieve No.	Size mm	No.	ASTM Sieve No.	Size mm	No.	ASTM Sieve No.	Size mm
-	6"	152	7	**No. 8**	**2.38**	16	No.70	0.21
-	5"	127	8	No.10	2.0	17	No.100	0.15
-	3"	76.2	9	No.12	1.68	18	No.140	0.10
1	**1.5"**	**38.1**	10	No.16	1.19	19	**No.200**	**0.074**
2	**3/4"**	**19.1**	11	No.20	0.84	20	No.270	0.053
3	3/8"	9.52	12	**No.30**	**0.59**	21	No.400	0.037
4	No.3	6.35	13	No.40	0.42			
5	**No.4**	**4.76**	14	**No.50**	**0.30**			
6	No.5	3.36	15	No.60	0.25			

3.2.1.1 Sieve analysis of Sutlej sand

Sand samples were taken from the left and right banks of the Sutlej river close to the project area. 21-sieve analyses were performed (Vlotman et al., 1992). The left bank river sample is a fine uniform sand, about 80% of the particles are in the range of 0.07 mm to 0.15 mm. In the right bank river sand, about 75% of the particles are in the range of .15 mm to .42 mm. The right bank sand is coarse and more graded than the left river bank (Figure 3.4).

3.2.2 Hydraulic conductivity

The hydraulic conductivities of the gravel envelopes were determined by the constant head method using Darcy's law under a hydraulic head of approximately 20 cm. The permeameter (Fig. 3.6) consists of vertically mounted plexiglass cylinder, 10 cm diameter and 25 cm high, filled with 10 cm gravel. As upward flow was applied, the gravel was supported by a screen with a coarse fabric filter material to prevent fine particles falling back to the bottom of the permeameter. The tests were carried out for 24 hours duration and the readings were taken for the first two hours and at the end of 24 hours. All tests were standardized to 20 °C by use of equation 3.3.

3.3 Soils

Three Soils samples from three subsurface drainage projects were taken at the drain depth of about 1.5 meter. These projects are the Fourth Drainage Project (FDP) Faisalabad, Chashma Right Bank Canal Project Dera Ismail Khan (DIK) and Fordwah Eastern Sadiqia Project (FES) Bhawalnagar. Soils samples that were taken from the FDP and DIK projects contain relatively large fractions of sand (> 60%), and from the FES project large fractions of silt (> 65%). All of These samples can be considered to represent the most problematic soil types in the area. Figure 3.5 gives the particle size analysis (average of five) curves of these soils.

Soils tending to cause siltation of pipes and clogging of envelopes are usually classified by parameters such as: mean particle size, clay content and

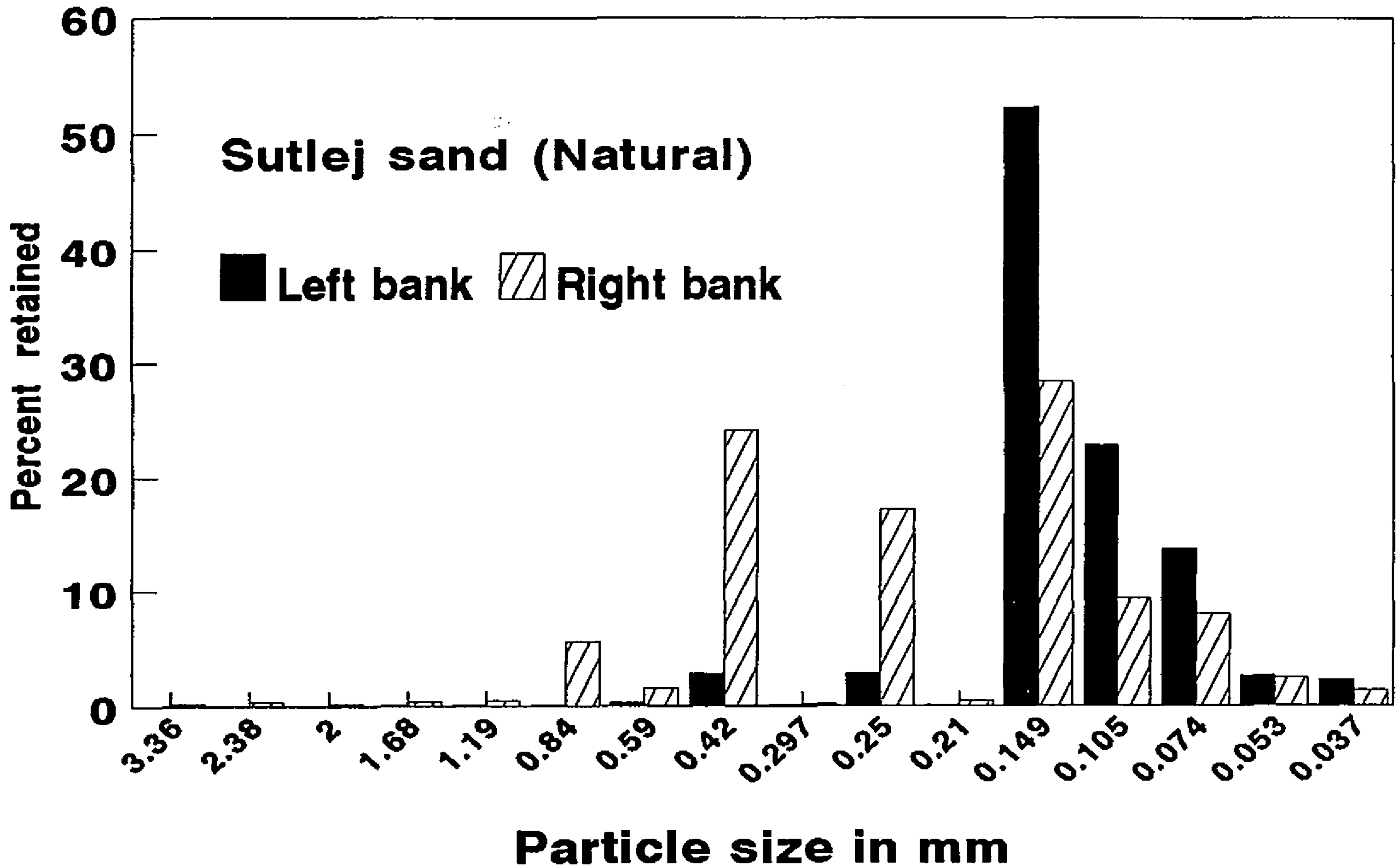
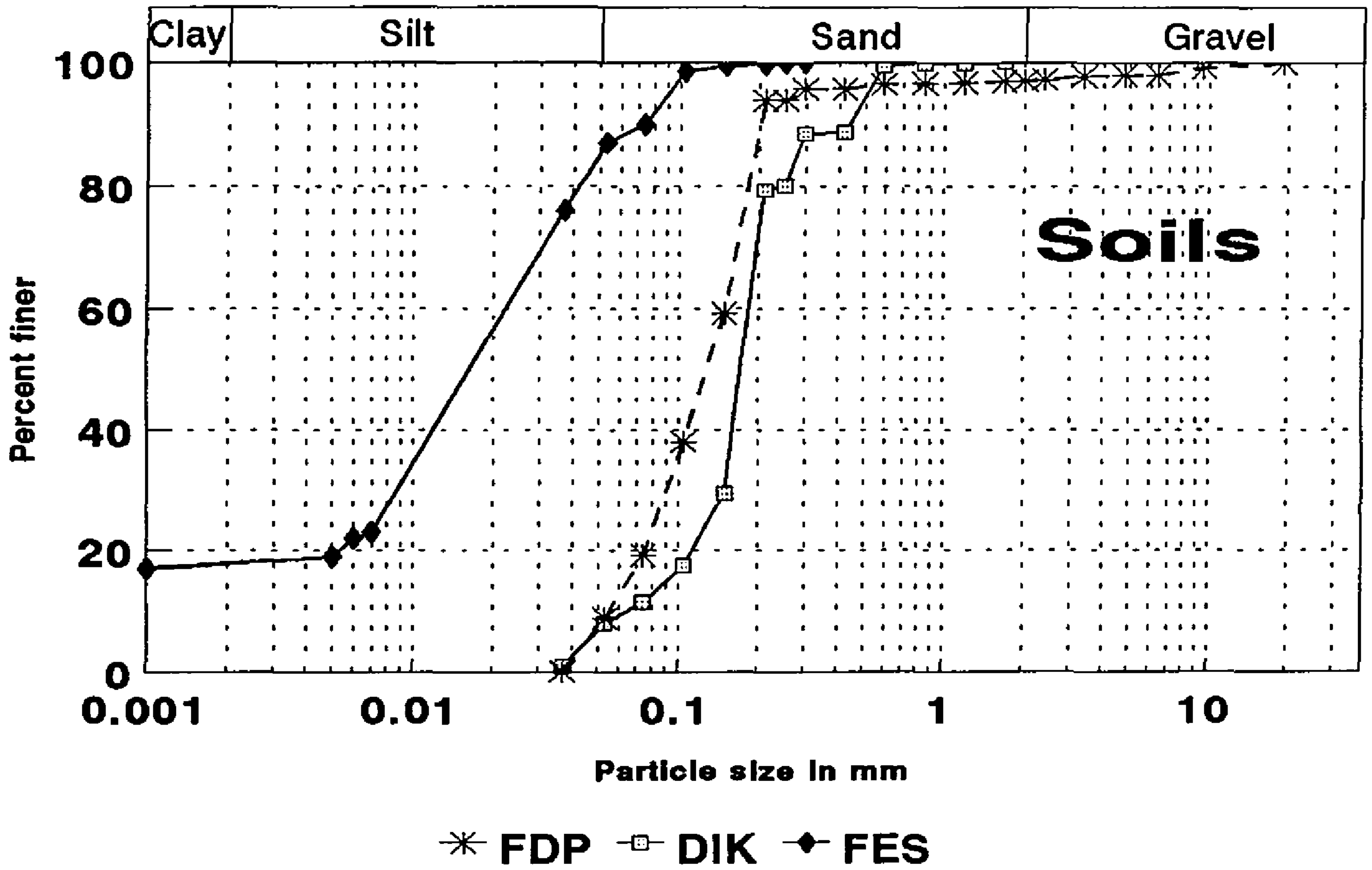


Figure-3.4 Percent retained on each sieves of Sutlej sand.



FES (Fordwah Eastern Sadiqia Project)
DIK (Dera Ismail Khan Project)
FDP (Fourth Drainage Project Faisalabad)

Figure 3.5 Particle size distribution of the soil samples.

uniformity of grading. Particles, washed out most frequently by flowing water, range from 50 to 150 µm (Dielman and Trafford 1976). Increasing clay content makes a soil more resistant to particle drift due to cohesive forces of the clay particles. Siltation tendency is correlated with the uniformity coefficient $C_u = d_{60}/d_{10}$ where d_{60} and d_{10} are the particle sizes at which 60% and 10% by weight passes a sieve, respectively. The FES soil is better graded and consequently has a higher C_u than the soils from the other two projects.

3.4 Permeameter test

The first selections of different envelopes are made using laboratory experiments. Permeameter experiments are easy to perform and can be reproduced; different envelope types and conditions can be simulated. The permeameter tests were done to determine the performance characteristics of the various envelopes with respect to:

i) The ability to retain soil;
ii) The occurrence of surface or internal clogging;

Previous tests performed in the laboratory with a cylindrical permeameter (Shafiq and Vlotman, 1992) using a 10 cm thick layer of soil, with fabric material or a 10 cm layer of gravel material did not yield conclusive data on envelope behaviour. Thus, the following tests (Table 3.5) were performed using a variety of soil and gravel layer thicknesses. Each test was replicated three times.

Table 3.5 Tests with soil and envelope thickness detail.

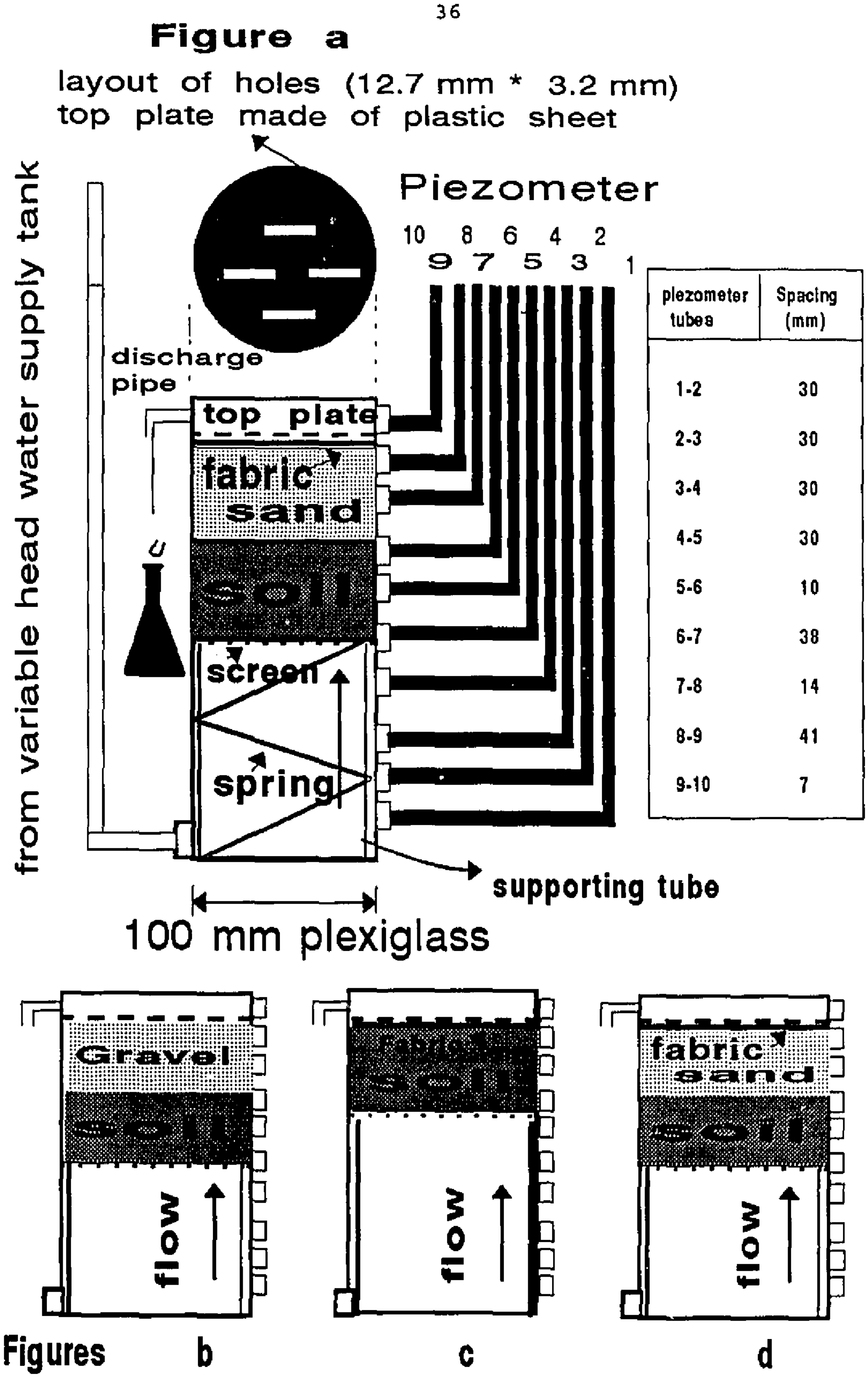
Type of Envelope Materials	Soil Thickness cm	Envelope Thickness cm	Test Numbers
Gravel	2.5	7.5	G88, G91, G94, G95, G96, G97, G98, G99, G100, G101, G102, G103, G104, G105, G109, G110, G111, G112, G113, G114
	5.0	7.5	G73, G74, G75, G76, G77, G78, G79, G80, G81, G89, G92,
	7.5	7.5	G90, G93
Synthetic fabric	2.5	As per fabric thickness	S43, S46, S49,
	5.0		S44, S47, S50, S55, S58, S61, S62, S63, S67, S68, S69
	7.5		S45, S48, S51, S56, S59
	10.0		S13, S14, S15, S28, S29, S30, S37, S38, S39, S57, S60
Synthetic fabric + Sand	5	Sand 5cm and Fabric as per thickness	GS1, GS2, GS3, GS4, GS5, GS6

3.4.1. General description of test procedure.

A permeameter test can be carried out with either downward or upward flow. Water flow exerts a drag force in the flow direction. Downward flow acts in the direction of the gravitational force and drags the soil particles downward, tending to stabilize the system. The lifting action of upward flow promotes an unstable situation. In the case of cohesionless soil, a quick-sand condition occurs as soon as the upward flow force equals the gravitational force. In the case of structured cohesive soils the quick-sand condition only appears when the cohesive forces are disrupted by the upward flow forces. All of the permeameter tests reported in this thesis were done with upward flow.

The permeameter consists of a vertically mounted plexiglass cylinder 10 cm internal diameter and 25 cm high, which is partly filled in layers with soil and envelope materials as indicated in Figure 3.6. A supporting screen covered by a coarse fabric (O_{90} = 300 μm) was placed to prevent soil particles from falling back down into the bottom of the permeameter. This screen and fabric supports the soil, the gravel or fabric envelope and the perforated transparent plate. In the case of the fabric envelope, both envelope and perforated transparent plate are fixed between flanges and eventually sealed with silicone. A spring (k=0.5 N/mm, 77 mm mean diameter and 3 mm wire diameter) beneath the supporting screen keeps the soil lightly in contact with the envelope. A moveable reservoir with overflow enables the setting of the hydraulic gradient. Piezometer tubes were located above the drain, below the fabric and along the gravel envelope and soil column. During the tests, piezometer readings, discharge and water temperature measurements were carried out.

Figure 3.6 shows the arrangement of the base soil and envelope material with respect to the water pressure measuring points of the permeameter set up. The head can be raised up to 200 cm from the base of the permeameter, creating gradients (head/sample heights) from 0 to 62. The maximum gradient of 62 was possible with a fabric envelope. Because of the greater height of the gravel envelope, the maximum hydraulic gradient was 16 for tests of gravel envelopes. Each material was tested starting with a minimum head of 5 cm and increasing to a maximum head of 200 cm. Each head was maintained for one to two days and readings of the water level in the manometer tubes was taken just before the head was increased or decreased. 48 tests out of total 69 tests were performed by first increasing the head to the maximum and then



piezometer tubes	Spacing (mm)
1-2	30
2-3	30
3-4	30
4-5	30
5-6	10
6-7	38
7-8	14
8-9	41
9-10	7

Figure 3.6 Schematic of Permeameter used for envelope materials.

reducing the head to its minimum. The maximum head was kept at 200 cm during the day time and the minimum head was kept during the night. After taking the reading in the morning, head was increased to the maximum position. Tests were carried out for two weeks on any one material-permeameter combination. Three permeameters were operated concurrently on any one test sequence under similar condition. There were a total of 9 permeameters in the laboratory. The soils from the projects: FDP Faisalabad, CRBC Dera Ismail Khan and FES Bhawalnagar were used for testing the synthetic materials. A total of 30 tests on synthetic fabrics were carried out in the laboratory. Out of them, 10 were carried out with 10 cm soil thickness and the rest of the tests were done with a thicknesses ranging from 2.5 cm to 7.5 cm . Table 3.6, Table 3.7 and Table 3.8 shows the detail of materials combinations of synthetic fabrics, Granular materials and synthetic sand combination materials respectively.

Table 3.6 Synthetic materials.

Base Soil	Type of Material	Test Nos.	Testing Condition
Fourth Drainage Project, (FDP) Faisalabad.	TS-22	S13, S14, S15	
	Texel 909	S28, S29, S30	
	United Karachi	S37, S38, S39	By surging
	Texel 912	S43, S44, S45	By surging
	Olympia No.3	S46, S47, S48	By surging
Chashma Right Bank Canal Project, Dera Ismail Khan (DIK)	Olympia No.3	S49, S50, S51	By surging
	United Karachi	S55, S56, S57	
	Texel 909	S58, S59, S60	
Fordwah Eastern Sadiqia (FES), Bhawalnagar	Nayyer Carpets	S61, S62, S63	
	TS-22	S67, S68, S69	By surging

Table 3.7 Granular materials.

Base Soil	Type of Envelope Materials	Test Nos.	Testing Condition
Fourth Drainage Project (FDP), Faisalabad	River Run FDP	G73, G74, G75 G88, G89, G90 G91, G92, G93	By surging By surging
	Crushed Rock + Sand	G76, G77, G78 G103, G104, G105	By surging
	River Run Natural	G79,G80,G81 G94,G95,G96 G109, G110, G111 G112, G113, G114	By surging By surging By surging
	Crushed Rock	G97, G98, G99 G100, G101, G102	By surging By surging

Table 3.8 Synthetic fabric combined with sand envelope.

Base Soil	Type of Envelope Materials	Test Nos.
Fordwah Eastern Sadiqia Project (FES), Bhawalnagar	United Karachi + Sand	SG1,SG4
	Texel 909 + Sand	SG2,SG5
	TS 22 + Sand	SG3,SG6

3.4.2 Filling procedure

- The filling of the cylinder was done by trial and error.

- A weighed amount of soil was poured in an open dish and the filling of the cylinder was started in layers of about 1.5 cm each. The soil was air-dried, crumbled, crushed and sieved on a 2 mm sieve.
- At each layer the soil surface was smoothed and the soil slightly and carefully compacted as uniformly as possible by means of a wooden tamping device of 5 cm diameter. The soil was packed in the cylinders so that a bulk density of approximately 1.5 g/cm^3 was obtained.
- The filling was perfect when the mark on the cylinder in the case of gravel envelope, or the top of the flange, in case of fabric material was reached. The contents of the cylinder appeared to be homogeneous when all the weighed soil was consumed. If there was a shortage of soil or if soil is left, then the filling has to be done over again.
- Further corrections of soil surface could be done by scraping the top with a steel ruler to get a required soil height.

3.4.3 Gravel preparation and permeameter filling.

- The weight percentages of each fraction of a gradation curve were determined.
- The required amount of each grain size was calculated as per ASTM standard 21-sieve basis for a preset total weight of 2 Kg to give slightly more than enough to fill the permeameter.
- All of these weights were poured together in a strong plastic bag and mixed carefully.
- The permeameter cylinder was filled evenly with gravel above the base soil.
- Once the top of the cylinder flange was reached, the gravel layer was scraped flat by a steel ruler.
- The remaining gravel was weighed.
- The bulk density of the gravel was calculated.

- The perforated transparent screen was placed and the cylinder was carefully closed.
- Before connecting the water supply tube to the permeameter (Figure 3.6 b), the valve was opened to remove all air bubbles. The water supply tube was connected to the permeameter, the valve was opened again and the permeameter was tilted forwards. The permeameter was moved slowly from left to right. The top of the permeameter and the supporting screen were inspected as the permeameter was being tilted. All the air bubbles had to be removed from this screen; they escaped through the manometer holes.
- As soon as the water compartment was filled, the permeameter was carefully straightened and the de-aeration of the manometers was started by disconnecting them one by one after lifting the moveable reservoir to the level of a next manometer. This procedure was continued until the entire soil and gravel columns were saturated. Water was added to the manometers with a plastic bottle.
- After the soil was saturated the water supply tank was raised to the required level.
- To overcome surface tension problem and obtain a regular discharge, a cotton thread was placed at the outlet pipe, extending some 2 cm out of the turned upward outlet.
- The test was ended if soil particles invaded the gravel filter up to the drain simulation plate, or about two weeks after the start of the experiment, if there were no soil particles invading the gravel.
- The water used was from reservoir on the laboratory roof that was filled from the tube well located approximately 75 meter close to a big canal, total dissolved solids approximately 250 mg/l.

3.4.4 Fabric envelopes filling

- The supporting tubes and screens were placed into the cylinder (Figure 3.6 c), so that, a required soil height to the top of the cylinder was made available.
- The soil sample was filled in the cylinder in layers of 1.5 cm. The layers were compacted gently with a special wooden tamper so that the whole sample was used and a homogeneous filling was obtained.
- The fabric envelope material was cut at a diameter equal to the external diameter of the rubber ring on top of the cylinder; then this fabric was placed on top of the cylinder. The perforated transparent screen was placed above the fabric.
- The P.V.C. ring was carefully cleaned, then placed over the filter material and the screen.
- Finally the bolts were fastened and the apparatus was ready for connection to the water supply tank.
- The permeameter was placed in its vertical position to let the air escape from the manometers by disconnecting each one on turn.
- When the water came up through the filter, the water supply valve was closed to let the water saturate the permeameter for 30 min.
- The pressure head was increased as required.
- The discharge and temperature measurements were recorded.
- After each set of readings, the head was increased stepwise. The next set of readings were recorded before increasing the head.

3.4.5 Data processing

During the permeameter research tests: outflow rates, hydraulic heads, water temperatures and thickness of the soil column were measured, and particles which passed through the envelope were observed. From these measurements the performance of envelope materials, either gravel or fabric envelopes, were deduced. The hydraulic conductivity of the soil and of the envelope in contact with the soil was calculated as per equation 3.3. The hydraulic gradient at different interfaces of soil-sand, soil-gravel, soil-fabric and sand-fabric were determined separately by observing the manometers (Fig 3.6 d), just before and after the interface. For example, in case of a sand-fabric interface (Figure 3.5 d), the gradient will be:

$$i_{sand\text{-}fabric}=\frac{H_9-H_{10}}{L_9-L_{10}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 3.4$$

Where i sand-fabric = hydraulic gradient between manometer tube 9 (sand layer) and tube 10 (above fabric and drain plate); H_9 = manometer tube in the sand layer just below the fabric; H_{10} = manometer tube above fabric and drain plate; L_9 -L_{10} = length between centres of manometer tubes 9 and 10.

The hydraulic conductivity of the interface was calculated by equation 3.5.

$$K_{sand\text{-}fabric}=\frac{V}{A*T*i}\left(\frac{\eta_t}{\eta_{20}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 3.5$$

Where K sand-fabric = hydraulic conductivity at sand-fabric interface (L/t); V = volume of water (L^3); A = cross sectional area of permeameter (L^2); t = time for the flow of the volume V (t); i = hydraulic gradient of each intersection (H_9-H_{10} /L_9-L_{10}).

CHAPTER 4

4. RESULTS

4.1 Permeameter Tests

The results of the permeameter tests include:

- the time distribution of measured hydraulic conductivities;
- piping along the plexiglass;
- sedimentation on the top plate due to massive soil movement through the top plate;
- comparison of the hydraulic conductivities of the envelope material and the soil;
- discharge versus time relationship.

The results of the permeameter tests are presented graphically. Each test is identified with a number allotted in the SCARP Monitoring Organization (SMO) laboratory, Lahore.

4.2 Synthetic materials

Table 4.1 gives data on the materials used and a summary of some results for the 30 test combinations. Detailed data sheets and analyses were prepared, a sample of one set of Tests S55, S56 and S57 is shown in Appendix-A.

Tests S13, S14 and S15 **Figure 4.1**

Pipe sedimentation: No passage of soil particles.

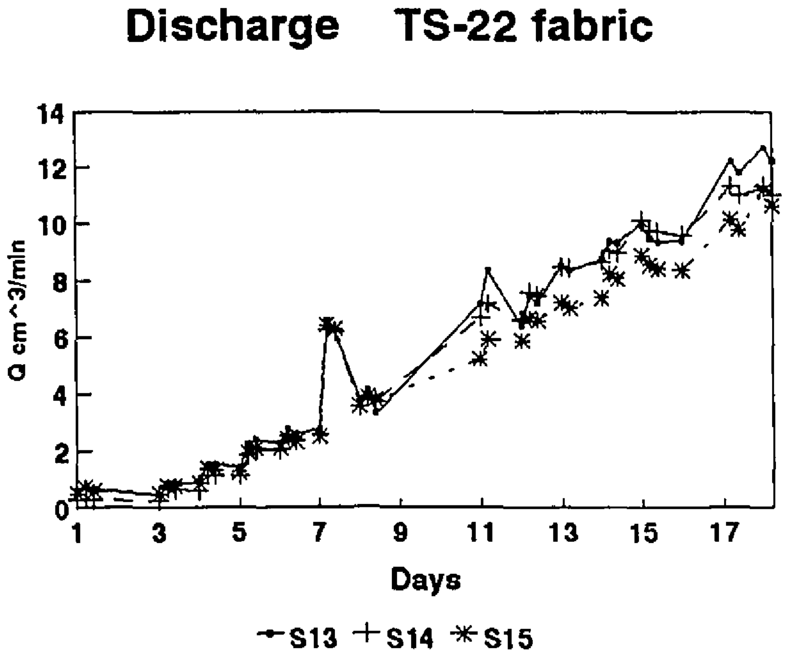
Discharge: Q increases because hydraulic gradient increases. The results of

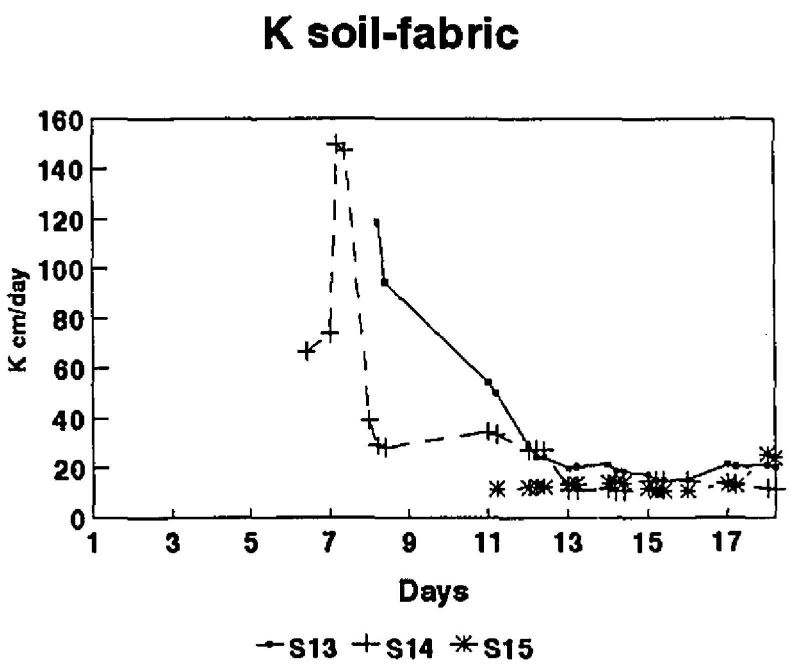
Table 4.1 Summary of the permeameter test results with synthetic envelope materials.

Type of Material	Test No.	Soil Thickness cm	Project Soil	d_{90} µm	O_{90} µm	O_{90}/d_{90}	Thickness 2Kpa loading mm	Average Q cm³/min	K Soil- Fabric Ave:	K Soil- Fabric S.D.
TS-22	S-13	10		200	130	0.65	0.85	6	32	27
	S-14	10		200	130	0.65	0.85	5	34	37
	S-15	10		200	130	0.65	0.85	5	14	14
Texel 909	S-28	10	F	200	84	0.42	2.72	16.5	57	18
	S-29	10		200	84	0.42	2.72	16	26	13
	S-30	10		200	84	0.42	2.72	14	25	24
United Karachi	S-37	10	D	200	340	1.7	5.58	10	542	233
	S-38	10		200	340	1.7	5.58	12	107	105
	S-39	10		200	340	1.7	5.58	12	171	162
Texel 912	S-43	2.5	P	200	65	0.32	2.916	78	30	31
	S-44	5		200	65	0.32	2.916	29	24	7
	S-45	7.5		200	65	0.32	2.916	22	32	26
Olympia No.3	S-46	2.5		200	40	.2	2.98	131	53	9
	S-47	5		200	40	.2	2.98	51	23	2
	S-48	7.5		200	40	.2	2.98	21	47	

Table 4.1 continued

Type of Material	Test No.	Soil Thickness cm	Project Soil	d_{90} μm	O_{90} μm	O_{90}/d_{90}	Thickness 2Kpa loading mm	Average Q cm³/min	K Soil- Fabric	
									Ave:	S.D.
Olympia No.3	S-49	2.5	D	300	40	.03	2.98	155	44	23
	S-50	5		300	40	.03	2.98	86	311	345
	S-51	7.5		300	40	.03	2.98	78	194	188
United Karachi	S-55	5	I	300	340	1.13	5.58	10.8	18	12
	S-56	7.5		300	340	1.13	5.58	9.6	23	11
	S-57	10	K	300	340	1.13	5.58	6.5	33	19
Texel 909	S-58	5		300	84	.28	2.72	12.7	18	8
	S-59	7.5		300	84	.28	2.72	5.5	59	46
	S-60	10		300	84	.28	2.72	6	89	60
Nayyer Carpet	S-61	5	F	100	400	.4	5.5	2.12	-	-
	S-62	5		100	400	.4	5.5	1.99	-	-
	S-63	5	E	100	400	.4	5.5	2.19	-	-
Polyfelt TS-22	S-67	5		100	130	1.3	0.85	1.7	0.75	0.49
	S-68	5	S	100	130	1.3	0.85	2	1	0.46
	S-69	5		100	130	1.3	0.85	10	2.23	1.33





Note:

- Soil FDP
- Gradient increased gradually

Figure 4.1 Flow rate VS time and Ksoil-fabric VS time for Tests S13, S14 and S15.

3 replicates are close.

Hydraulic conductivity: Initially K soil-fabric was not measurable due to negligible head loss in the interface layer. It became measurable approximately at hydraulic gradient of 3 on day 6. K started with high values at a hydraulic gradient of 3 in two tests S13 and S14, then K decreased continuously until gradient 6 on day 11. At higher hydraulic gradients K soil-fabric became stable in all the three tests at a value of 20 cm/day.

Tests S28, S29 and S30 **Figure 4.2**

Pipe sedimentation: In test No. S30 at hydraulic gradient 4, soil passed through the envelope due to the leakage through the manometer tubes of the permeameter. There was no movement of soil particles in tests S28 and S29 even though hydraulic gradients were increased to 16.

Discharge: Q kept on increasing from gradient 0.5 till gradient 5. No further change was observed with gradients higher than 5.

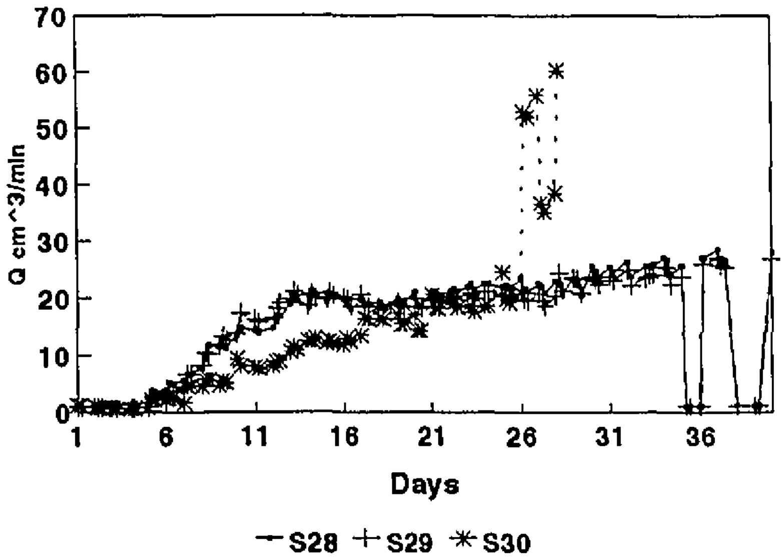
Hydraulic conductivity: K soil-fabric decreased from the beginning until gradient 10, However it remained stable from that value onward.

Tests S37, S38 and S39 **Figure 4.3**

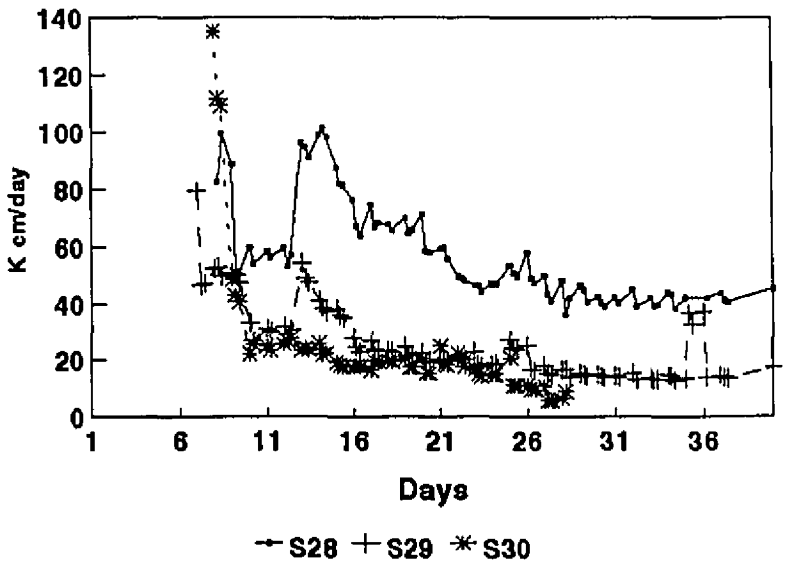
Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with the increase in gradient till gradient 3 on day 7. From day 8 to 30, no increase in Q was observed even though the gradient was increased to 12. However Q increased during surging. This revealed that the soil particles were trapped during the regular increase in gradient. But

Discharge (Texel 909)



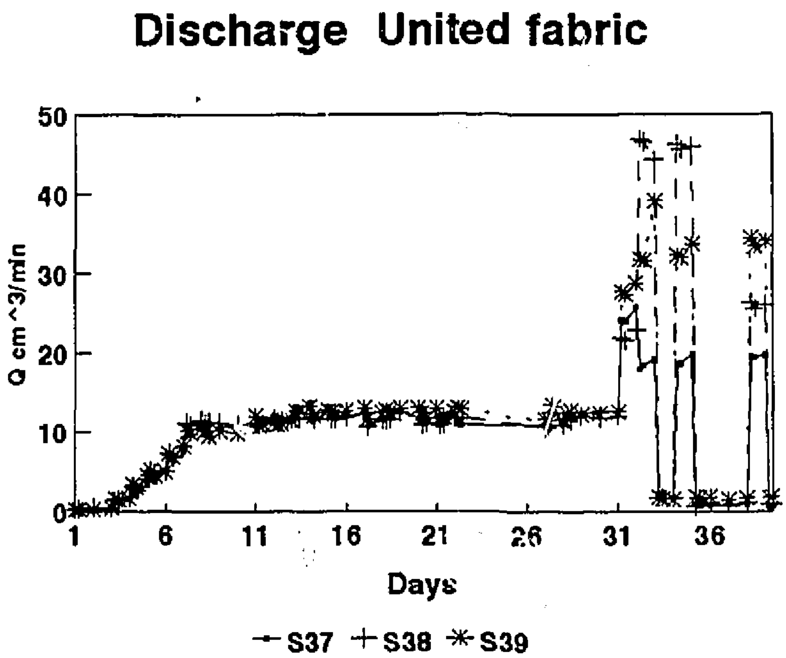
K soil-fabric

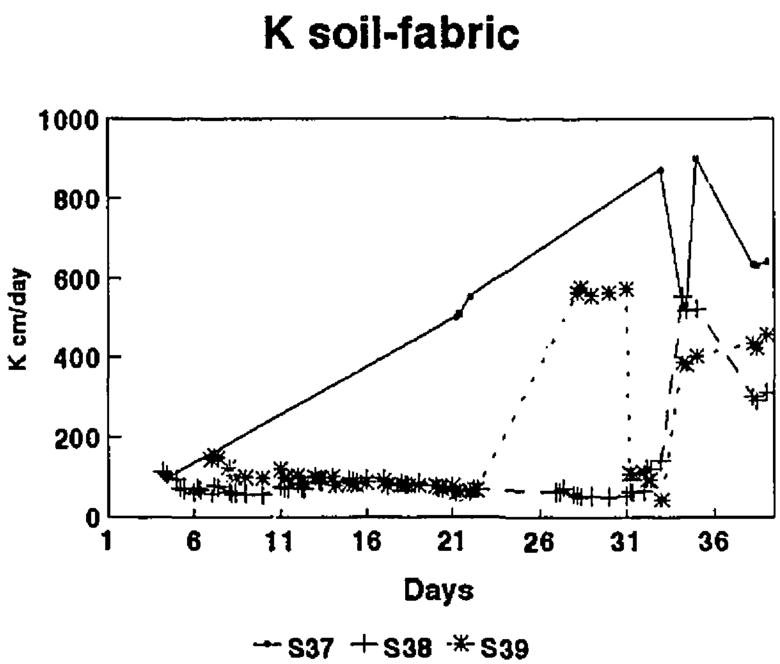


Note:

- Soil FDP
- Surging started on day 36
- On day 26 leakage started through piezometer tubes in Test S30

Figure 4.2 Flow rate VS time and Ksoil-fabric VS time for Tests S28, S29 and S30.





Note:

- Soil FDP
- Surging started on day 31

Figure 4.3 Flow rate VS time and K soil-fabric VS time for Tests S37, S38 and S39.

due to abrupt changes in head, some fine soil particles were washed out through the top plate. This is a favourable condition for the performance of the envelope.

Hydraulic conductivity: K soil-fabric remained stable during the regular increase in head, but in surging the conductivity became higher.

Tests S43, S44 and S45 **Figure 4.4**

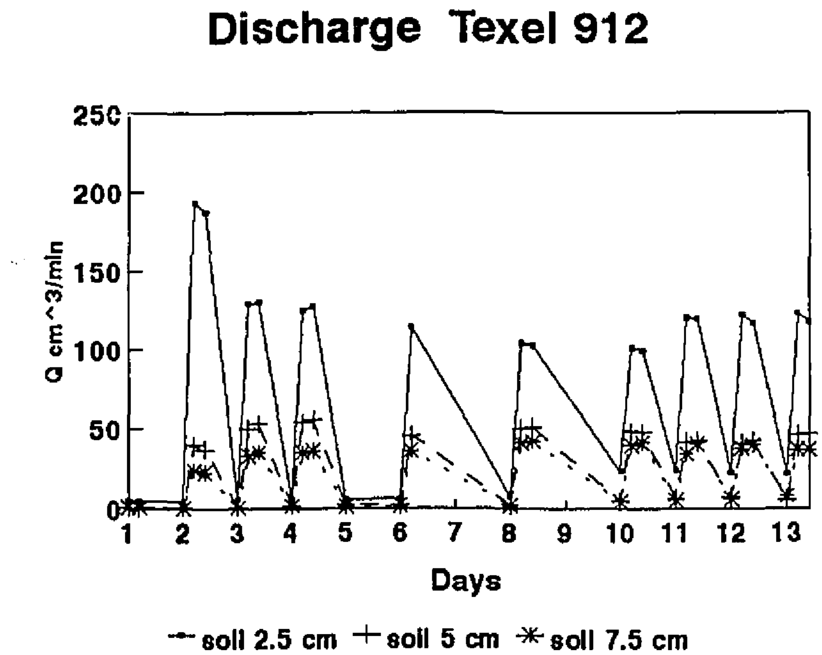
Pipe sedimentation: No passage of soil particles even though the hydraulic gradients were abruptly increased from 0.65 to 62 and returned to low and high gradients on subsequent days for 9 cycles.

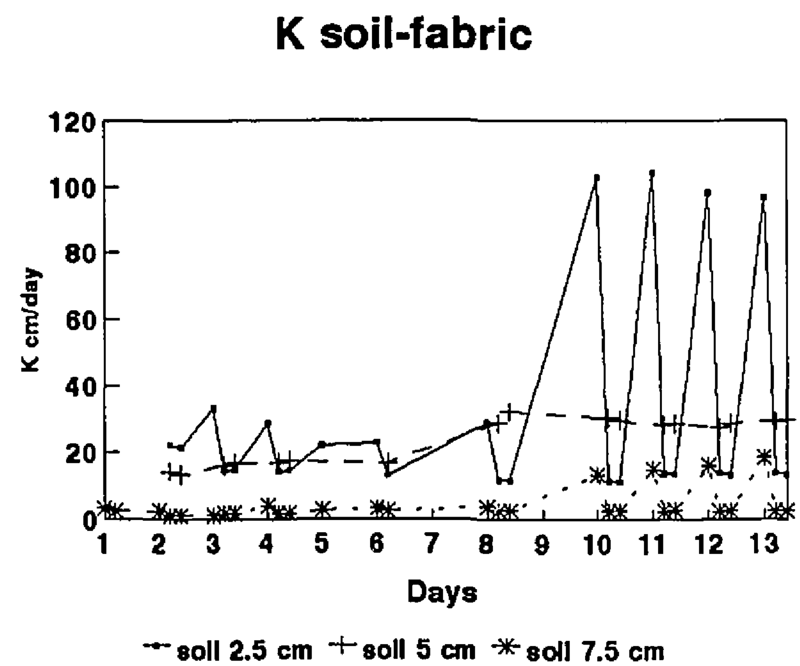
Discharge: Q remained stable in the three tests with different soil depths. However Q was higher with the 2.5 cm soil thickness. The other two tests have shown little differences in discharges, although the gradient in test S44 was double the gradient in test S45. The discharge was sufficient to give adequate drainage.

Hydraulic conductivity: The hydraulic conductivities fluctuated more and reached higher values with soil thicknesses of only 2.5 cm than with 5 and 7.5 cm soil thicknesses. The data for the 2.5 cm soil thickness have lower relative accuracy and may be misleading. This could be due to the piping along the plexiglass sides. Later, after tests S46 to S48, observations were made with soil thickness of 5 cm, 7.5 cm and 10 cm.

Tests S46, S47 and S48 **Figure 4.5**

Pipe sedimentation: No passage of soil particles.

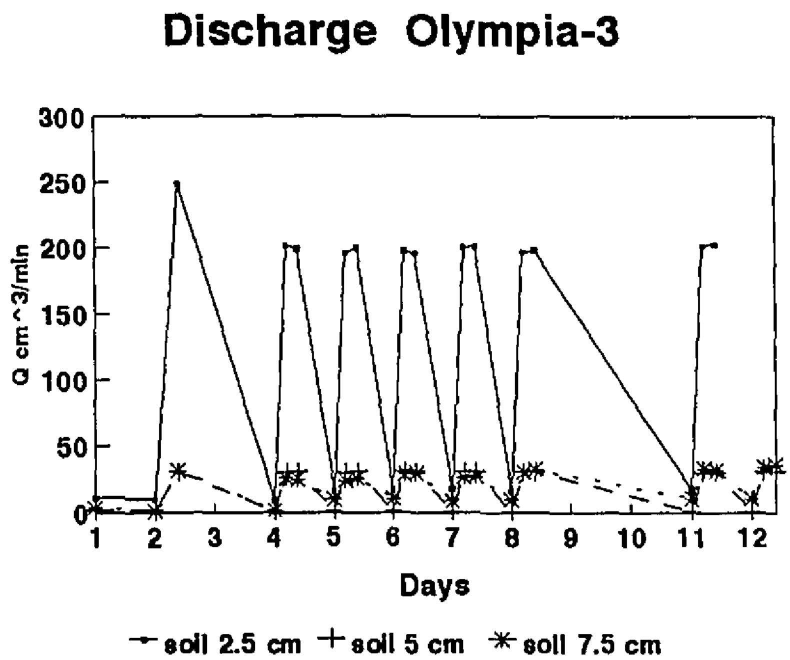


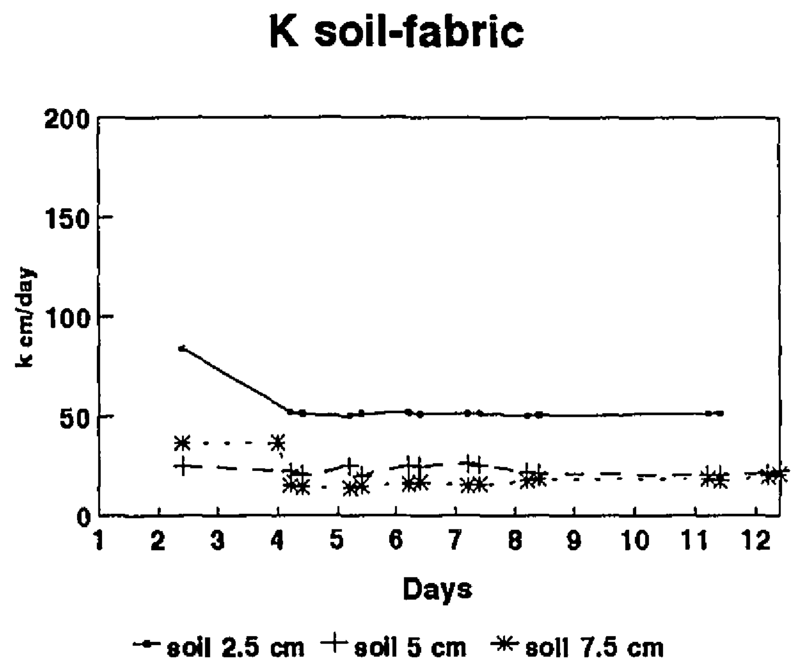


Note:

- Soil FDP
- Surging started from start of the test

Figure 4.4 Flow rate VS time and Ksoil-fabric VS time for Tests S43, S44 and S45.





Note:

- Soil FDP
- Surging started from start of the test

Figure 4.5 Flow rate VS time and Ksoil-fabric VS time for Tests S46, S47 and S48

Discharge: Uniform flows. Rate of Q was higher in the test with 2.5 cm soil depth.

Hydraulic conductivity: At low gradients, the head loss and discharge measurements in tests with 2.5 and 5 cm soil thicknesses were not precise enough to give consistent values of K soil-fabric. At high gradients, it became measurable and no decrease in K is evident.

Tests S49, S50 and S51 **Figure 4.6**

Pipe sedimentation: No passage of soil particles.

Discharge: No difference in flows was observed in these tests at higher gradients. At low heads Q was higher in soil depth of 5 cm than in soil thickness of 10 cm.

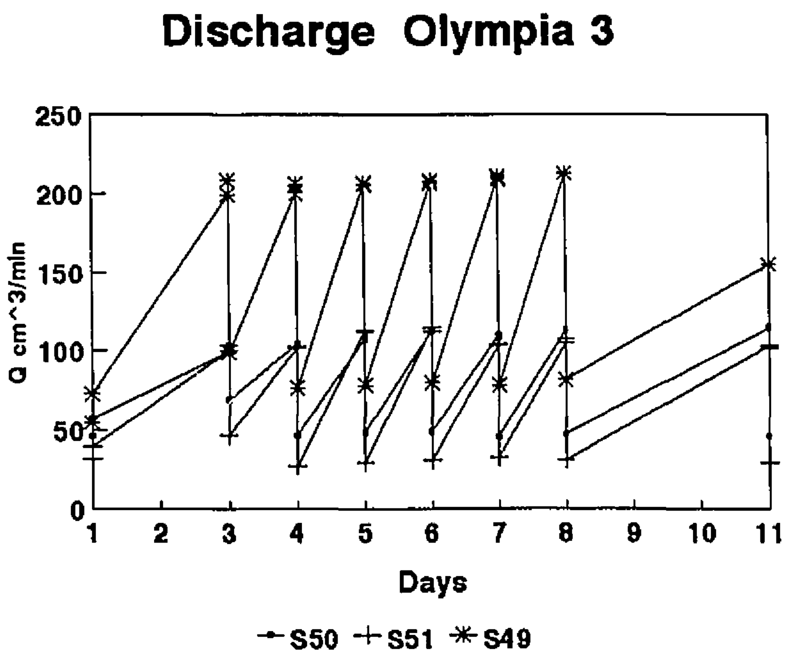
Hydraulic conductivity: K at low heads remained stable . At higher heads, initially some variations were observed, but it became stable at the end of test.

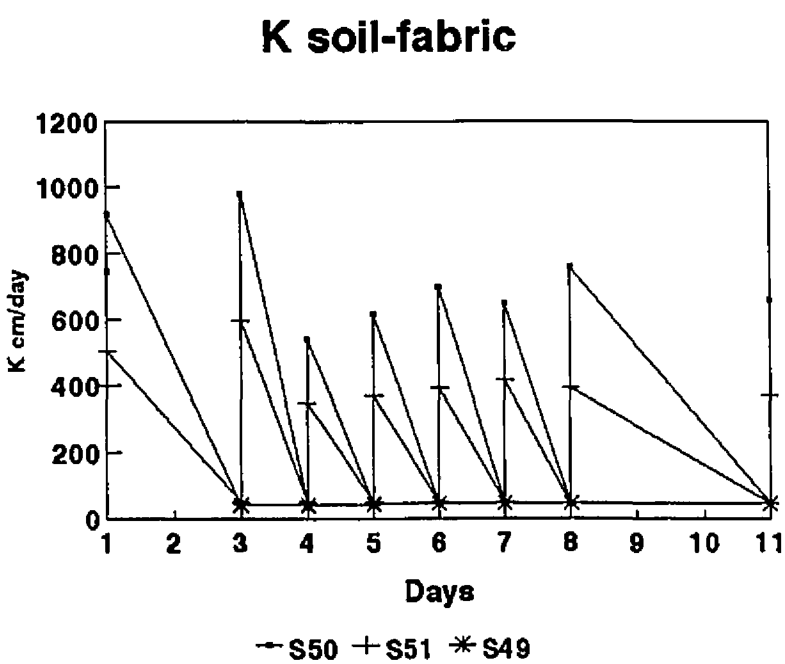
Tests S55, S56 and S57 **Figure 4.7**

Pipe sedimentation: No passage of soil particles.

Discharge: Q increases with increasing gradient. Soil thicknesses of 5 and 7.5 cm show higher increasing trends of flows as compared to 10 cm soil thickness. The fabric is the finest used; the Q is much higher due to the sandy soil of the DIK project.

Hydraulic conductivity: In the beginning K sand-fabric has shown a

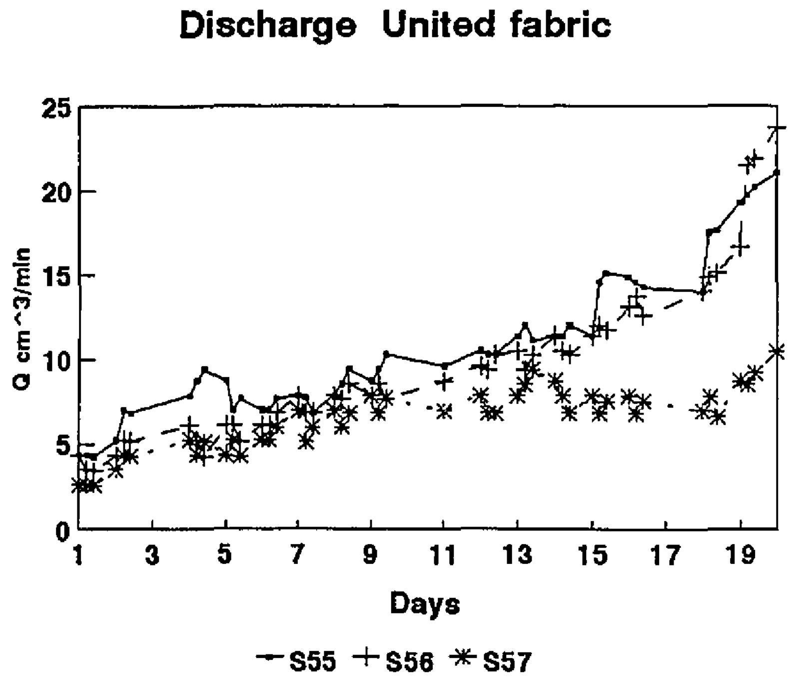


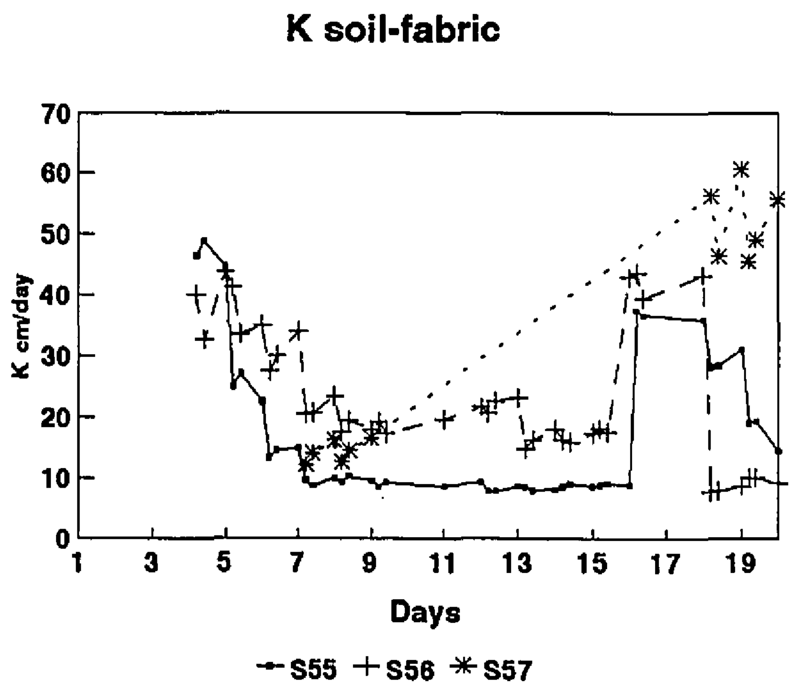


Note:

- Soil DIK
- Surging started from the start of the test.

Figure 4.6 Flow rate VS time and K soil-fabric VS time for Tests S49, S50 and S51.





Note:

- Soil DIK
- Gradient increased gradually

Figure 4.7 Flow rate VS time and Ksoil-fabric VS time for Tests S55, S56 and S57.

decreasing trend. It remained stable in the middle of the test, but near the end it has shown a favourable increase.

Tests S58, S59 and S60 **Figure 4.8**

Pipe sedimentation: No passage of soil particles.

Discharge: Q increases with increasing gradient.

Hydraulic conductivity: K sand-fabric is decreasing with time. A clogging behaviour is observed till the end of the test. It shows that some soil particles are partially blocking the fabric pores.

Tests S61, S62 and S63 **Figure 4.9**

Pipe sedimentation: Two tests were destroyed at gradient 22.

Discharge: An increasing trend was observed initially until gradient 7. Thereafter flow was constant until gradient 22. Soil particles came through the fabric of the two tests on day 7. It could be due to the larger pores of the fabric, which did not retain the soil particles at the higher gradients. This fabric had an O_{90} of 400 µm.

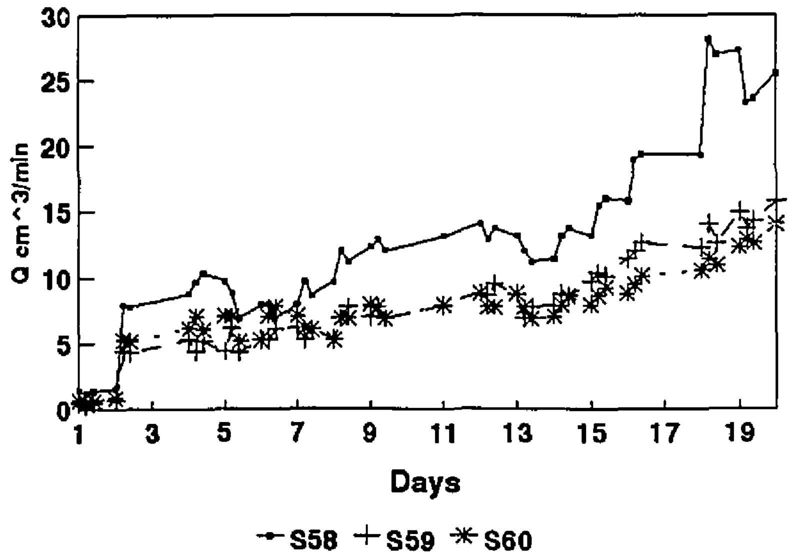
Hydraulic conductivity: Head loss was too small to calculate hydraulic conductivities.

Tests S67, S68 and S69 **Figure 4.10**

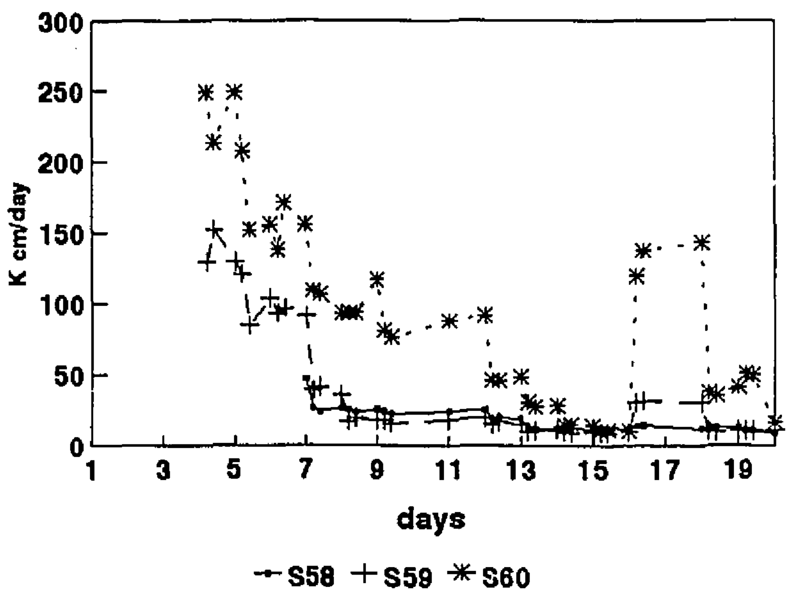
Pipe sedimentation: No passage of soil particles.

Discharge: Q was very low due to the very fine textured soil. However in

Discharge Texel 909



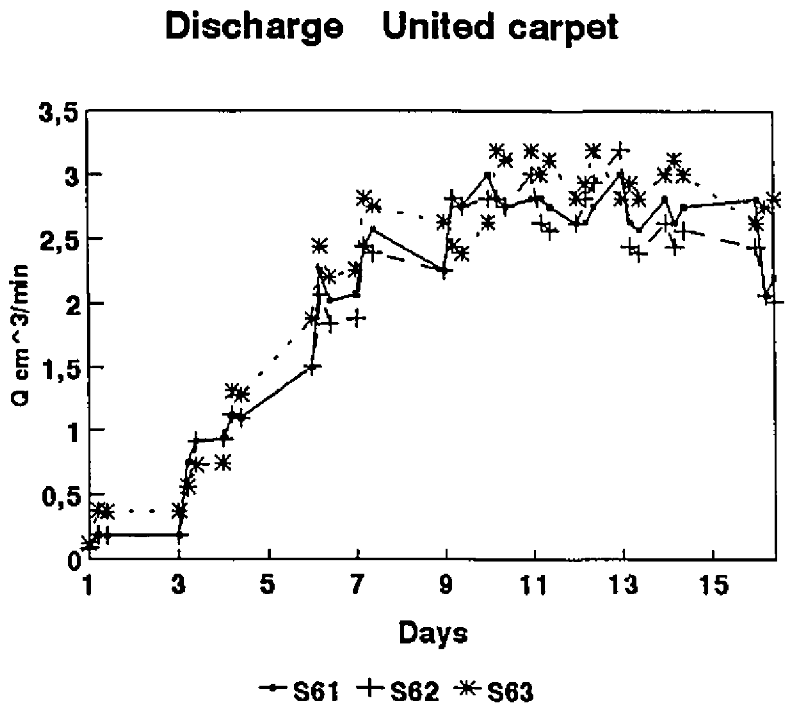
K soil-fabric



Note:

- Soil DIK
- Gradient increased gradually

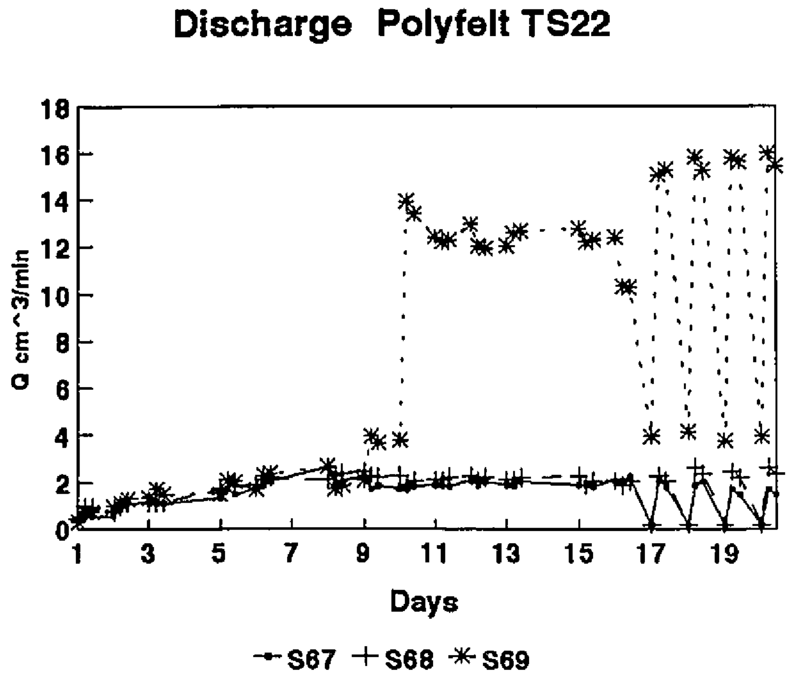
Figure 4.8 Flow rate VS time and Ksoil-fabric VS time for Tests S58, S59 and S60.

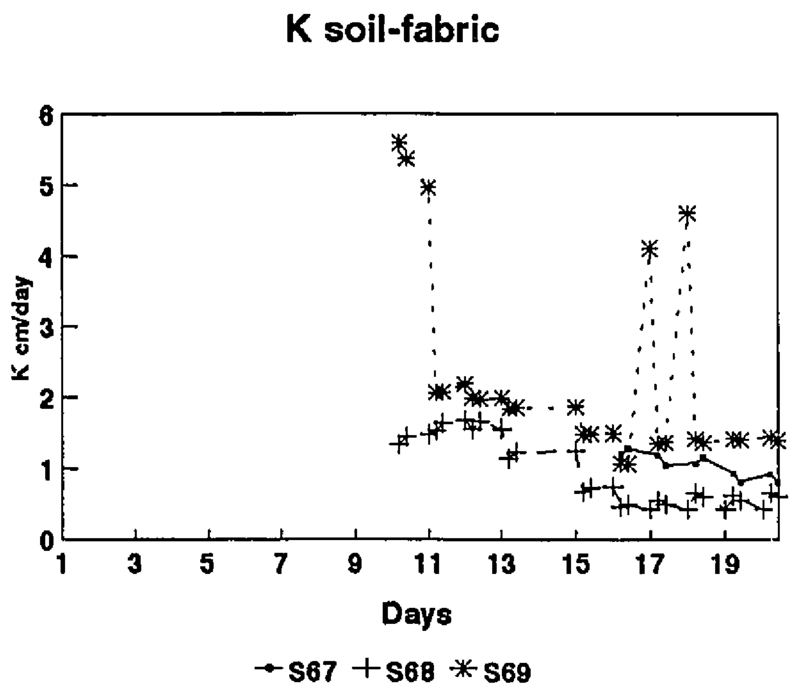


Note:

- Soil FES
- Head loss was too small to calculate K soil-fabric
- Tests S61 and S62 failed at gradient 22

Figure 4.9 Flow rate VS time for Tests S61, S62 and S63.





Note:

- Soil FES
- Surging started on day 17
- Higher flow rates in S67 due to piping through plexiglass sides

Figure 4.10 Flow rate VS time and Ksoil-fabric VS time for Tests S67, S68 and S69.

Test No.S67, discharge become very high on day 7 as compared to other tests. It could be due to the piping along the plexiglass.

Hydraulic conductivity: K interface of soil and fabric remained lower than the K soil. In test No.S67.

4.3 Granular envelope materials.

Blending of these materials were done in the range of the FDP upper, lower and some finer than the FDP specification. Some tests were run using pit-run gravel and sand in the natural form. Particle size distributions are shown in the figure 4.11 and summary of the results in Table 4.2. Detailed data sheets and analyses were prepared, a sample one set of Tests G112, G113 and G114 are shown in Appendix A.

Tests G73, G74 and G75 **Figure 4.12**

Pipe sedimentation: No passage of soil particles.

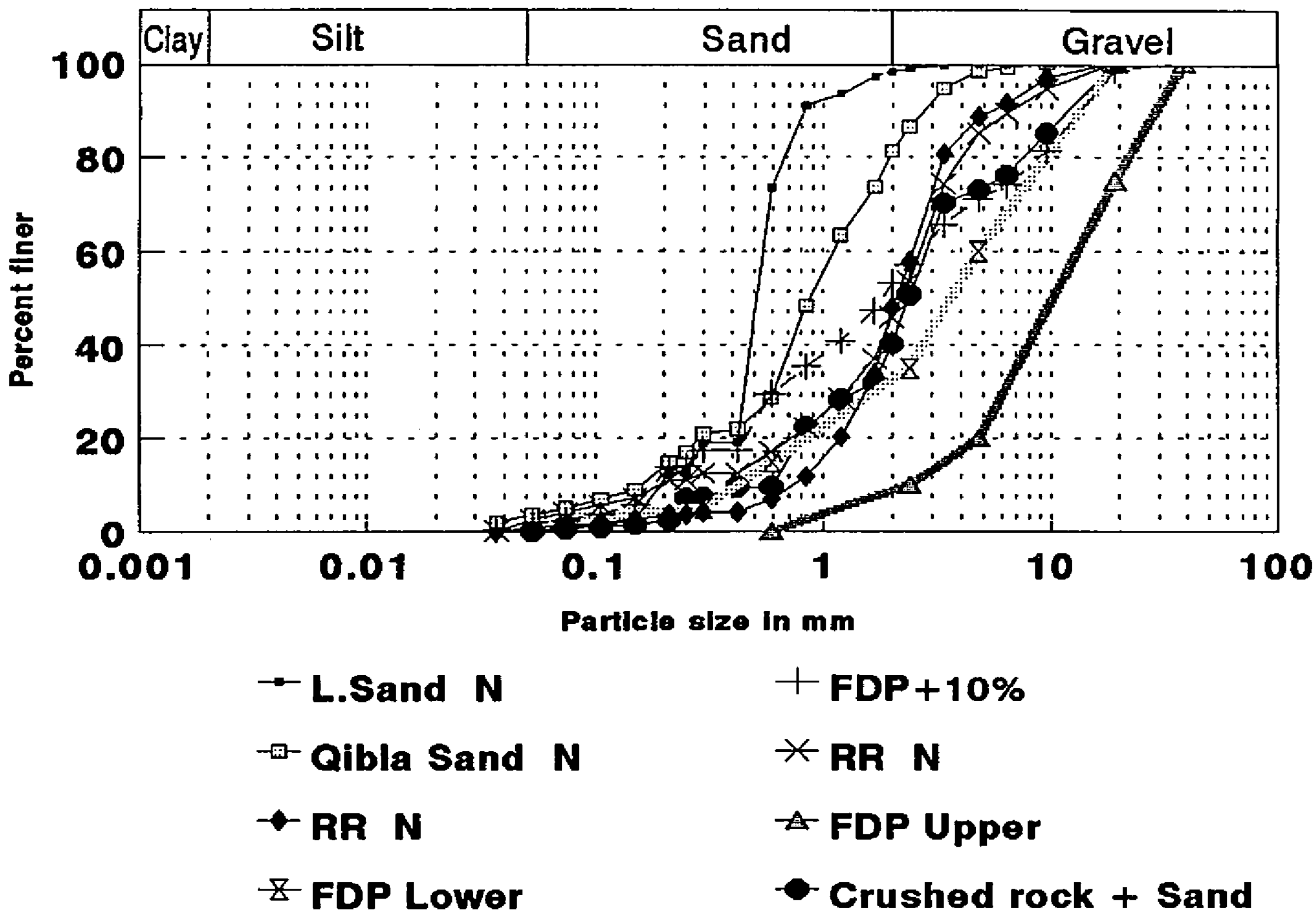
Discharge: Q increased with increasing hydraulic gradient.

Hydraulic conductivity: K envelope was not measurable in one replicate. However, no sign of clogging or blocking was observed in other tests.

K interface (soil-envelope) initially decreased till a hydraulic gradient of 3.5, thereafter no change was observed.

Tests G76, G77 and G78 **Figure 4.13**

Pipe sedimentation: No passage of soil particles.



N (Natural)
L(Lawrencepur), RR(River Run Attock)
FDP(Fourth Drainage Project Faisalabad)

Figure 4.11 Particle size distribution of the granular envelope materials.

Table 4.2 Summary of the permeameter test results with granular envelope materials.

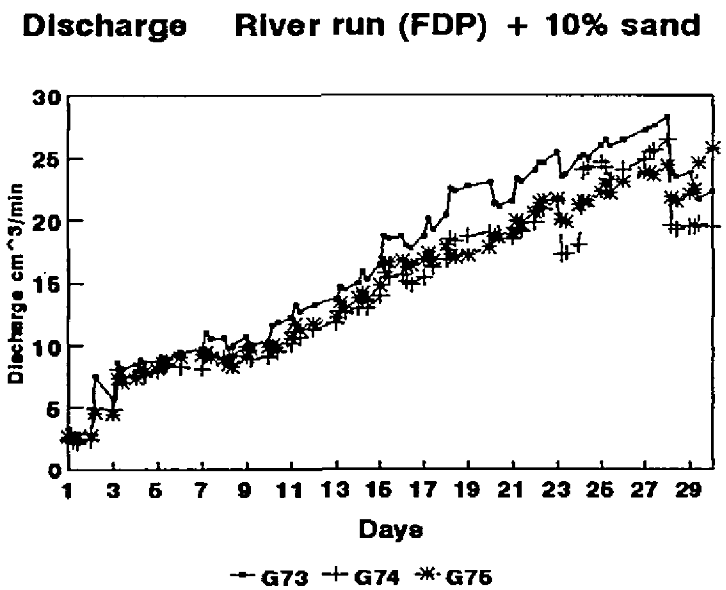
Type of Material	Test No.	Thickness cm		Soil d_{90}	Gravel D_{90}	Average Q cm^3/min	K Soil Interface cm/day		K Envelope cm/day		Remarks
		Soil	Gravel				Avg:	S.D.	Avg:	S.D.	
River Run Texla + 10% Sand	G73	5	7.5	.195	15	17	52	26	2237	497	
	G74	5	7.5	.195	15	14.37	37	14	1596	66	
	G75	5	7.5	.195	15	15	55	27	2827	1178	
Crushed Rock + Sand	G76	5	7.5	.195	7	16.43	55	22	3492	2340	
	G77	5	7.5	.195	7	13.28	56	18	1623	110	
	G78	5	7.5	.195	7	16.8	48	26	-	-	
River Run attock Natural	G79	5	7.5	.195	6.5	9	26	8	-	-	
	G80	5	7.5	.195	6.5	6.5	38	11	-	-	
	G81	5	7.5	.195	6.5	16	55	15	7040	123	
River Run Lower FDP	G88	2.5	7.5	.195	15	29	17	6	-	-	
	G89	5	7.5	.195	15	15	24	20	-	-	
	G90	7.5	7.5	.195	15	11	13	8	-	-	

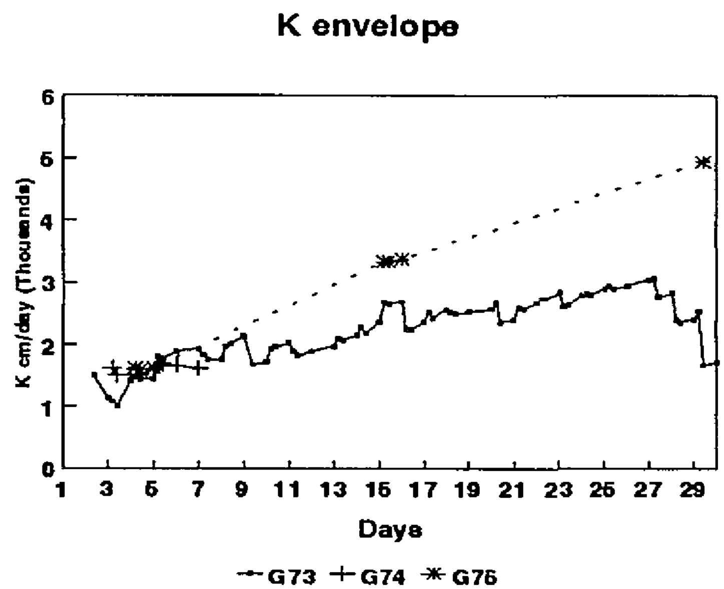
Table 4.2 continued

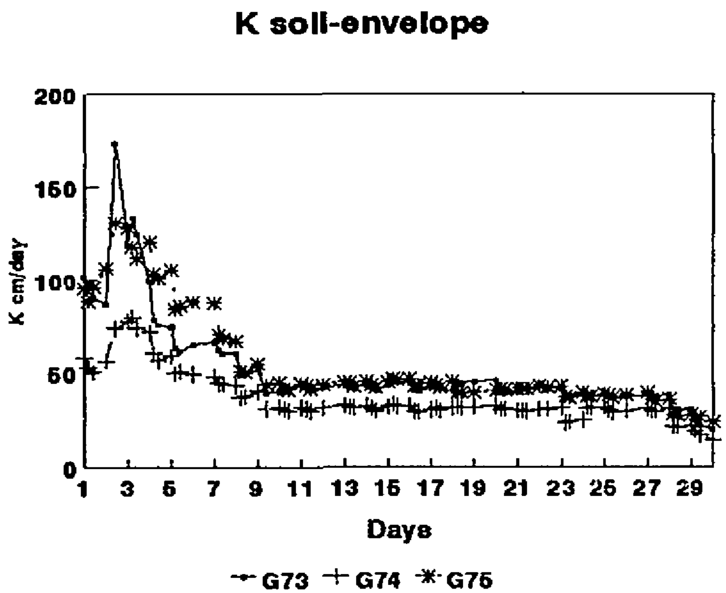
Type of Material	Test No.	Thickness cm		Soil d_{90}	Gravel D_{90}	Average Q cm^3/min	K Soil Interface cm/day		K Envelope cm/day		Remarks
		Soil	Gravel				Avg:	S.D.	Avg:	S.D.	
River Run Upper Limit FDP	G91	2.5	7.5	.195	30	-	-	-	-	-	Destroyed
	G92	5	7.5	.195	30	17	24	12	-	-	
	G93	7.5	7.5	.195	30	8	21	11	-	-	
River Run Attock Natural	G94	2.5	7.5	.195	6.5	34	59	88	3328	4610	
	G95	2.5	7.5	.195	6.5	48	268	585	2620	5182	
	G96	2.5	7.5	.195	650	18	21	10	2029	529	
Crushed Rock Upper Limit	G97	2.5	7.5	.195	30	-	-	-	-	-	Destroyed
	G98	2.5	7.5	.195	30	-	-	-	-	-	
	G99	2.5	7.5	.195	30	-	-	-	-	-	
Crushed Rock Lower Limit	G100	2.5	7.5	.195	15	-	-	-	-	-	Destroyed
	G101	2.5	7.5	.195	15	-	-	-	-	-	
	G102	2.5	7.5	.195	15	-	-	-	-	-	

Table 4.2 continued

Type of Material	Test No.	Thickness cm		Soil d_{90}	Gravel D_{90}	Average Q cm^3/min	K Soil Interface cm/day		K Envelope cm/day		Remarks
		Soil	Gravel				Avg:	S.D.	Avg:	S.D.	
Crushed Rock + Qibla Sand	G103	2.5	7.5	.195	7	175	171	168	2384	850	
	G104	2.5	7.5	.195	7	125	95	37	3598	3182	
	G105	2.5	7.5	.195	7	-	-	-	-	-	Destroyed
Qiblabundi Sand Natural	G109	2.5	7.5	.195	5.5	67	65	30	1563	241	
	G110	2.5	7.5	.195	5.5	77	68	28	2758	442	
	G111	2.5	7.5	.195	5.5	67	58	57	2160	346	
Lawrencepur Sand Natural	G112	2.5	7.5	.195	10	11	65	36	3040	1626	
	G113	2.5	7.5	.195	10	99	80	33	4491	2112	
	G114	2.5	7.5	.195	10	136	119	48	1906	784	



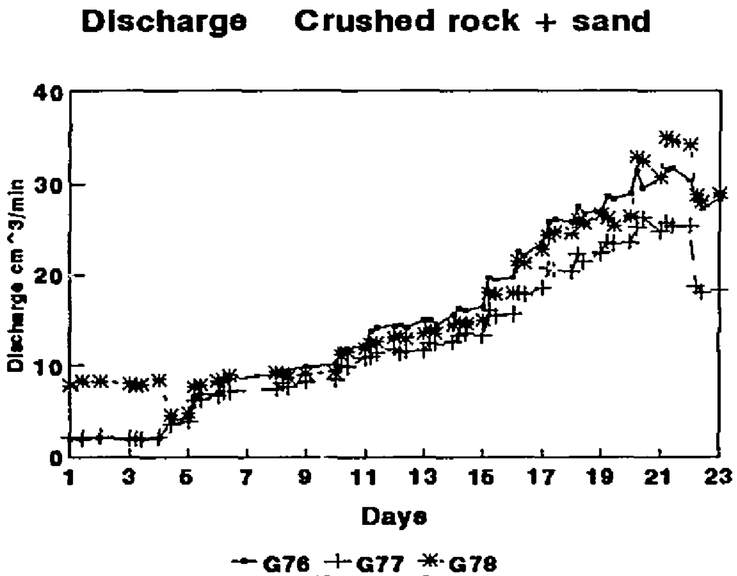


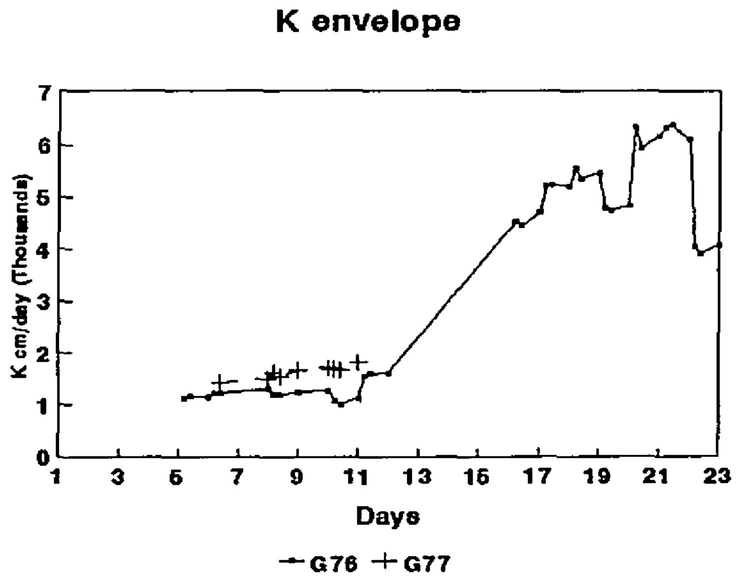


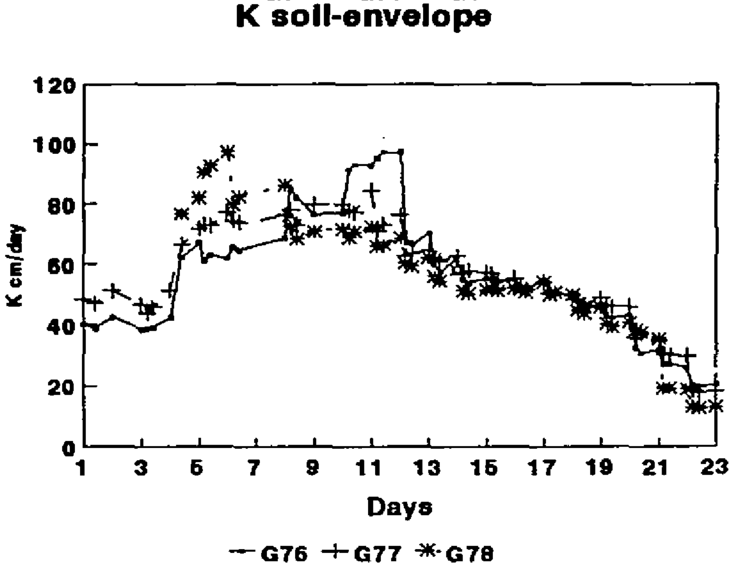
Note:

- Soil FDP
- Gradient was increased gradually

Figure 4.12 Flow rate VS time, Ksoil-envelope VS time and K envelope VS time for Tests G73, G74 and G75.







Note:

- Soil FDP
- Gradient increased gradually

Figure 4.13 Flow rate VS time, Ksoil-envelope VS time and K envelope VS time for Tests G76, G77 and G78.

Discharge: Q increased with increasing hydraulic gradient.

Hydraulic conductivity: K envelope increased with increasing hydraulic gradient. K envelope was not possible to measure in one of the tests because of negligible head loss.

K interface decreased throughout the tests, which infers that fine soil particles moved in this zone and reduced the K interface.

Tests G79, G80 and G81 Figure 4.14

Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with increasing hydraulic gradient.

Hydraulic conductivity: K envelope was not measurable due to negligible head loss in this zone.

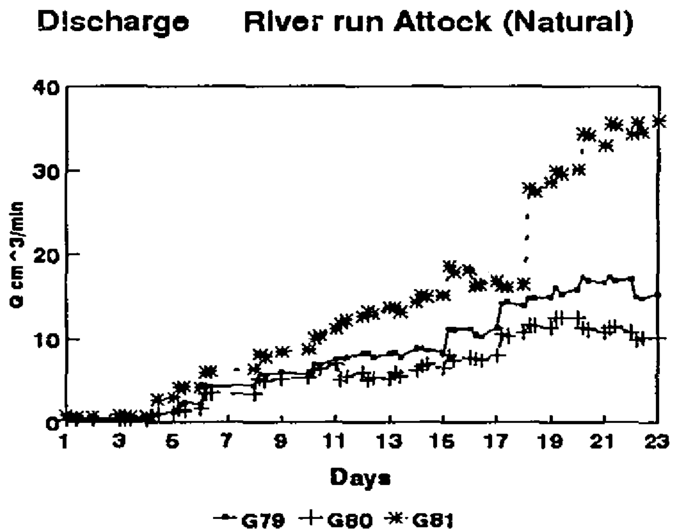
K interface decreased throughout the test. Which infers that fine soil particles moved in this zone.

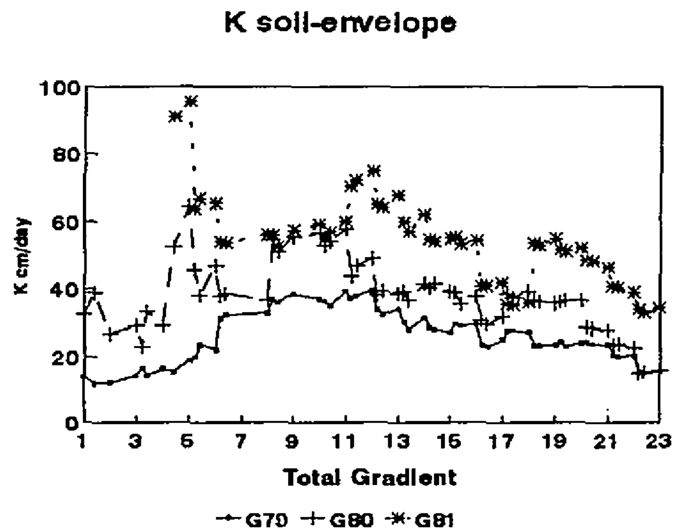
Tests G88, G89 and G90 Figure 4.15

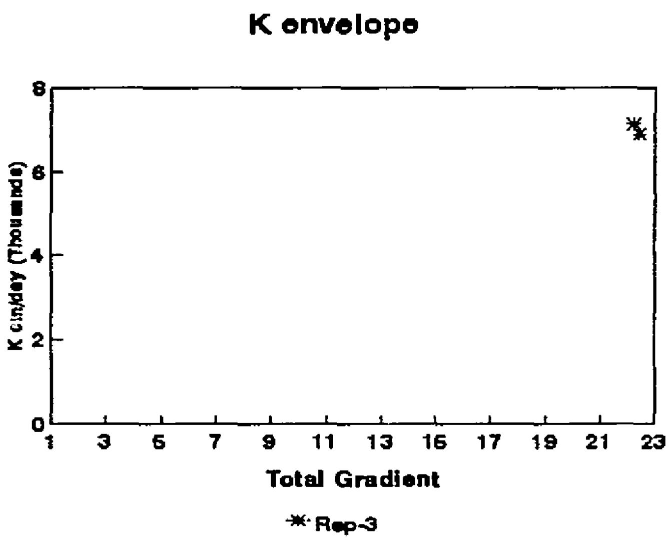
Pipe sedimentation: No passage of soil particles.

Discharge: Q was stable through the surging process.

Hydraulic conductivity: K envelope was not possible to measure in any test because of negligible head loss at this section.



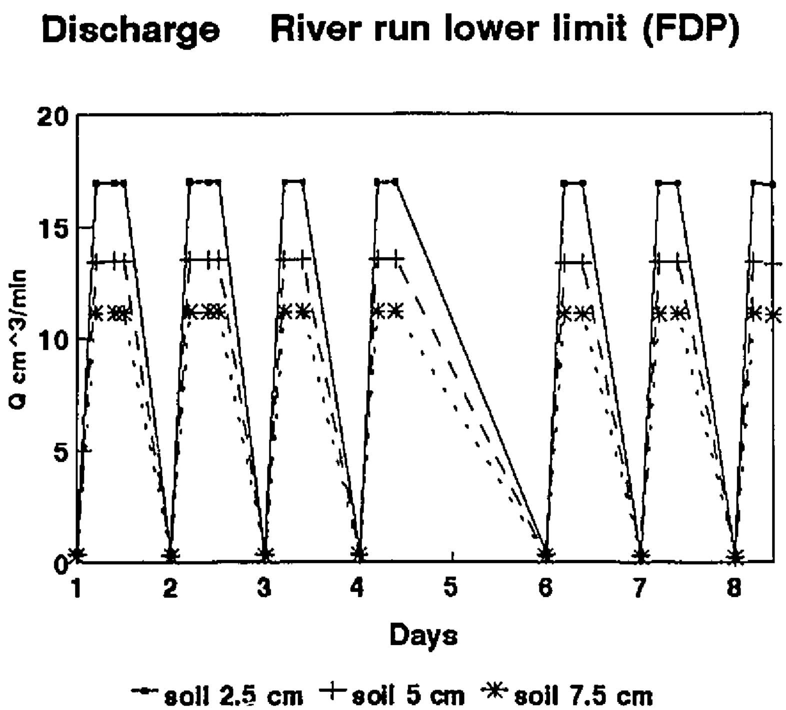


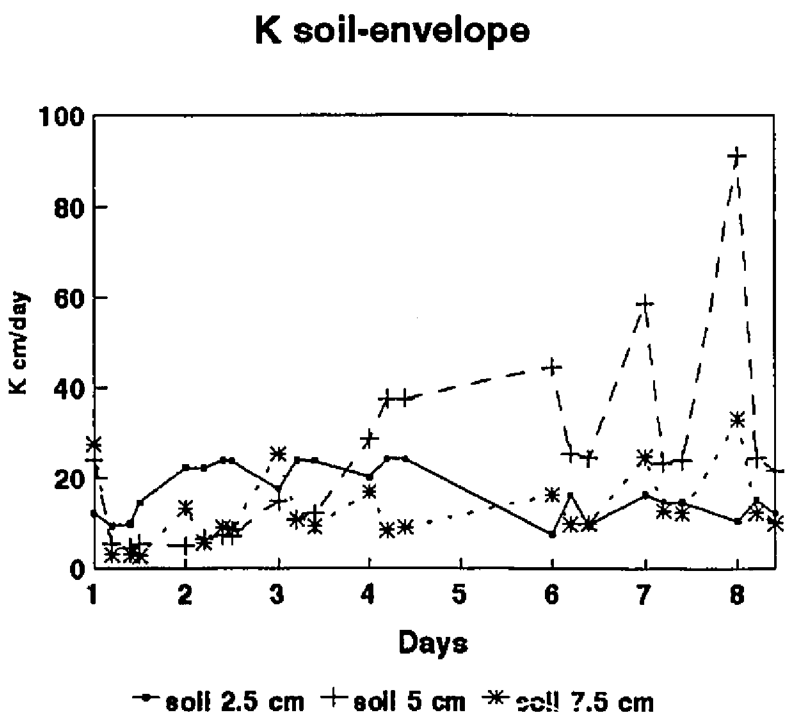


Note:

- Soil FDP
- Gradient increased gradually
- Kenvelope was not measureable

Figure 4.14 Flow rate VS time, Ksoil-envelope VS time and K envelope VS time for Tests G79, G80 and G81.





Note:

- Soil FDP
- Surging started from start of the test

Figure 4.15 Flow rate VS time and Ksoil-envelope VS time for Tests G88, G89 and G90.

K interface stayed constant or increased with time indicating no soil particles movement in this zone.

Tests G91, G92 and G93 **Figure 4.16**

Pipe sedimentation: Soil moved through the envelope from one replicate of 2.5 cm soil thickness at hydraulic gradient of 2.

Discharge: Q was stable at lower and higher gradients in the other two replicates.

Hydraulic conductivity: It was not possible to measure K envelope in any test because of negligible head loss at this section.

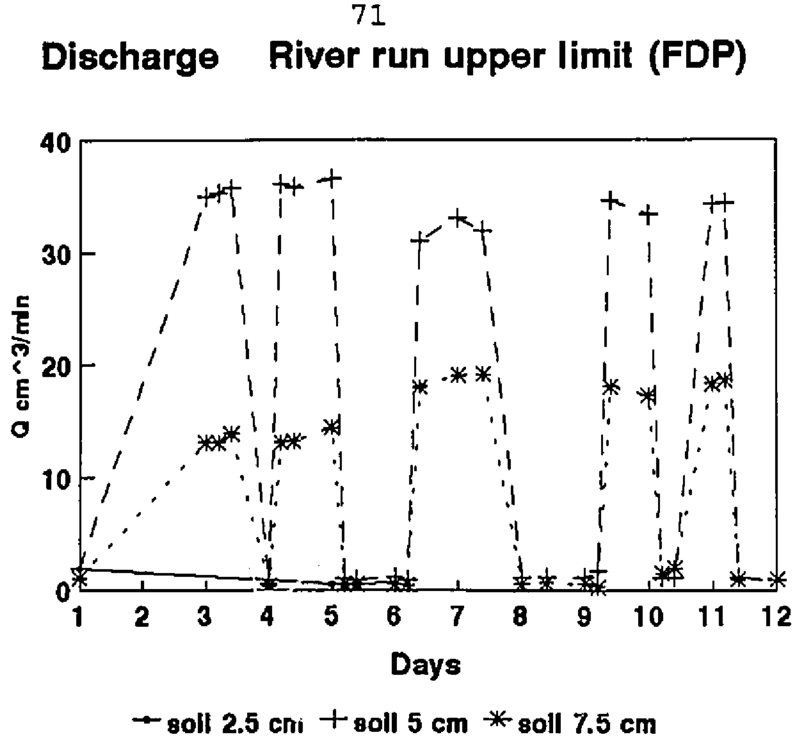
K interface has shown no sign of movement of soil particles in this zone.

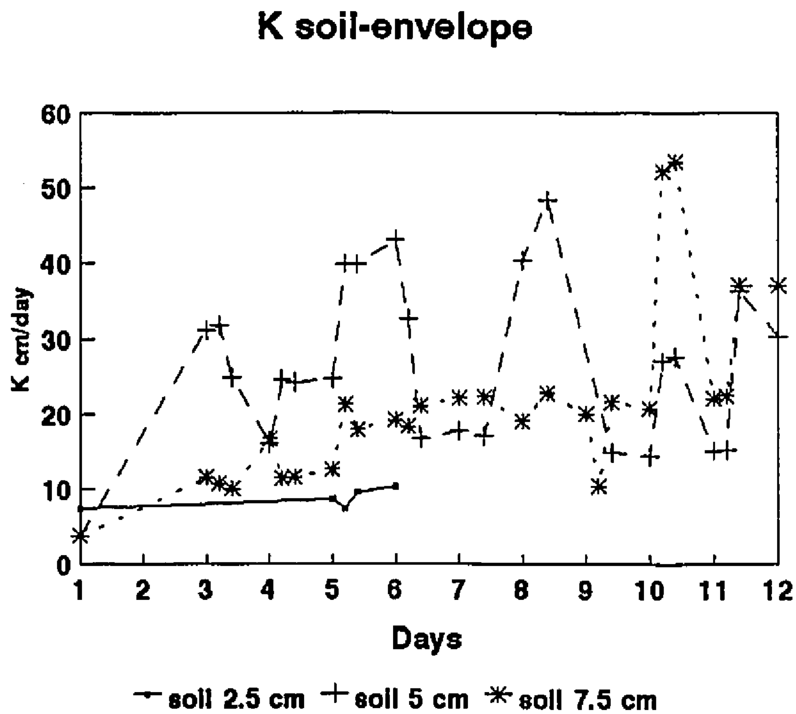
Tests G94, G95 and G96 **Figure 4.17**

Pipe sedimentation: No passage of soil particles.

Discharge: Q was stable till day 10, thereafter two replicates showed higher discharges.

Hydraulic conductivity: K envelope was possible to measure only at higher hydraulic gradients; a favourable increasing trend was observed at the higher gradients.

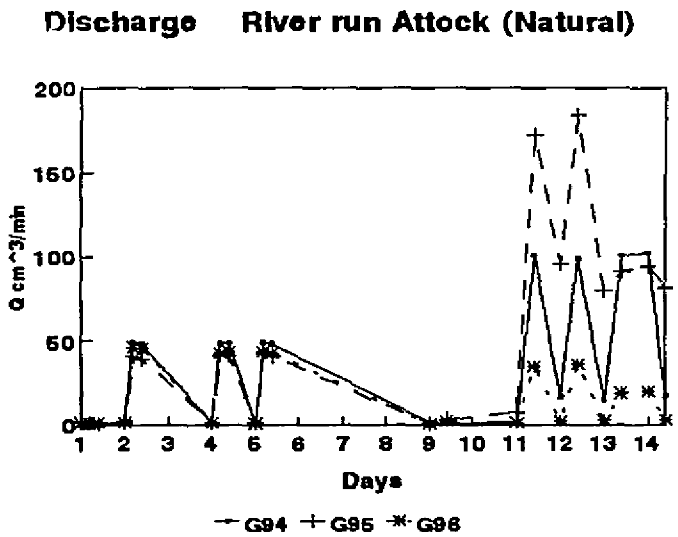


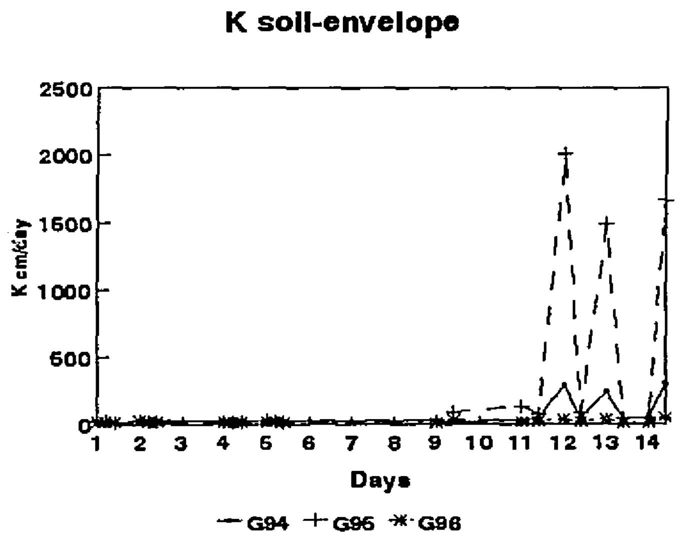


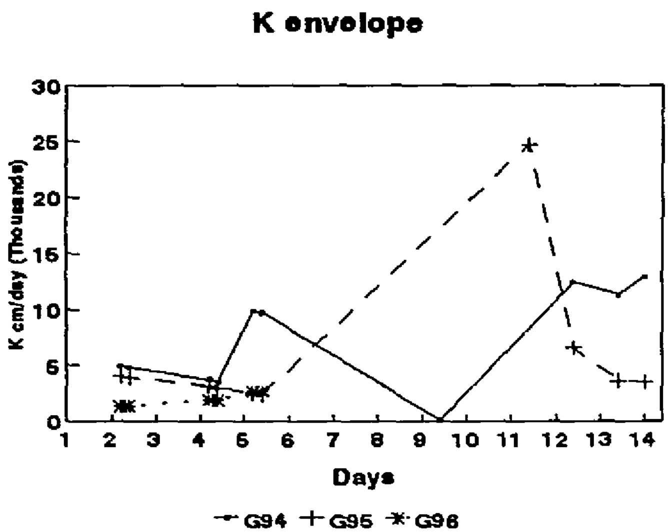
Note:

- Soil FDP
- Surging started from start of the test
- Test G91 of 2.5 cm soil thickness failed twice

Figure 4.16 Flow rate VS time and Ksoil-envelope VS time for Tests G91, G92 and G93.







Note:

- Soil FDP
- Surging strarted from start of the test
- Higher flow rates in Tests G94 and G95 could be due to piping from the plexiglass sides after day 10

Figure 4.17 Flow rate VS time, Ksoil-envelope VS time and K envelope VS time for Tests G94, G95 and G96.

Tests G103, G104 and G105 Figure 4.18

Pipe sedimentation: No passage of soil particles.

Discharge: Q remained stable in two replicates. Measurement were stopped on one replicate due to leakage near the piezometer openings.

Hydraulic conductivity: K envelope was not possible to measure during low heads, at higher gradients it became stable at the end of the test.

A continuous decrease in K interface was observed throughout the test. However this reduction had not influenced the K envelope.

Tests G109, G110 and G111 Figure 4.19

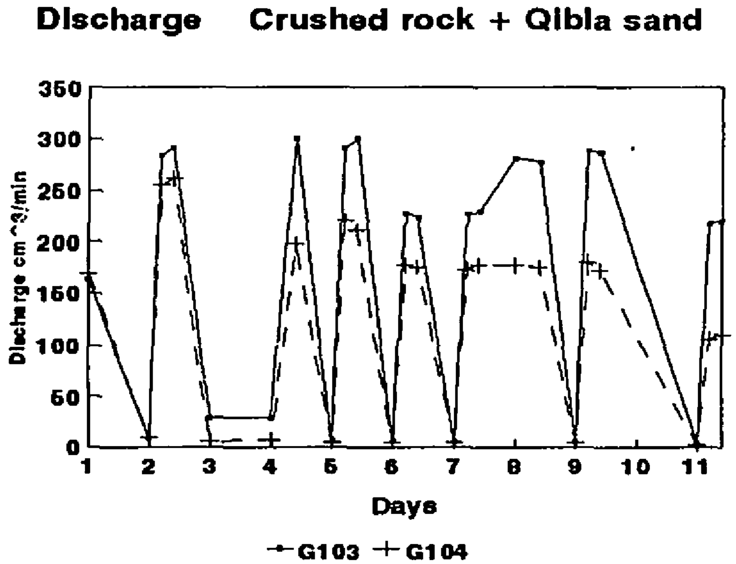
Pipe sedimentation: No passage of soil particles.

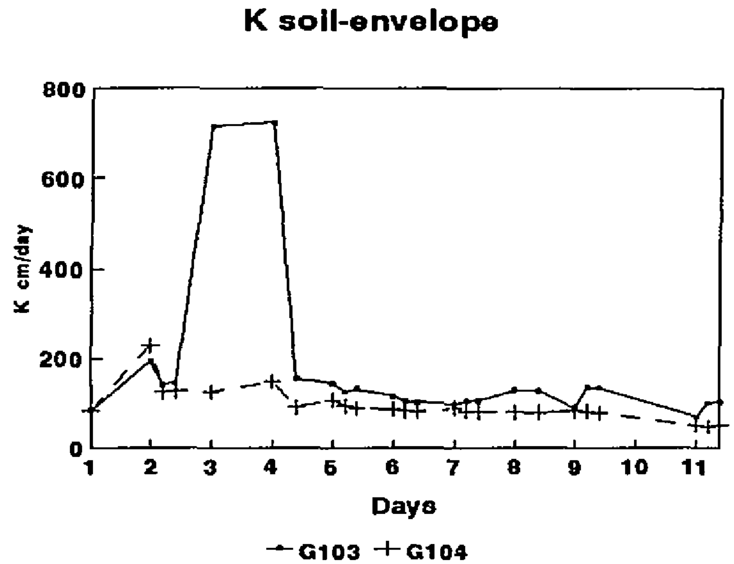
Discharge: Q decreased at low and as well at the high gradients.

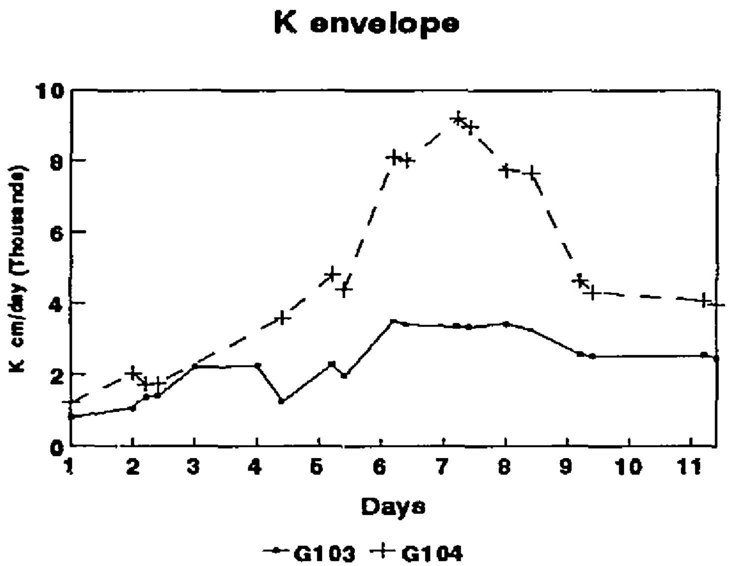
Hydraulic conductivity: Qiblabandi sand was used in natural form to observe the base soil using finer envelope material. Qiblabandi itself is in graded form and could be a good envelope for certain soils. Tests were run for about 20 days.

K envelope became stable after day 10 of the test. K in Test G110 was kept very high as compared to other two tests.

K interface gave higher values at the beginning , but after day 10, it became stable throughout the test. This showed that the bridging process was completed in a period of ten days.



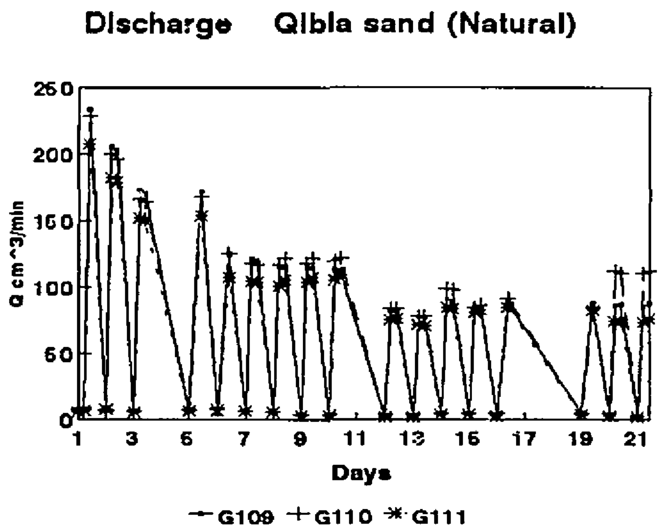


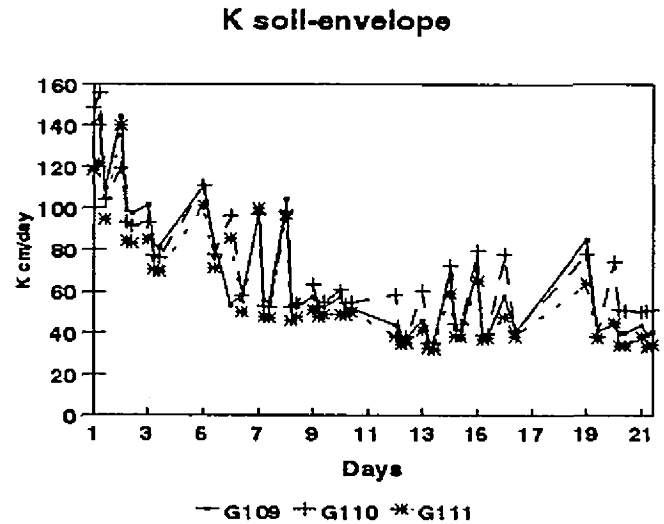


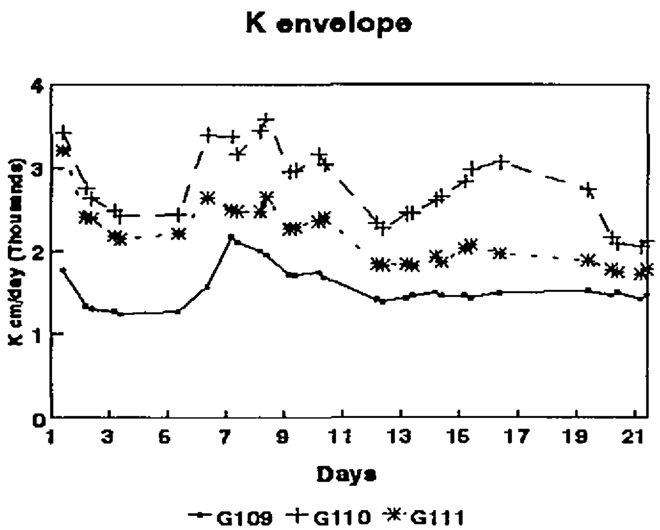
Note:

- Soil FDP
- Surging started from start of the test
- At low gradients Kenvelope was not measurable
- G105 was stopped due to leakage near the piezometer openings

Figure 4.18 Flow rate VS time, Ksoil-envelope VS time and K envelope VS time for Tests G103, G104 and G105.







Note:

- Soil FDP
- Surging started from start of the test
- Some fines were lost from the envelope itself

Figure 4.19 Flow rate VS time, Ksoil-envelope VS time and K envelope VS time for Tests G109, G110 and G111.

Tests G112, G113 and G114 **Figure 4.20**

Pipe sedimentation: No passage of soil particles.

Discharge: Q decreased with low as well as high gradients.

Hydraulic conductivity: Lawrencepur sand is uniform and 80% retained on three sieves. K envelope became stable at the end of the test.

K interface showed a decreasing trend till the end of the test. Which showed soil particles movement into the envelope close to the interface.

4.4 Synthetic fabric with combination of sand.

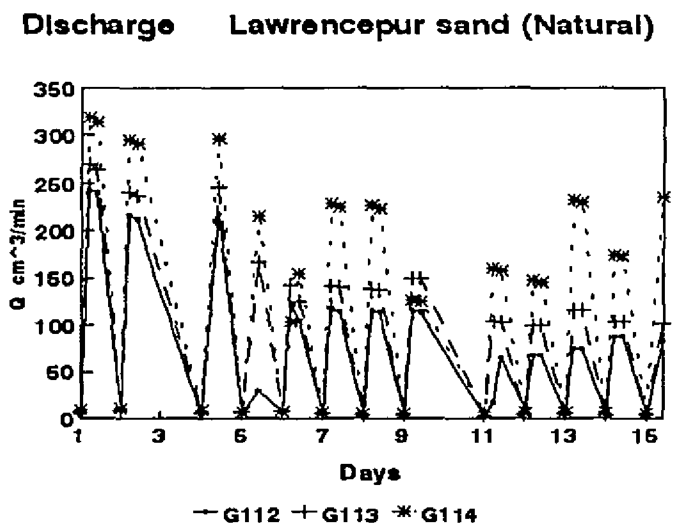
The use of sand and synthetic envelopes as combined dual envelope materials has been tested to check the behaviour. For this purpose Sutlej coarse and fine sands were used with three different fabric materials. Results are given in Table 4.3 and data analysis in Table GS-1 to GS-6 in Appendix A. Figure 4.21 shows the gradation analysis of Sutlej sand.

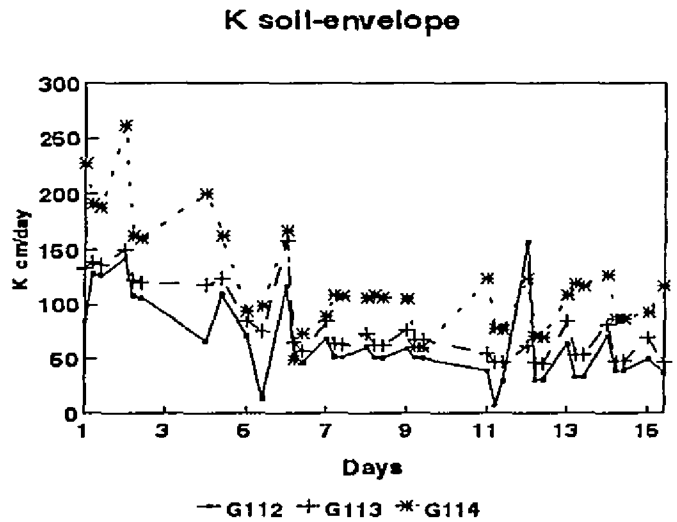
Test GS1 **Figure 4.22**

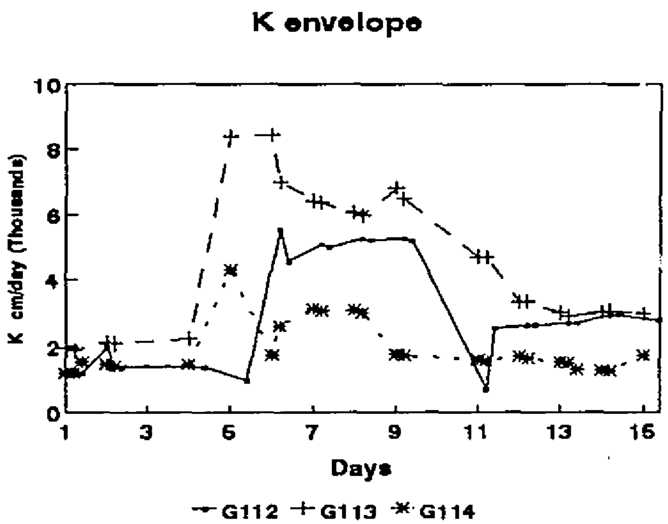
Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with increasing gradient and remained stable during the surging process.

Hydraulic conductivity: Head loss in the sand and synthetic interface was not measurable to calculate hydraulic conductivity except at a few times. This is an indication of no clogging. K sand remained stable till the end of the test.







Note:

- Soil FDP
- Surging started from start of the test
- Fines were lost during the test

Figure 4.20 Flow rate VS time, Ksoil-envelope VS time and K envelope VS time for Tests G112, G113 and G114.

Table 4.3 Summary of the test results of sand-fabric envelopes.

Type of Envelope Material		Test No.	Density g/cm^3		d_{50}	D_{50}	O_{90} µm Fabric	D_{50}/d_{50}	O_{90}/D_{90}	Av: Q cm^3/ min	Average			
												K Soil-Sand	K Sand	K Sand-Fabric
			Soil	Sand	Soil µm	Sand µm		Soil-Sand	Sand-Fabric		cm/day			
Coarse Sand	United Karachi	GS-1	1.52	1.44	16	250	340	16	3.4	12.7		40	1144	702
											S.D.	14	329	19
	Texel 909	GS-2	1.52	1.44	16	250	100	16	1	15		30	1561	823
											S.D.	15	432	215
	Polyfelt TS-22	GS-3	1.52	1.44	16	250	130	16	1.3	12.4		44	1058	422
											S.D.	28	175	26
Fine Sand	United Karachi	GS-4	1.52	1.44	16	150	340	9	3.4	12		32	498	658
											S.D.	22	60	99
	Texel 909	GS-5	1.52	1.44	16	150	100	9	1	12		28	346	404
											S.D.	20	165	92
	Polyfelt TS-22	GS-6	1.52	1.44	16	150	130	9	1.3	11		29	475	164
											S.D.	40	92	34

S.D.: Standard Deviation

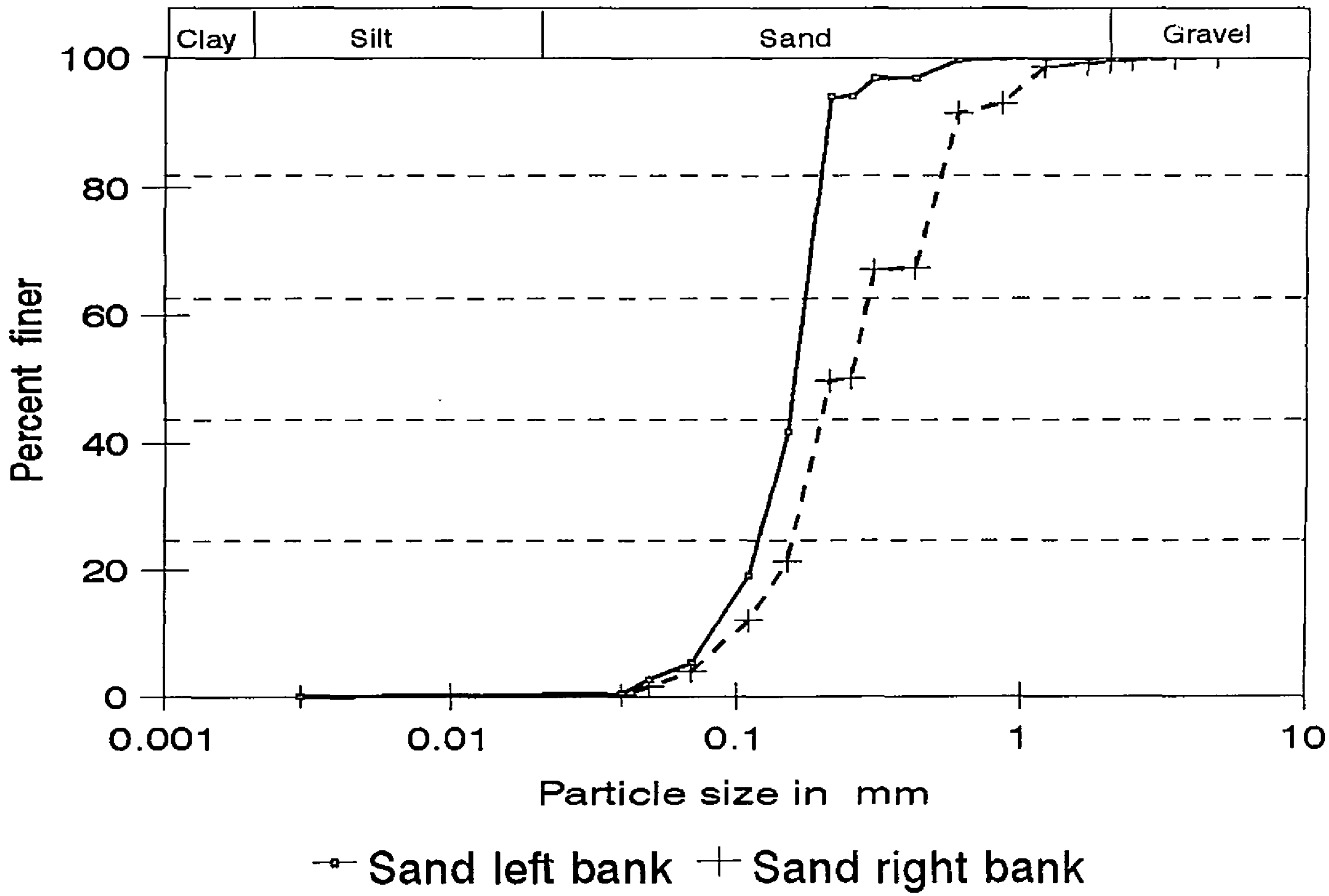


Figure 4.21 Particle size distribution of Sutlej river sand

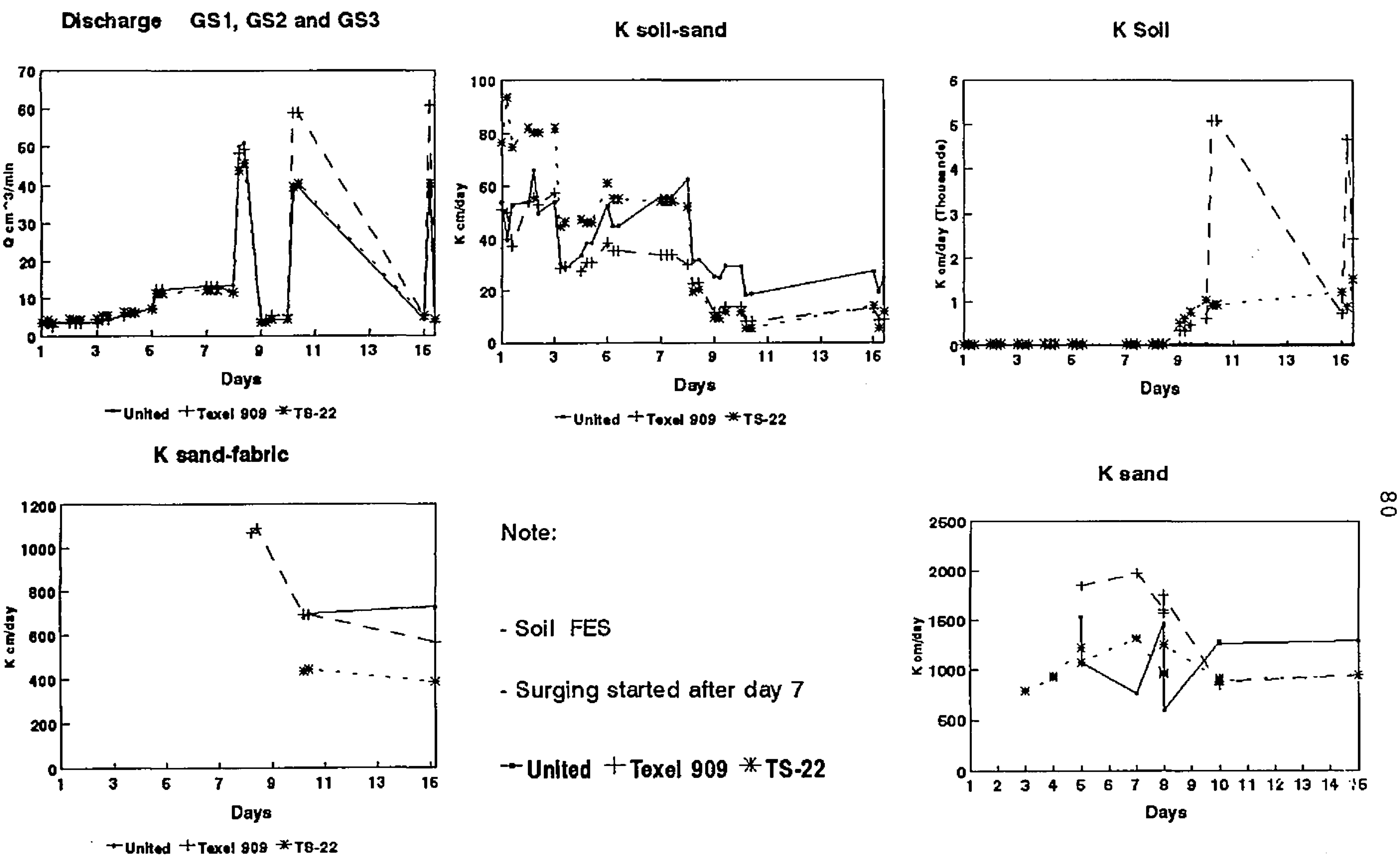


Figure 4.22 Flow rate VS time, Ksoil-sand VS time, K soil VS time , K sand VS time and K sand-fabric VS time for Tests GS1, GS2 and GS3.

Test GS2 **Figure 4.22**

Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with increasing gradient and remained stable during the surging process.

Hydraulic conductivity: At the beginning, K sand-fabric could not be measured due to the negligible head loss. Later a continuous decrease was observed till the end of test. K sand remained stable till the end of the test. At the end of the tests K sand-fabric was more than 400 cm/day which was still more than 12 times K soil, so the sand-fabric made a good envelope.

Test GS3 **Figure 4.22**

Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with increasing gradient and remained stable during the surging process.

Hydraulic conductivity: At the beginning it was not possible to measure K sand-fabric due to the negligible head loss. Later a gradual decrease was observed till the end of test. K sand remained stable till the end of the test.

Test GS4 **Figure 4.23**

Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with increasing gradient and remained stable during the surging process.

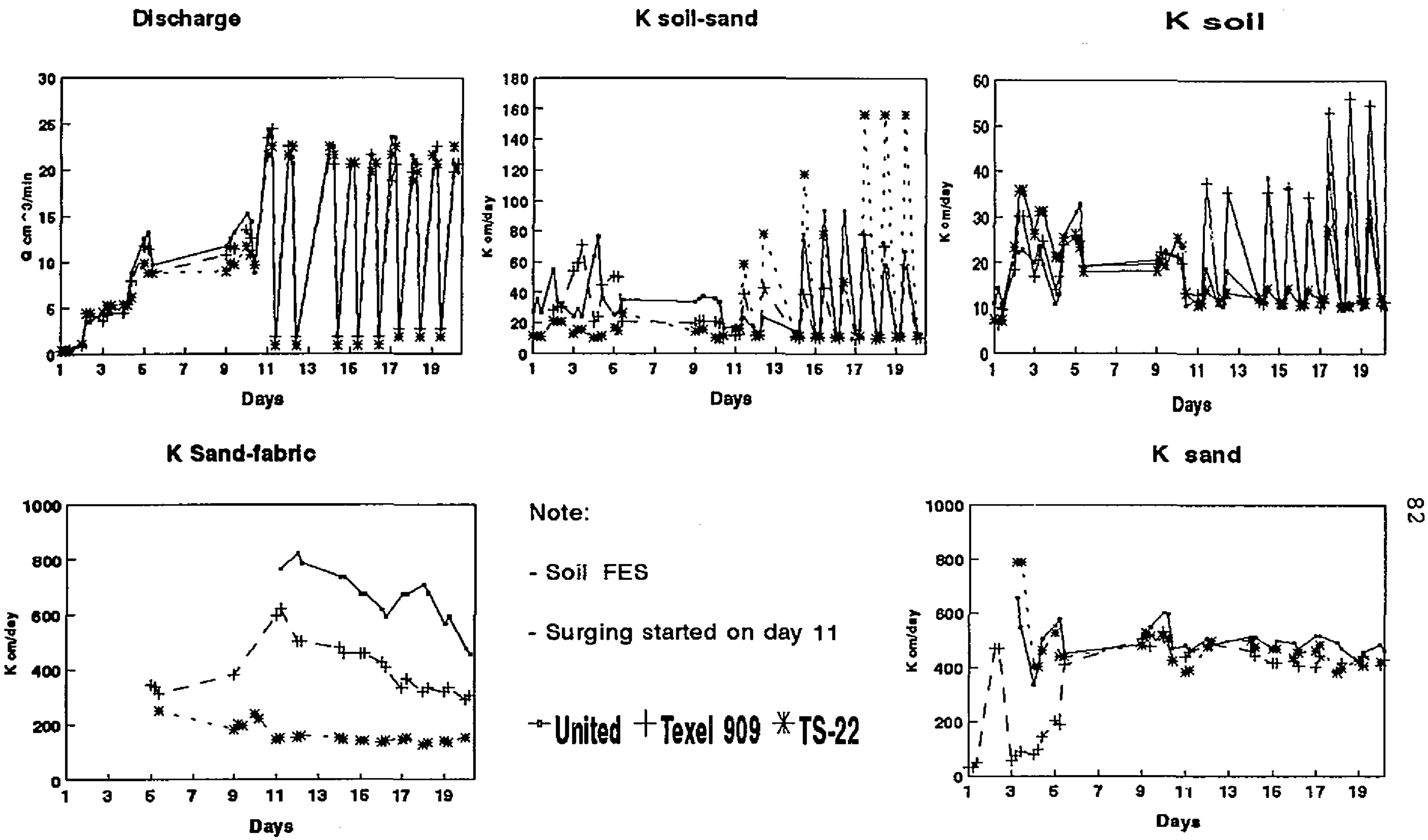


Figure 4.23 Flow rate VS time, Ksoil-sand VS time, K sand VS time, K soil VS time and K sand-fabric VS time for Tests GS4, GS5 and GS6.

Hydraulic conductivity: K sand remained constant throughout the test in the fine sand zone, however a continuous decrease was noticed in the sand-fabric interface. This indicates movement of sand particles into the fabric. At the end of 20 days testing, K sand-fabric was 600 cm/day which is about 15 times larger than K soil-sand, so the envelope is satisfactory.

Test GS5 **Figure 4.23**

Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with increasing gradient and remained stable during the surging process.

Hydraulic conductivity: K soil-sand increased with the increase in the overall hydraulic gradient. However during the surging process no change was observed. A gradual decrease of K in the interface of sand-fabric was noticed till the end of the test. K sand remained constant during the test. After a gradient of 6 no change was noticed.

Test No. GS6 **Figure 4.23**

Pipe sedimentation: No passage of soil particles.

Discharge: Q increased with increasing hydraulic gradient and remained stable during the surging process.

Hydraulic conductivity: K sand and K sand-fabric remained constant during the test.

CHAPTER 5

5 Discussions of observations

5.1 Soils

Soil samples from these three projects were taken at the drain depth of about 1.5 meters. Soils which contain large fractions of silt and sand are called "problem soils". Table 5.1 shows the soil texture composition of soil samples from the three projects. The granulometric analysis are presented in Figure 3.4.

Table 5.1 Soil texture classification.

Location of Soil Sample	Particle size fractions %			C_u	Soil Texture[1]
	Sand	Silt	Clay		
FDP	55	30	15	3	Sandy Loam
DIK	70	22	8	2.7	Sandy Loam
FES	13	68	19	12	Silt Loam

5.2 Synthetic fabrics

All investigated envelopes prevented massive movement of soil particles passing through the drain pipe. Hence failure of the envelopes by non-retention of soil particles did not occur. Figure 5.1 shows the range of fines lost during the tests less than 4%.

1 USDA soil texture classification.

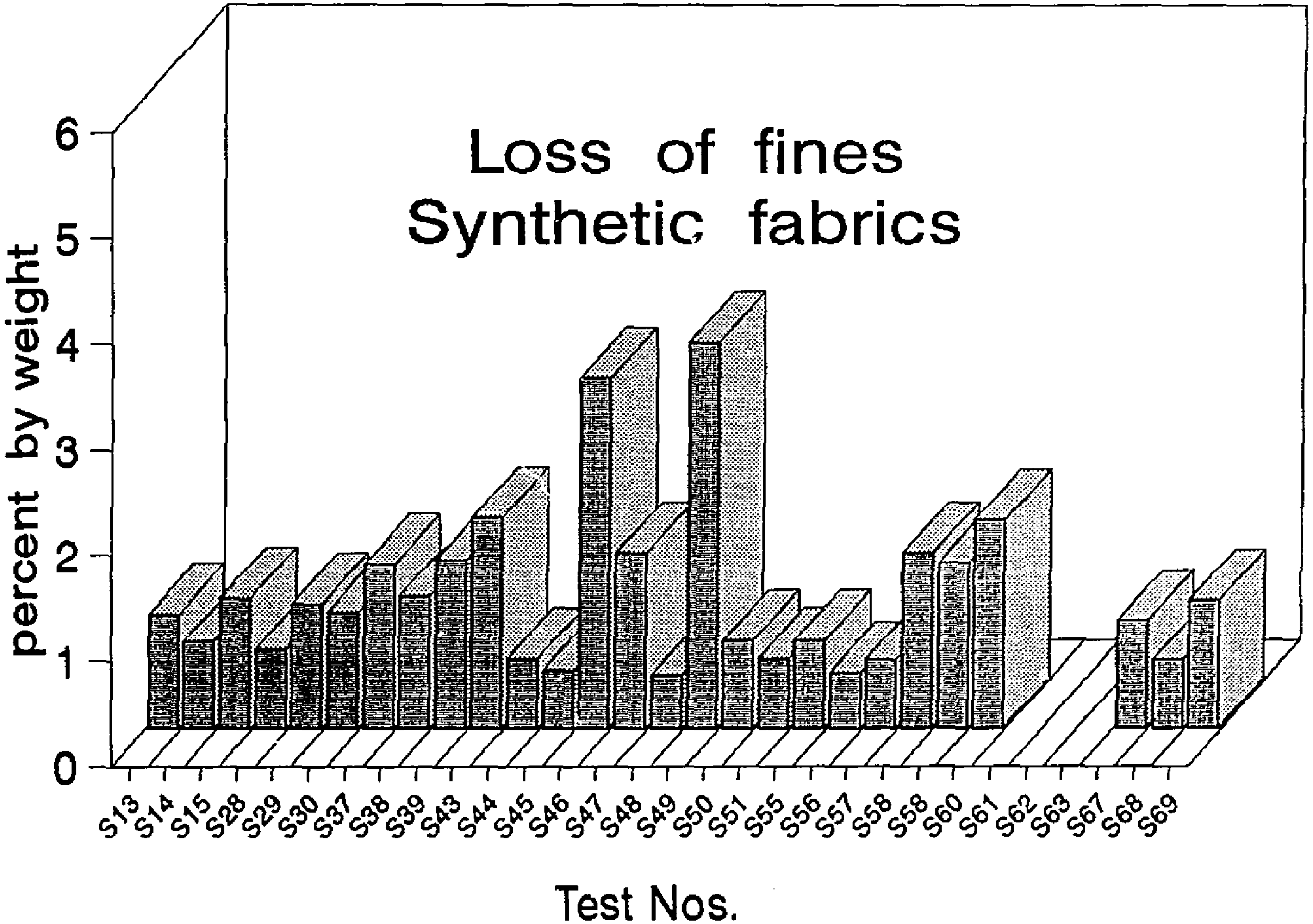


Figure 5.1 Loss of fines through the synthetic fabrics.

Other phenomena checked were the internal soil erosion, the internal soil structure failure and the likelihood of envelope clogging. Internal erosion may occur when the soil particles move through the soil pores between larger particles. Internal soil failure is the collapse of the cohesive bonds between the soil particles. Envelope clogging is the accumulation of fine soil particles in, or on, the surface of the envelope resulting in a reduced combined hydraulic conductivity of a thin soil layer and the envelope itself (Salem et al., 1995). The behaviour of the envelope materials and soil can be evaluated from changes of the combined hydraulic conductivity of the top thin soil layer and the envelope at the top of the permeameter, hydraulic conductivity, K at the interface and the hydraulic conductivity of the adjacent soil.

5.2.1 Voluminous fabric envelopes with O_{90} > 300 µm.

Voluminous materials were evaluated in Tests S37 to S39, S55 to S57 and S61 to S63. In Tests S37 to S39, some fines moved through the top plate and thereafter improved the system. In the surging process the soil remained stable. The same fabric when tested with DIK soil, which is coarser than the FDP soil has shown favourable results. In both the tests Q was increased with increasing hydraulic gradient. However K interface was not measurable because of the negligible head loss at this section.

A very coarse fabric in Tests S61 to S63 was tested with a silty loam soil of the FES project with O_{90}/d_{90} ratio equal to 4. This ratio was the maximum of all the ratios of the tests performed with fabric envelopes. Q was kept quite low because of the fine textured soil. Q increased with increasing gradient till a gradient 16. At gradients from 16 to 22, no change in Q was observed; perhaps due to the higher gradients, the soil was compacted or it may possible that due to compaction, the thickness of fabric became less, which reduced the permeability of the interface. At a hydraulic gradient of 22, on all these tests, soil particles moved through the fabric and the soil was washed away.

5.2.2 Thin fabric with O_{90} >100 μm.

Only one fabric of this type was tested with soil thickness of 5 and 10 cm. Evidence of soil particle movement was observed in the interface of soil-fabric in tests S13, S14 and S67 to S69. K interface decreased continuously, which could be due to the partially blocking the pores of the fabric. Only test S15 showed no problem and remained stable through the test duration. In test S69, soil structurally failed at a hydraulic gradient of 16 (Figure 4.10).

5.2.3 Fabric with O_{90} < 100 μm.

Fabrics having O_{90}/d_{90} < 0.32 showed an excellent performance. Discharges through these fabrics were much higher as compared to the fabrics having O_{90} > 300 μm. Maximum flows were observed in Tests S43 to S51 having O_{90}/d_{90} < .32. It appears that no soil particles were entrapped in these fine fabrics. Small amounts of fines were lost through these fabrics at the start of the tests (See Figures 4.4 to 4.6), but after the system became stabilized, no more fine particles passed through; which shows a favourable performance of the soil-fabric system. A similar rate of flow was observed in Test S28 having O_{90}/d_{90}< 0.42. No evidence of clogging at the sand-fabric interface was observed.

5.2.4 Flows at different hydraulic gradients

Table 5.2 shows the average rate of flow at minimum and maximum hydraulic gradients. It is interesting to see that flows were higher through the fabrics having finer openings and thickness in the range of 2 to 3 mm.

Table 5.2 Rate of flows of synthetic envelopes at minimum and maximum hydraulic gradients.

Materials	Test No.	Av: Q cm^3/min		Hydraulic gradient range	
		Low head	High head	Min	Max
TS-22	S13	0.6	12	0.4	10.0
	S14	0.3	11		
	S15	0.6	10		
Texel 909	S28	1	27	0.4	16.5
	S29	1	26		
	S30	0.7			
United Karachi	S37	0.93	19	0.4	17
	S38	1.0	39		
	S39	1.0	34		
Texel 912	S43	11	125	1.4	62
	S44	3	47	0.6	26
	S45	3	36	0.4	15
Olympia 3	S46	14	203	2	62
	S47	8	76	1	31
	S48	7	29	0.7	21
Olympia 3	S50	51	109	0.6	17
	S51	33	106		
Olympia 3	S55	4.4	10	1.6	16
	S56	4	10		
	S57	4.5	8		
Texel 909	S58	1.4	13	0.5	16
	S59	0.5	12		
	S60	0.6	13		
Nayyer	S61	0.2	3	1.4	16
	S62	0.2	2.5		
	S63	0.3	3.0		
Ts 22	S67	0.2	1.8	2.7	16
	S68	0.2	2.0		
	S69	0.5	13.5		

5.3 Granular materials

5.3.1 Twenty one sieve analyses

Figure 5.2a shows river run natural material (rounded particles). Except for sieve numbers 14 and 16 all sieves have a fairly good amount of material. Note that sieve numbers shown are serial numbers. Table 3.4 gives ASTM numbers and dimensions. The peak on sieve 7 is not a problem as it does not occur on coarser sieves 1 - 5. The material falls within the FDP specified gravel bands for the finer material but not for the coarser part (Figure 4.11) and has a Cu= 7.0 and a Cc= 0.9.

Figure 5.2b shows the results with crushed rock (angular particles): large particle sizes dominate. The sample falls within the FDP specified gravel band, near the upper boundary, but is not well graded although Cu= 3.8 and Cc= 2.3 would tend to indicate the contrary (well graded gravel should have Cu $\geq$ 4 and Cc = 1 to 3). River run upper has shown better representation on sieves as compared to crushed rock upper. However, segregation and poor flow characteristics in the trencher chute were observed with similar crushed rock materials (Vlotman and Bhatti 1990).

Blending crushed rock with sand (Figure 5.2a) and FDP with 10% fines (Figure 5.2a) have shown good representations on the sieves. The sample was finer than the FDP gravel band with Cu= 7.7 and Cc= 1.1.

Crushed rock lower in Figure 5.2b shows sieve 4 having 30% materials, which could perhaps be the reason for the failure in all the three Tests G100, G101 and G103. Figures 5.2a and 5.2b shows twenty one sieve analyses for selected materials.

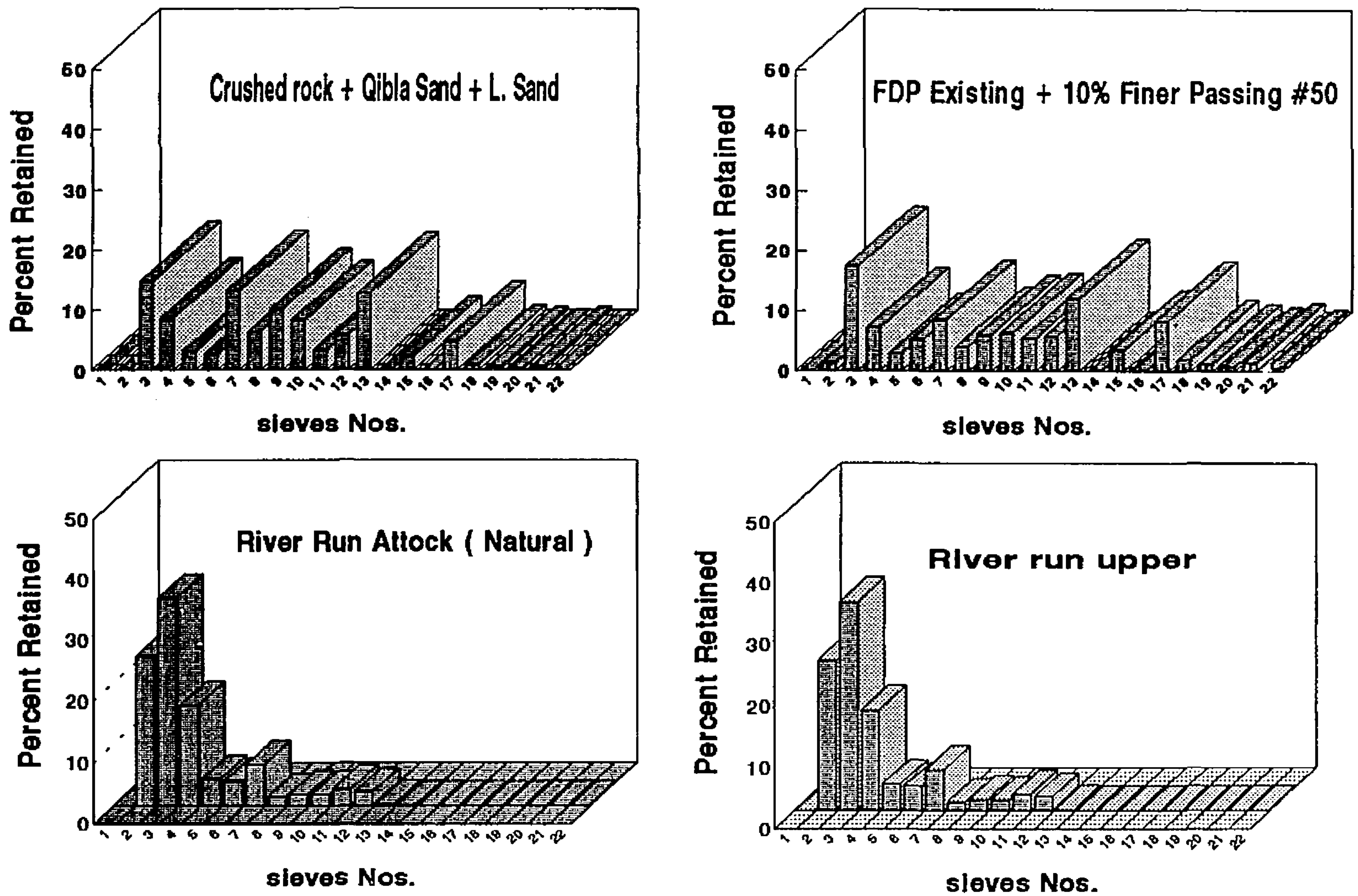


Figure 5.2a   Twenty one sieve analyses for tested granular materials

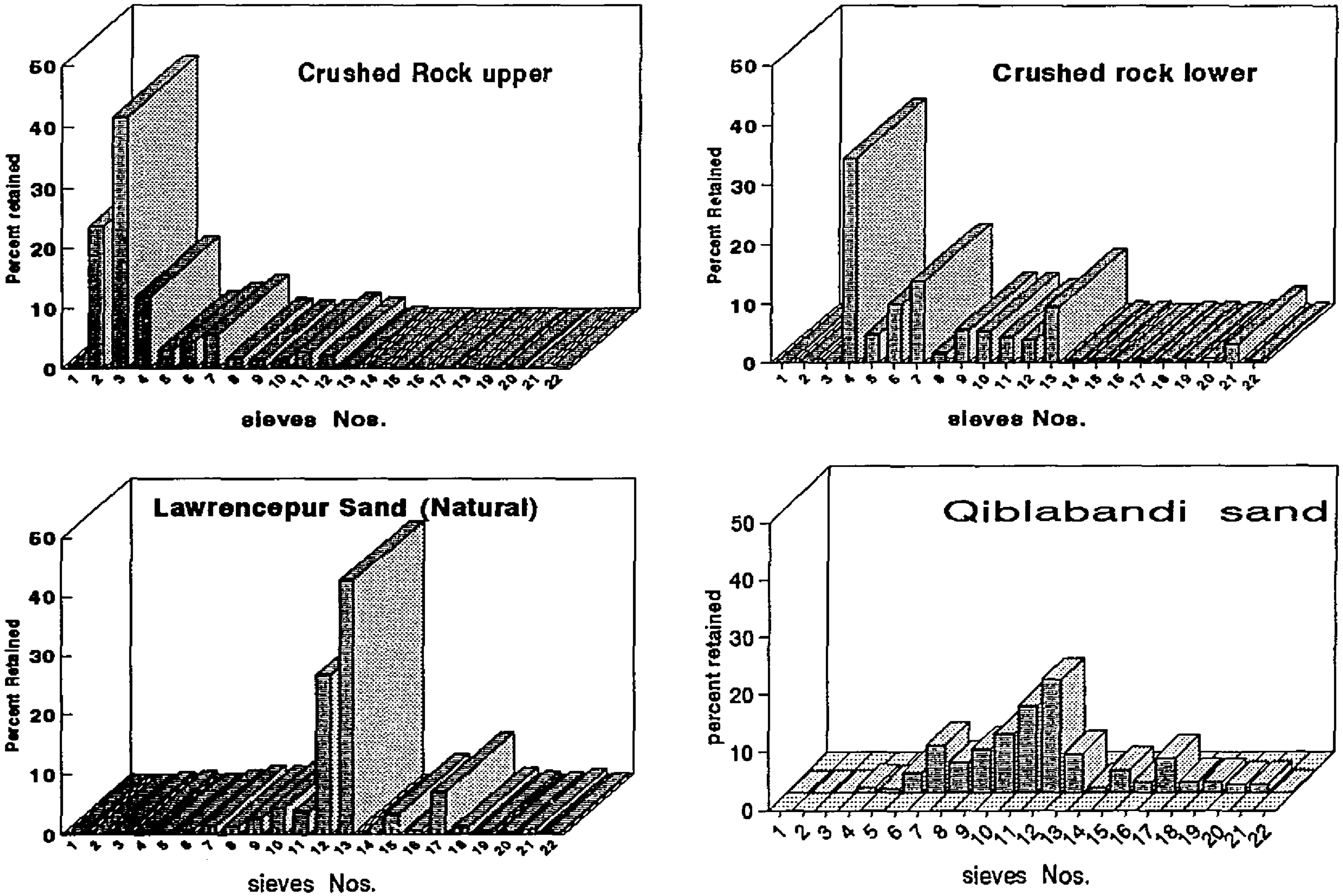


Figure 5.2b Twenty one sieve analyses for tested granular materials

5.3.2 Hydraulic conductivity tests

Hydraulic conductivities of all materials were determined in the permeameter separately (Shafiq and Vlotman, 1992). The apparent hydraulic conductivity of the crushed rock (CR) was much higher than the river run (RR) material (Table 5.3). The main reason for the different hydraulic conductivities is the packing of the particles in the permeameter. The angular shape of the crushed rock and the larger sized particles are thought to be the main factors for the high hydraulic conductivities. The results for the crushed material mixed with Qiblabandi sand show that the hydraulic conductivity can be controlled by mixing Qiblabandi sand with the coarser materials. With substantial amounts of material on ASTM sieves 1.5" and 3/4" (38.1 and 19.1 mm), hydraulic conductivities tended to be very high.

Table 5.3 Description of granular hydraulic conductivities.

Description of material	Hydraulic Conductivity* at 20 °C	
	cm/day	ft/day
Lawrencepur sand	2030	67
Crushed rock (lower FDP)	43695	1434
River run (lower FDP)	22904	751
Crushed rock coarse (upper FDP)	160954	5281
River run (upper FDP)	145817	4784
FDP Existing + 10% Sand Passing # 50	12710	417
Crushed Sargodha 66% + Qibla Sand 28% + Local sand 6%	115137	3777
River Run Attock (Natural)	14630	480

After Shafiq and Vlotman, 1992

*: Average hydraulic conductivity as determined in separate permeameter test with gravel material only.

5.3.3 Permeameter results

A total of 33 tests (11 different granular envelopes, with three replicates) have been performed to find the best potential envelope materials for the field. Sand, crushed rock with irregular and blocky structure, and river run materials, with rounded particles, were tested, as well as blends of the three source materials. Tables 4.2 give an overview of the tests and shows the key parameters for evaluating the performance. Figure 3.4 shows the gradation of the base soil used. Figure 4.11 give the range in which the granular envelope materials fall. Figure 4.11 also gives the FDP specified envelope gradation boundaries (FDP upper, FDP lower).

5.3.3.1 Non-blended envelope materials.

River run Attock material was evaluated in tests (G79 - G81, G94 - G96), and it performed well. It is an excellent natural available material, which can be used without blending and mixing. This material met the requirements of the SCS 1988 criteria except that the D_{15} size, about 0.5 mm that was smaller than the minimum of 0.6 mm. The Cu was > 7 and the Cc was approximately 0.9.

Lawrencepur sand by itself (G112-G114) did not bridge properly over the allowable maximum perforation size. The after test analysis (ATA) shows that 10% of fines from the envelope passed through the top plate (Figure 5.3), which could be due to the 12 % of fines in the sand itself. However, if the top plate perforation size was reduced to 0.5 mm (from its existing 3.2 mm) bridging took place and no noticeable passage of fines occurred. Manufacturing of such a small perforation is not practical. Also, K interface has shown a continuous reduction in the hydraulic conductivity, which shows soil particles movement into the sand. Therefore, it is not recommended to use Lawrencepur sand as an envelope. An alternative possibility would be to use fabric materials for retaining Lawrencepur sand or other sands to provide a good envelope; see section 5.2.3 on dual envelopes.

Similarly Qibla sand (G109 to G111) did not bridge the fine particles. ATA shows 6 to 15% of fines lost during the test (Figure 5.3). This sand is coarser than Lawrencepur sand in its coarser part, but more finer in the finer side. This could be the reason of more loss of fines as compared to Lawrencepur sand. However, this material can be used, if 10% fines are removed from it.

5.3.3.2 Blends of one material only.

Both crushed rock and river run materials were adjusted by removing or adding fractions to obtain gradation curves close to the lower and upper FDP gravel boundaries in Tests G88 to G93 and G97 to G102. Tests G88 to G90, G92 and G93, performed satisfactorily; the other tests performed unsatisfactorily.

Tests G88 to G90 were made with river run Attock material that was prepared to fall close to the lower FDP boundary (finer). The head loss through this sections was negligible. Therefore it was not possible to determine the hydraulic conductivity at this zone. K interface of soil-envelope has shown no clogging. No evidence of soil particles movement in this section was seen. Even though the thickness of soil was 2.5 cm and envelope thickness was 7.5 cm. It also remained stable during the surging process. D_{15} of this material was greater than 0.3 mm. Which is appropriate according to Vlotman et al. (1992).

In Tests G91 to G93 of river run FDP upper limit, Test G91 with a soil

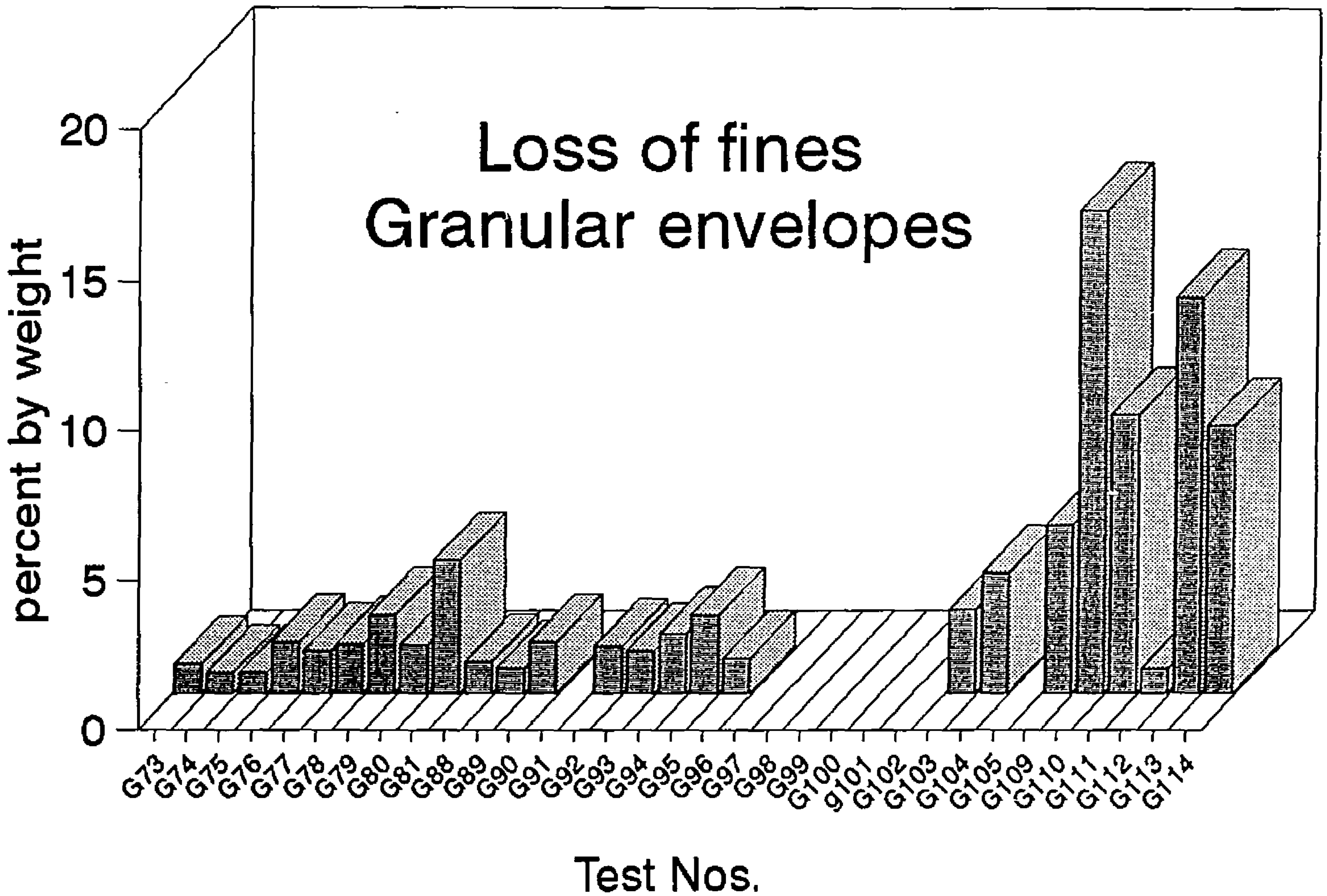


Figure 5.3 Loss of fines through the granular envelope materials

thickness of 2.5 cm failed immediately, soon after the pressure head started to raise. In the same test, new materials were refilled, but again failed. In Test G92 with a soil thickness of 5 cm, movement of fine soil particles can be seen at low pressure head in Figure 4.16. However, Test G93 with a soil thickness of 7.5 cm performed satisfactorily with no obvious particle movement. This indicates that by reducing the soil thickness in the permeameter, the working of the envelope for retaining soil particles may be more clearly evaluated.

None of the Tests G97 to G102 with soil thickness of 2.5 cm succeeded to prevent the soil from passing through the top plate. All these envelopes failed during the increasing pressure head process. Envelopes in the same gradations did not give clear indication of failures, when 10 cm of soil thickness were used in the permeameter (Shafiq and Vlotman, 1992). Also this crushed rock envelope did not work satisfactorily in the field.

Tests G73 to G75 were undertaken using the envelope material used at FDP, except that fines were added to allow 10% passing ASTM sieve number 50 (0.3 mm). Generally the tests performed well. No soil particles were washed through this material and no clogging was observed. The D_{15} of this material was greater than 0.3 mm.

5.3.3.3 Blends of crushed rock with sand

In tests G76 to G78 and G103 to G105, where crushed rock and Qibla Sand were blended in different proportions, no persistent particle movement was observed. The addition of sand with crushed rock has produced an envelope that successfully protected the drains from sediment inflow. The D_{15} size of this envelope mixture was approximately 0.4 mm, which is appropriate according to Shered et al. (1984).

5.3.4 Flows at different hydraulic gradients

Table 5.4 shows the average rate of flows at minimum and maximum hydraulic gradients. It is interesting to see that envelopes having more sand have given higher flow rates. One reason could be due to the flushing of fines from the envelope in tests G109 to G114 that improved it's hydraulic conductivity. Whereas in tests G103 to G105 no fines were lost, but the flow rates were also maximum at higher gradients.

5.4 Dual sand-fabric envelopes

Due to the wide range of conflict between theories, or opinions for the selection of the type of fabric to be used, three different fabrics have been selected i.e. thin, medium and thick. Opening size ranged between 84 to 400 µm. The main reason for using sand around the fabric is to reduce the risk of clogging of the envelope. The use of sand-fabric will enhance the performance of drainage systems as compared to the use of the fabric only. Beside increasing the flow area around the pipe, it will improve side support for the pipe and prevent damage due to soil lumps falling during blinding and backfilling. It will improve the filtration capability of the envelope and thus increase the life of the drainage system.

5.4.1 Permeameter results

The filtering performance of the fabric-sand envelope proved good, as no soil particles have been washed through the top plate in any of the tests. In order to have effective drainage the sand should not contain more than 5% soil finer than .05 mm, so that it has a relatively high permeability compared to the base soil material. Both the sands have shown much higher permeability values as compared to the soil. However, the average K of coarse

Table 5.4 Rate of flow of granular envelopes at minimum and maximum hydraulic gradients.

Materials	Test No.	Average Q cm^3/min		Hydraulic gradient range	
		Low head	High head	Min	Max
FDP + 10% fines	G73 G74 G75	3 2.4 2.7	23 19 22	0.4	9.0
Crushed rock +sand	G76 G77 G78	1.9 2 8.3	30 26 32	0.4	9.0
River run Attock Natural	G79 G80 G81	0.4 0.3 0.8	17 11.5 37	0.3	9.0
River run Lower FDP	G88 G89 G90	1 0.9 0.7	42 22.4 15	0.5 0.4 0.3	7.0 13.0 11.0
River run Upper FDP	G91 G92 G93	- 1.1 0.8	- 34.4 16.	- 0.3 0.3	 13.0 11.0
River run Attock Ntural	G94 G95 G96	5 23 1	70 79 37	0.5 0.5 0.4	15.0 16.0 16.0
Crushed Rock +Sand	G103 G104 G105	12 5.8 -	257 184 -	0.4	16.0
Qiblabandi Sand	G109 G110 G111	- 5.5 4.5	- 121 106	0.4	16.0
Lawrencepur Sand	G112 G113 G114	5 5.3 8.4	121 151 214	0.5	16.0

sand is more than double the average K of fine sand (Table 4.3). On the other hand, the primary functions of the geotextile are to keep the sand from entering the drain pipe and to increase the flow area and improve the flow mechanism. Therefore, it may not be so coarse that the fine sand particles become trapped in it and block the pores, and at the same time, it should not be so fine that has a very low permeability. It is interesting to see that the average discharge in all the tests is about 12 cm^3 per min (Table 4.3). Fabric and sand do not effect the flow mechanism. Since the same soil has been used in all these tests, it could be the soil type and structure that controls the discharge.

The thin TS-22 fabric (O_{90} 130 µm), attained equilibrium from the start of the test and showed no clogging trend, although the K sand-fabric was lower than the other two fabrics. The K sand-fabric of United and Texel fabric kept on decreasing until the end of the test. It might eventually reach the TS-22-K sand-fabric level.

Zeijts, (1992) has not recommended thin fabric for soils having d_{50} < 120 µm due to the envelope blocking. According to him, TS-22 is acceptable for fine sand having D50 > 120 µm. As reported by Rollin et al., (1987), field studies indicated that the thin fabric envelope materials installed in silty soils were successful in preventing soil from entering drain pipes while maintaining good drainage rates. They observed that no sediment clogging of the drainage systems occurred after a period of three years. Bonnell et al. (1992) found some of these drainage systems performing very well with no clogging of the fabric envelopes 9 years after installation. Field drainage rate peaks exceeded 10 mm/day. The United fabric having O_{90} of 350 µm behaved better than the other two fabrics with the coarser sand having D_{50} > 200 µm.

In studying the soil and sand properties, according to USBR for a uniform filter, the D_{50}/d_{50} ratio should be between 5 to 10. The fine Sutlej sand having 80% of grain size between 0.15 mm to 0.09 mm , meet the above criteria. Similarly SCS D_{15}/d_{85} for uniform sand should be less than 5, whereas it is 1.71, and hence meet the above criteria as well.

For graded sand, USBR filter criteria and SCS (1971) criteria recommend a D_{50}/d_{50} in a range between 12 to 58 for graded envelope. Since Sutlej course sand is graded and also meets the above criteria, it has performed better with the FES soil.

5.4.2 Results at different hydraulic gradients

A better picture of the three fabrics tested with coarse and fine Sutlej river sand is shown in Table 5.5 and Figure 5.4 and 5.5. These values are based on the average values at the minimum and maximum hydraulic gradients. In the case of higher gradients, in all the tests, the K soil-sand remained stable. Fig 5.4 and 5.5 shows higher conductivity values at low gradients and low conductivity values at higher gradients. Thus at higher gradients, drainage systems become more stable.

5.5 Influence of soil thicknesses in permeameter testing.

The main reason to carryout the tests with low soil thickness was to apply higher hydraulic gradients to provoke the movement of soil particles. In this way, a more clear picture of the envelope behaviour can be obtained. Tests using a 10 cm soil thickness does not give a clear picture of success/failure (Vlotman et al. 1992). Also, because of the limitations of the roof height, it was not possible to create a higher gradients. With the reduction in soil depths, it became possible to test envelopes at higher hydraulic gradients.

Table 5.5 Results of dual sand-fabric envelopes at minimum and maximum hydraulic gradient.

Sand	Fabric Envelope Material	Test No.	Av: Q cm^3/min	Average values (cm/day): K Soil- Sand	K Sand	K Sand-Fabric	Hydraulic gradient
Coarse Sand	United Karachi	GS-1	4	40	-	-	1
			44	24	1346	391	19
	Texel 909	GS-2	4	33	-	-	1
			55	14	1168	593	19
	Polyfelt TS-22	GS-3	4	31	-	-	1
			42	11	934	376	19
Fine Sand	United Karachi	GS-4	1	56	-	-	0.5
			21	14	478	369	18
	Texel 909	GS-5	2	50	39	-	0.5
			21	11	433	300	18
	Polyfelt TS-22	GS-6	1	77	-	-	0.5
			21	12	437	129	18

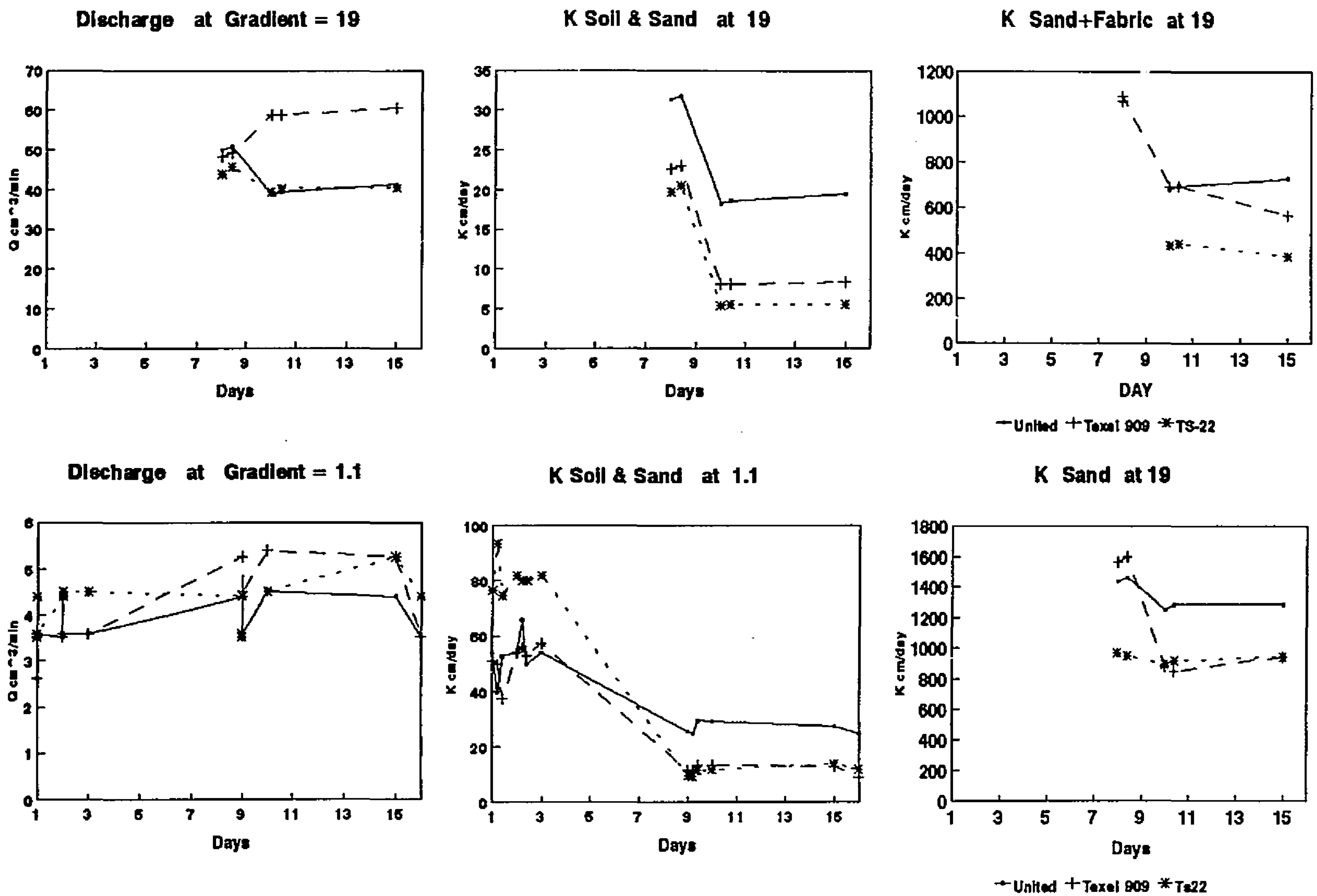


Figure 5.4 Flow rate VS time, K soil-sand VS time, K sand-fabric VS time and K sand VS time for the Test GS1, GS2 and GS3 at minimum and maximum gradient.

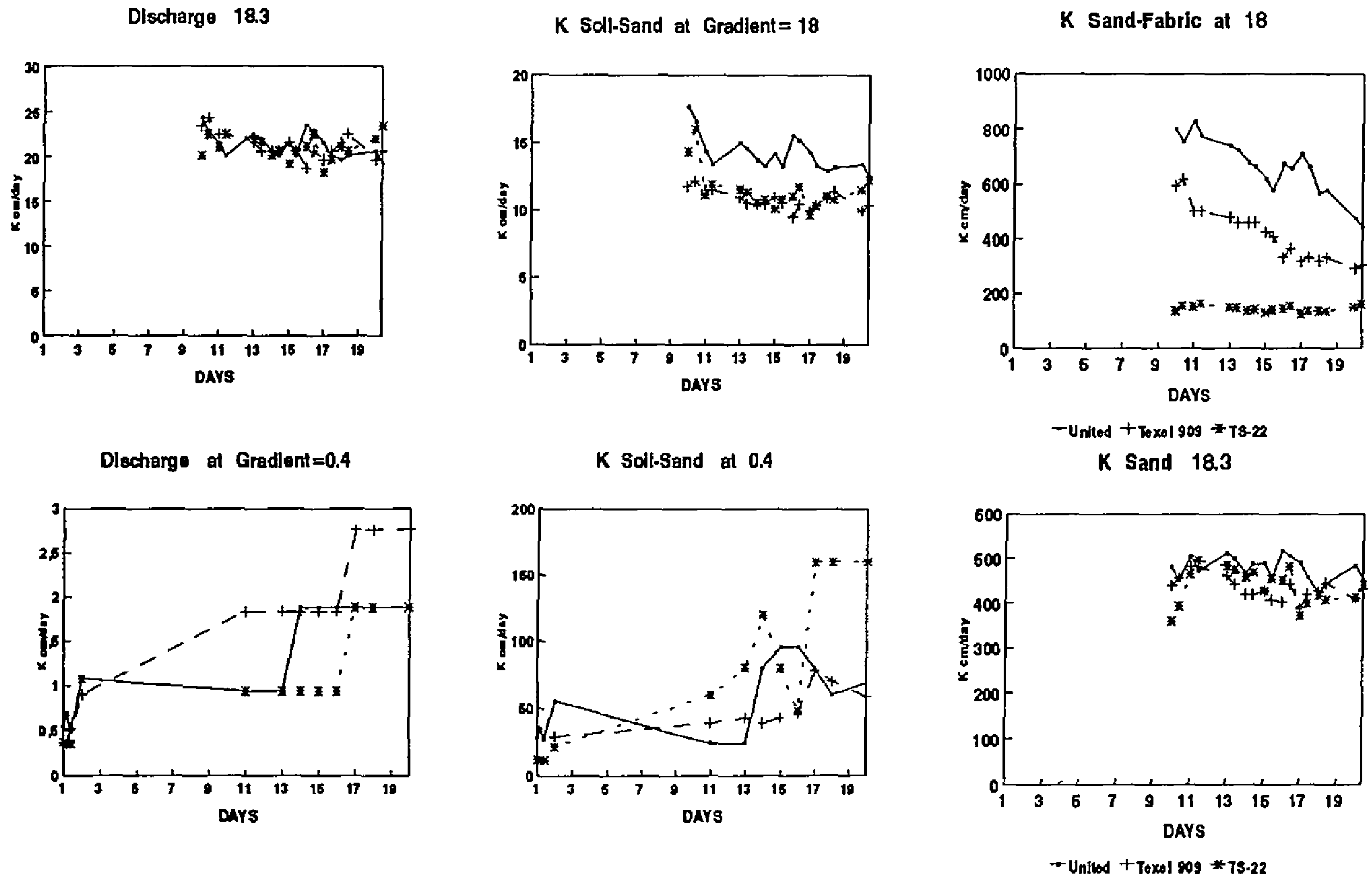


Figure 5.5 Flow rate VS time, K soil-sand VS time, K sand VS time and K sand-fabric VS time for Tests GS4, GS5 and GS6 at minimum and maximum gradient.

In the field, envelopes sometimes have to work under high hydraulic gradients; in cases such as a piping due to sink hole development, either by rain or irrigation, flow directly hits the envelope due to poor backfilling or in structureless soils. Such conditions should be checked under high hydraulic gradients. Other reasons of high hydraulic gradients are due to the power load shedding (as in Pakistani conditions), pumps can not run round the clock due to the lack of electricity. Under this situation, the head at the top of the drain becomes very high near the pumping units. When the pumps start working, then head starts to decrease quickly close to the pumping unit. To simulate this condition a surging method was introduced to evaluate envelopes performance, where pressure head is changed abruptly from minimum to maximum and from maximum to minimum.

In fabric envelopes, the rate of flow in tests with 2.5 cm soil thickness were significantly higher than with soil thicknesses of 5 and 7.5 cm. This could be explained by the piping along the sides of the plexiglass cylinder, because of the less resistance offered due to the thin soil column layer. Therefore it is not recommended to use 2.5 cm soil thickness. However, 5 cm soil thickness is recommended for further tests, because it has not shown any piping problems.

In granular envelopes a combination of 2.5 cm soil depth and 7.5 cm envelope thickness has shown more effective results as compared to other conditions. Tests performed with upper FDP curves using 2.5 cm soil thickness gave a clear picture of it's failure, whereas 5 cm to 10 cm soil thicknesses did not give any conclusive results. Some other combinations with the 2.5 cm soil thickness did not fail, even though piping took place at the soil sections, which shows good performance of this envelope. Hence for future tests of gravel envelopes, 2.5 cm soil thickness is recommended.

6. Conclusions

6.1 Synthetic fabrics

a) All the synthetic fabrics were successful in retaining the base soils except the Nayyer Carpet fabric when used with FES soil.

b) Most of the synthetic fabrics tested in the permeameter are fine except local United Carpet fabric. The synthetic envelope having O_{90} less than 100 µm such as local synthetic Olympia 3, Texel 909 and Texel 912 performed much better than any other fabrics with the sandy loam soils of FDP and DIK projects.

c) Local United Carpet with O_{90} > 340 µm, has shown no problem with FDP soils. However coarser fabrics are not suitable for the fine textured soils as Nayyer Carpet of O_{90} > 400 µm with the FES project silty loam soils did not retain the silt soils.

c) Results indicated that a soil thickness of 2.5 cm is not enough to prevent piping along plexiglass sides. In the same tests at the higher gradients air is sometimes entrapped in the flows and it effects the results. The air may have come out of the solution as the water pressure dropped passing through the permeameter.

d) Less time is required to check the equilibrium conditions (when there is no change in Q and K at the same gradients), when several surging cycles from low to high and back to low hydraulic gradients are used rather than a gradual increase of gradients over a period of weeks with steady state in between.

6.2 Granular envelopes

a) This study confirms the findings of Vlotman et al. (1992), that drain envelopes designed with USBR (1978) criteria are too coarse to retain fine sand and silty soils such as occur in many places that need subsurface drains in Pakistan. USBR specifications are suitable for envelopes which improve flow characteristics around the pipe but seem less suited for envelopes that are expected to function as filters as well.

b) River run material having rounded particles performed much better than crushed rock with angular shaped particles with the same particle size distribution as on paper. The finer crushed rock envelope used on FDP did not retain the soil particles whereas river run material of the same gradation retained the soil particles and provided satisfactory drainage.

c) Sand alone would not bridge over the perforations if the maximum perforation of 0.5 mm was allowed. River run material from the quarries near Attock performed very well and would fit most gravel bands derived from SCS 1988 criteria. The Attock gravel had very little material larger than 19 mm. The SCS (1988) and USBR (1978) criteria allow gravel up to 38 mm. Experience at FDP and Mardan in Pakistan shows that there are frequent problems of soil moving into or through the gravel pack, if gravel larger than 19 mm is allowed.

d) Blending of crushed rock with sand improved the performance when the percentage of sand was 20% - 40%. Sands from Qiblabandi, Lawrencepur, and one other local source were used. The maximum size allowed for this combination should not be greater than 9.5 mm.

e) Combination of 2.5 cm and 7.5 cm soil and envelope thickness in the permeameter yielded a conclusive results with granular envelopes.

6.3 Dual sand-fabric envelope

a) The permeability of coarse Sutlej river sand is about three times higher than the fine Sutlej river sand.

b) There was less evidence of air locking in the soil and sand in the permeameter when surging test method was used, than when long duration permeameter runs with gradual increases in head were used.

c) United Carpet with coarse sand and TS-22 with fine sand have shown very good flow rates and no clogging. These fabrics are recommended for the pilot field testing programme of FES project.

d) No sediment came through to the laboratory drain with any of the fabric-sand-soil combinations. Thus, the concept of using a fabric envelope plus run of the river sand as an envelope has a very high chance of successful field operation. There is no laboratory evidence to reject the functionality of this concept.

7. Recommendations

Based on the laboratory tests, the following are recommended for Pakistan:

7.1 Synthetic fabrics

a) A minimum of 5 cm for base soil thickness is recommended for further tests on the synthetic fabrics in permeameters.

b) Testing of synthetic envelopes should be continued with various soil types until an acceptable fabric material has been found which can be used for a wider range of soils.

c) Based on the laboratory testing the following synthetic materials were recommended for field testing at Fourth Drainage Project:

- Local Olympia sample No.3.
- Local United Carpets from Karachi.
- Texel 909, from Canada.
- Texel 912, from Canada.

d) For Fordwah Eastern Sadiqia drainage project the following materials are recommended to test in the laboratory:

- Texel 909, Canada.
- Texel 912, Canada.
- Local Synthetic Olympia 3.

7.2 Granular envelopes

a) To select the best potential gravel envelope material, a twenty one sieve analysis and hydraulic conductivity test of the gradations proposed should be performed;

b) Drain envelopes generally will need to function as a filter with typical Pakistani soils. SCS 1988 criteria, with modifications as suggested below, should be used to design gravel specifications based on the project base soils at drain depth;

- $D_{100} < 19$ mm (3/4") be used for river run materials.

- $D_{100} < 9$ mm (1/2") be used for crushed rock materials.

c) It was found that the criteria of SCS 1988 which specifies that D_{15} should not be less than 0.6 mm could be relaxed; tests with D_{15} of 0.3 mm performed equally well in the laboratory. $D_{15} > 0.3$ mm is suggested (No more than 15% passing ASTM sieve no. 50).

d) Thicknesses of 2.5 cm and 7.5 cm of soil and granular materials respectively are recommended to use for further laboratory permeameter testing.

7.3 Dual sand-fabric envelopes

a) It is recommended that United Carpet fabric be used with coarse Sutlej river sand and TS-22 fabric with fine river Sutlej sand be used as combination envelopes in the FES project.

b) It is recom nded that more laboratory and field tests with the above combinations be run.

c) It is recommended that air dry sand be used in field installations to have a continuous flow through the hopper on the drain pipe installations machines. The sand can be dug and piled to air dry weeks before needed.

d) The use of a power auger is highly recommended to get a uniform sand thickness around the fabric wrapped pipe.

e) A field trial of about 12 laterals should be installed with the fabric wrapped pipe at the bottom of the trench and sand placed in the trench on top and sides of the pipe to a depth of approximately 8 cm above the pipe as shown in the Figure 7.1.

g) TS-22 or similar fabrics are preferable because of their low cost and lesser weight.

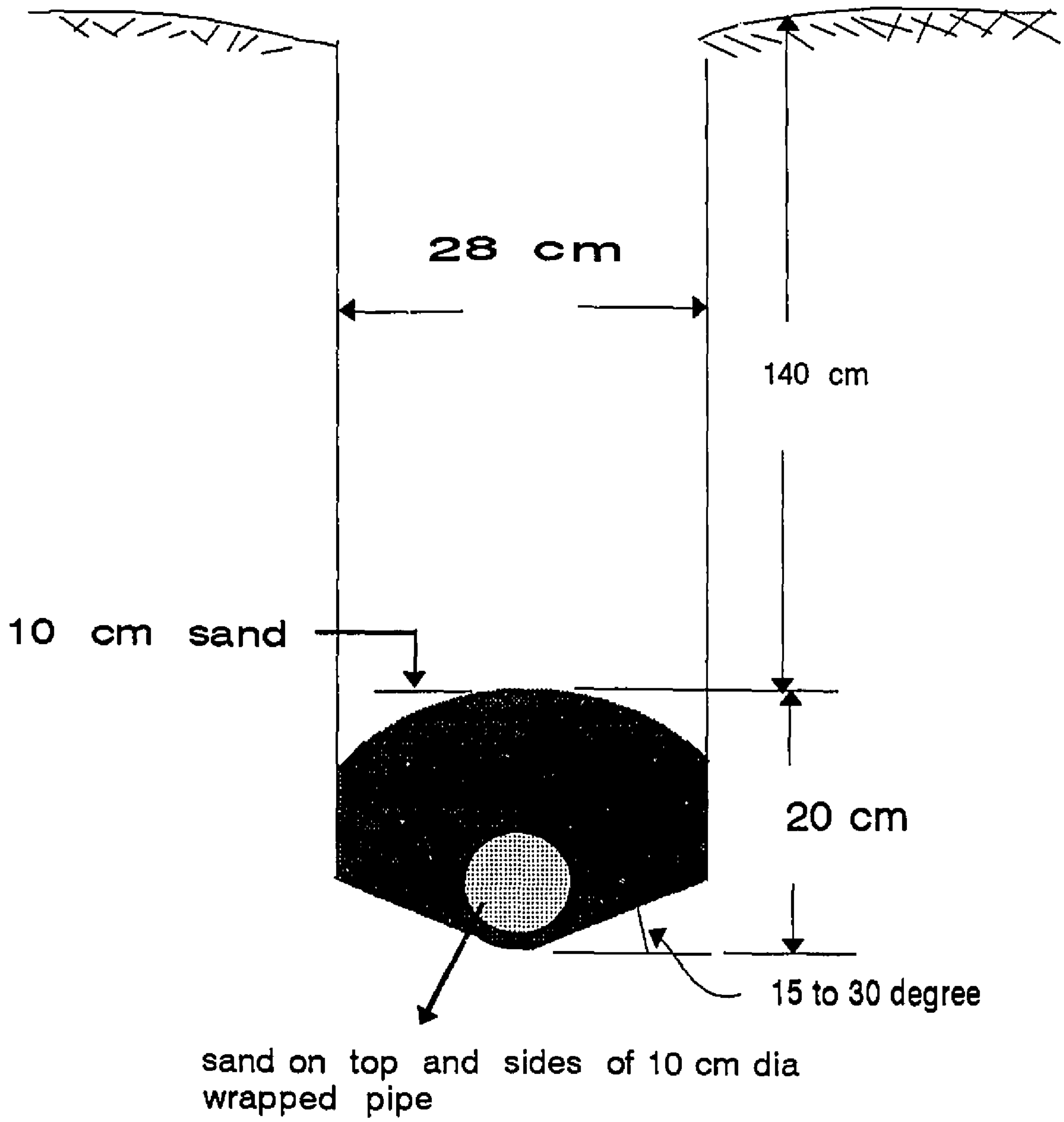


Figure 7.1 **Diagram of trench with V sand around drain pipe with fabric envelope medium or coarse sand.**

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DATE	TIME	TEMP °C	H7 Soil-column cm	H8 Envelope-column cm	H9 cm	H10 outlet cm	Time Vol. Sec	Meas. water cc	gradient i1-10	Q cm³/min	Average velocity cm/min	Ksoil H8-H9 cm/day	Ks&f H9-H10 cm/day

Test No. S 55 Permeameter No. 7
Soil thickness = 5 cm Soil wt.= 600.0 g Density = 1.53 g/cm³
Filter Specification: United Karachi
Soil Specification: D.I.Khan base soil

DATE	TIME	TEMP °C	H7	H8	H9	H10	Time Vol. Sec	Meas. water cc	gradient i1-10	Q cm³/min	Average velocity cm/min	Ksoil H8-H9 cm/day	Ks&f H9-H10 cm/day
04-Aug-93	09:30	26	20.70	20.70	10.50	10.40	60.00	5.00	2.0	4.39	0.06	32.19	
04-Aug-93	11:30	26	20.80	20.80	10.50	10.40	60.00	5.00	2.0	4.39	0.06	31.88	
04-Aug-93	13:30	27	20.80	20.80	10.50	10.40	60.00	5.00	2.0	4.30	0.05	31.19	
05-Aug-93	09:30	26	20.80	20.80	10.50	10.40	60.00	6.00	2.0	5.27	0.07	38.26	
05-Aug-93	11:30	26	30.90	30.90	12.40	10.40	60.00	8.00	4.0	7.02	0.09	28.40	
05-Aug-93	13:30	27	30.90	30.90	12.40	10.40	60.00	8.00	4.0	6.87	0.09	27.79	
07-Aug-93	09:30	26	30.80	30.80	12.40	10.40	60.00	9.00	4.0	7.90	0.10	32.12	
07-Aug-93	11:30	26	40.90	40.90	14.70	10.40	60.00	10.00	6.0	8.78	0.11	25.07	46.57
07-Aug-93	13:30	27	40.80	40.80	14.80	10.40	60.00	11.00	6.0	9.45	0.12	27.19	48.98
08-Aug-93	09:30	26	40.90	40.90	14.90	10.40	60.00	10.00	6.0	8.78	0.11	25.26	44.50
08-Aug-93	11:30	26	50.90	50.90	16.80	10.40	60.00	8.00	7.9	7.02	0.09	15.41	25.03
08-Aug-93	13:30	27	50.90	50.90	16.90	10.40	60.00	9.00	7.9	7.73	0.10	17.01	27.13
09-Aug-93	09:30	26	50.50	50.50	17.60	10.50	60.00	8.00	7.8	7.02	0.09	15.97	22.56
09-Aug-93	11:30	26	60.00	60.00	22.50	10.50	60.00	8.00	9.7	7.02	0.09	14.01	13.35
09-Aug-93	13:30	27	60.00	60.00	22.60	10.50	60.00	9.00	9.7	7.73	0.10	15.46	14.57
10-Aug-93	09:30	26	60.00	60.00	22.60	10.50	60.00	9.00	9.7	7.90	0.10	15.80	14.89
10-Aug-93	11:30	27	70.00	70.00	28.80	10.50	60.00	9.00	11.7	7.73	0.10	14.04	9.64
10-Aug-93	13:30	27	70.00	70.00	28.90	10.70	60.00	8.00	11.6	6.87	0.09	12.51	8.61
11-Aug-93	09:30	26	70.20	70.20	28.80	10.70	60.00	9.00	11.7	7.90	0.10	14.28	9.96
11-Aug-93	11:30	27	80.00	80.00	31.70	10.70	60.00	10.00	13.6	8.59	0.11	13.30	9.33
11-Aug-93	13:30	27	80.00	80.00	31.80	10.80	60.00	11.00	13.6	9.45	0.12	14.67	10.26
12-Aug-93	09:30	26	80.00	80.00	31.90	10.90	60.00	10.00	13.5	8.78	0.11	13.65	9.53
12-Aug-93	11:30	27	90.00	90.00	36.20	10.70	60.00	11.00	15.5	9.45	0.12	13.14	8.45
12-Aug-93	13:30	27	90.00	90.00	36.20	10.70	60.00	12.00	15.5	10.31	0.13	14.33	9.22
14-Aug-93	09:30	26	90.00	90.00	36.30	10.70	60.00	11.00	15.5	9.66	0.12	13.45	8.60
15-Aug-93	09:30	26	90.20	90.20	36.50	10.70	60.00	12.00	15.6	10.54	0.13	14.68	9.31
15-Aug-93	11:30	27	100.00	100.00	40.90	10.60	60.00	12.00	17.5	10.31	0.13	13.05	7.76
15-Aug-93	01:30	27	100.00	100.00	40.90	10.60	60.00	12.00	17.5	10.31	0.13	13.05	7.76
16-Aug-93	09:30	26	100.20	100.20	40.80	10.60	60.00	13.00	17.6	11.41	0.14	14.37	8.62
16-Aug-93	11:30	27	109.80	109.80	42.90	10.60	60.00	14.00	19.5	12.03	0.15	13.45	8.49
16-Aug-93	01:30	27	109.80	109.80	42.90	10.60	60.00	13.00	19.5	11.17	0.14	12.49	7.89
17-Aug-93	09:30	26	109.90	109.90	42.90	10.60	60.00	13.00	19.5	11.41	0.14	12.74	8.06
17-Aug-93	11:30	26	119.70	119.70	41.00	10.60	60.00	13.00	21.4	11.41	0.14	10.85	8.56
17-Aug-93	01:30	27	119.80	119.80	41.20	10.60	60.00	14.00	21.4	12.03	0.15	11.45	8.96
18-Aug-93	09:30	26	119.70	119.70	41.20	10.60	60.00	13.00	21.4	11.41	0.14	10.88	8.51
18-Aug-93	11:30	27	130.00	130.00	48.80	10.60	60.00	17.00	23.4	14.60	0.19	13.45	8.72
18-Aug-93	01:30	28	130.00	130.00	48.90	10.60	60.00	18.00	23.4	15.14	0.19	13.96	9.01
19-Aug-93	09:30	26	130.20	130.20	48.90	10.60	60.00	17.00	23.5	14.93	0.19	13.73	8.89
19-Aug-93	11:30	27	140.00	140.00	19.50	10.60	60.00	17.00	25.4	14.60	0.19	9.07	37.42
19-Aug-93	01:30	28	140.00	140.00	19.50	10.60	60.00	17.00	25.4	14.30	0.18	8.87	36.63
21-Aug-93	09:30	26	140.20	140.20	19.50	10.60	60.00	16.00	25.4	14.05	0.18	8.71	36.00
21-Aug-93	11:30	26	151.30	151.30	24.80	10.60	60.00	20.00	27.6	17.56	0.22	10.38	28.20
21-Aug-93	01:30	28	151.30	151.30	24.90	10.70	60.00	21.00	27.6	17.66	0.22	10.45	28.36
22-Aug-93	09:30	26	151.40	151.40	24.90	10.70	60.00	22.00	27.6	19.32	0.24	11.42	31.02
22-Aug-93	11:30	27	160.40	160.40	34.40	10.70	60.00	23.00	29.4	19.76	0.25	11.73	19.01
22-Aug-93	01:30	28	160.50	160.50	34.60	10.80	60.00	24.00	29.4	20.18	0.26	11.99	19.34
23-Aug-93	09:30	26	160.20	160.20	43.70	10.50	60.00	24.00	29.4	21.07	0.27	13.53	14.47
									Average	10.757	0.136	16.610	17.555

Test No. S 56 Permeameter No. 8
Soil thickness = 7.5 cm Soil wt. = 940.0 g Density = 1.60 g/cm³
Filter Specification: United Karachi
Soil Specification: D.I.Khan base soil

DATE	TIME	TEMP °C	H7 Soil-column cm	H8 Envelope-column cm	H9 cm	H10 outlet cm	Time Vol. Sec	Meas. water cc	gradient i1-10	Q cm³/min	Average velocity cm/min	Ksoil H8-H9 cm/day	Ks&f H9-H10 cm/day
04-Aug-93	09:30	26	19.8	17.9	10.0	9.9	60	5	1.6	4.39	0.06	41.57	
04-Aug-93	11:30	26	20.0	18.0	10.0	9.9	60	4	1.6	3.51	0.04	32.84	
04-Aug-93	13:30	27	20.0	18.0	10.0	9.9	60	4	1.6	3.44	0.04	32.13	
05-Aug-93	09:30	26	20.0	18.0	10.2	10.0	60	5	1.6	4.39	0.06	42.10	
05-Aug-93	11:30	26	29.4	26.3	11.8	10.0	60	6	3.2	5.27	0.07	27.18	
05-Aug-93	13:30	27	29.5	26.3	11.8	10.0	60	6	3.2	5.15	0.07	26.59	
07-Aug-93	09:30	26	29.5	26.3	11.7	10.0	60	7	3.2	6.15	0.08	31.49	
07-Aug-93	11:30	26	38.2	33.4	13.0	10.0	60	6	4.6	5.27	0.07	19.32	40.05
07-Aug-93	13:30	27	38.3	33.5	13.0	10.0	60	5	4.6	4.30	0.05	15.67	32.65
08-Aug-93	09:30	26	38.4	33.6	13.2	10.0	60	7	4.6	6.15	0.08	22.54	43.80
08-Aug-93	11:30	26	47.3	40.7	13.4	10.0	60	7	6.0	6.15	0.08	16.84	41.22
08-Aug-93	13:30	27	47.4	40.7	13.5	10.0	60	6	6.0	5.15	0.07	14.17	33.59
09-Aug-93	09:30	26	42.2	41.3	14.0	10.0	60	7	6.1	6.15	0.08	16.84	35.04
09-Aug-93	11:30	26	55.7	48.9	15.3	10.2	60	7	7.6	6.15	0.08	13.68	27.48
09-Aug-93	13:30	27	55.8	48.8	15.4	10.2	60	8	7.6	6.87	0.09	15.39	30.14
10-Aug-93	09:30	26	55.8	48.8	15.5	10.2	60	9	7.6	7.90	0.10	17.75	34.00
10-Aug-93	11:30	27	67.0	60.3	17.9	10.2	60	8	9.8	6.87	0.09	12.12	20.35
10-Aug-93	13:30	27	67.2	60.4	17.8	10.2	60	8	9.8	6.87	0.09	12.07	20.62
11-Aug-93	09:30	26	67.3	60.5	17.9	10.2	60	9	9.9	7.90	0.10	13.88	23.40
11-Aug-93	11:30	27	77.4	72.4	20.5	10.4	60	9	12.2	7.73	0.10	11.14	17.46
11-Aug-93	13:30	27	77.5	72.5	20.5	10.4	60	10	12.2	8.59	0.11	12.36	19.40
12-Aug-93	09:30	26	77.6	72.7	20.5	10.4	60	9	12.2	7.90	0.10	11.32	17.84
12-Aug-93	11:30	27	87.2	81.8	20.7	10.5	60	10	14.0	8.59	0.11	10.52	19.21
12-Aug-93	13:30	27	87.2	81.8	20.7	10.5	60	9	14.0	7.73	0.10	9.47	17.29
14-Aug-93	09:30	26	87.3	81.9	20.7	10.5	60	10	14.0	8.78	0.11	10.73	19.63
15-Aug-93	09:30	26	87.4	81.8	20.7	10.5	60	11	14.0	9.66	0.12	11.82	21.59
15-Aug-93	11:30	27	98.0	94.0	20.9	10.5	60	11	16.4	9.45	0.12	9.67	20.72
15-Aug-93	01:30	27	98.2	94.0	20.9	10.5	60	12	16.4	10.31	0.13	10.55	22.61
16-Aug-93	09:30	26	98.2	94.0	20.9	10.5	60	12	16.4	10.54	0.13	10.78	23.10
16-Aug-93	11:30	27	107.0	105.9	25.0	10.5	60	11	18.7	9.45	0.12	8.74	14.86
16-Aug-93	01:30	27	107.2	105.9	25.0	10.5	60	12	18.7	10.31	0.13	9.53	16.21
17-Aug-93	09:30	26	107.2	105.9	25.0	10.5	60	13	18.7	11.41	0.14	10.55	17.95
17-Aug-93	11:30	26	116.4	110.5	25.3	10.5	60	12	19.6	10.54	0.13	9.25	16.24
17-Aug-93	01:30	27	116.7	110.6	25.4	10.5	60	12	19.6	10.31	0.13	9.05	15.78
18-Aug-93	09:30	26	116.5	110.7	25.5	10.5	60	13	19.6	11.41	0.14	10.02	17.35
18-Aug-93	11:30	27	126.9	123.0	25.7	10.5	60	14	22.1	12.03	0.15	9.25	18.04
18-Aug-93	01:30	28	126.8	123.0	25.8	10.5	60	14	22.1	11.77	0.15	9.06	17.55
19-Aug-93	09:30	26	126.8	123.0	17.5	10.5	60	15	22.1	13.17	0.17	9.34	42.91
19-Aug-93	11:30	27	136.4	131.9	17.7	10.5	60	16	23.8	13.75	0.17	9.00	43.54
19-Aug-93	01:30	28	136.5	131.8	17.8	10.5	60	15	23.8	12.62	0.16	8.28	39.41
21-Aug-93	09:30	26	136.5	131.9	17.9	10.5	60	16	23.8	14.05	0.18	9.22	43.29
21-Aug-93	11:30	26	146.9	137.9	54.4	10.5	60	17	25.0	14.93	0.19	13.37	7.75
21-Aug-93	01:30	28	146.8	137.8	54.5	10.5	60	18	25.0	15.14	0.19	13.59	7.85
22-Aug-93	09:30	26	146.7	137.9	54.6	10.5	60	19	25.0	16.68	0.21	14.98	8.63
22-Aug-93	11:30	27	155.5	146.0	59.8	10.5	60	25	26.6	21.48	0.27	18.64	9.93
22-Aug-93	01:30	28	155.6	146.2	59.9	10.5	60	26	26.6	21.87	0.28	18.95	10.09
23-Aug-93	09:30	26	154.5	146.5	70.0	10.5	60	27	26.7	23.71	0.30	23.18	9.09
									Average	9.616	0.122	15.884	23.442

DATE	TIME	TEMP °C	H7 Soil-column cm	H8 Envelope-column cm	H9 cm	H10 outlet cm	Time Vol. Sec	Meas. water cc	gradient i1-10	Q cm^3/min	Average velocity cm/min	Ksoil H8-H9 cm/day	Ks&f H9-H10 cm/day

Test No. S 57 Permeameter No. 9
Soil thickness = 10 cm Soil wt. = 1230.0 g Density 1.57 g/cm^3
Filter Specification: United Karachi
Soil Specification: D.I.Khan base soil

DATE	TIME	TEMP °C	H7 cm	H8 cm	H9 cm	H10 cm	Time Vol. Sec	Meas. water cc	gradient i1-10	Q cm^3/min	Average velocity cm/min	Ksoil H8-H9 cm/day	Ks&f H9-H10 cm/day
04-Aug-93	09:30	26	15.0	14.2	9.8	9.8	60	3	0.9	2.63	0.03	44.78	
04-Aug-93	11:30	26	15.0	14.2	9.9	9.9	60	3	0.8	2.63	0.03	45.82	
04-Aug-93	13:30	27	15.0	14.2	9.9	9.9	60	3	0.8	2.58	0.03	44.83	
05-Aug-93	09:30	26	15.2	14.4	9.9	9.9	60	4	0.9	3.51	0.04	58.38	
05-Aug-93	11:30	26	21.8	19.4	10.2	10.0	60	5	1.8	4.39	0.06	35.69	
05-Aug-93	13:30	27	21.8	19.5	10.3	10.0	60	5	1.9	4.30	0.05	34.92	
07-Aug-93	09:30	26	21.9	19.6	10.4	10.0	60	6	1.9	5.27	0.07	42.83	
07-Aug-93	11:30	26	28.0	24.5	10.5	9.9	60	5	2.9	4.39	0.06	23.46	
07-Aug-93	13:30	27	28.2	24.6	10.5	9.9	60	6	2.9	5.15	0.07	27.34	
08-Aug-93	09:30	26	28.2	24.7	10.5	9.9	60	5	2.9	4.39	0.06	23.13	
08-Aug-93	11:30	26	34.3	29.5	10.7	10.0	60	6	3.8	5.27	0.07	20.96	
08-Aug-93	13:30	27	34.3	29.5	10.7	10.0	60	5	3.8	4.30	0.05	17.09	
09-Aug-93	09:30	26	35.5	30.7	10.9	10.0	60	6	4.1	5.27	0.07	19.90	
09-Aug-93	11:30	26	42.3	36.4	11.6	10.0	60	6	5.2	5.27	0.07	15.89	
09-Aug-93	13:30	27	42.3	36.5	11.6	10.0	60	7	5.2	6.01	0.08	18.06	
10-Aug-93	09:30	26	42.4	36.5	11.6	10.0	60	8	5.2	7.02	0.09	21.10	
10-Aug-93	11:30	27	51.5	44.0	19.7	10.0	60	6	6.7	5.15	0.07	15.87	12.12
10-Aug-93	13:30	27	51.6	44.0	19.8	10.0	60	7	6.7	6.01	0.08	18.59	13.99
11-Aug-93	09:30	26	51.7	44.2	19.9	10.0	60	8	6.7	7.02	0.09	21.62	16.18
11-Aug-93	11:30	27	59.5	51.3	20.8	10.0	60	7	8.1	6.01	0.08	14.75	12.70
11-Aug-93	13:30	27	59.6	51.4	20.8	10.0	60	8	8.1	6.87	0.09	16.80	14.51
12-Aug-93	09:30	26	59.7	51.5	20.9	10.0	60	9	8.1	7.90	0.10	19.32	16.53
12-Aug-93	11:30	27	67.3	57.0	12.2	10.0	60	8	9.2	6.87	0.09	11.47	
12-Aug-93	13:30	27	67.4	57.2	12.2	10.0	60	9	9.3	7.73	0.10	12.85	
14-Aug-93	09:30	26	67.5	57.2	12.3	10.0	60	8	9.3	7.02	0.09	11.70	
15-Aug-93	09:30	26	67.7	57.3	12.2	10.0	60	9	9.3	7.90	0.10	13.11	
15-Aug-93	11:30	27	75.2	63.7	12.5	10.2	60	8	10.5	6.87	0.09	10.04	
15-Aug-93	13:30	27	75.2	63.7	12.6	10.2	60	8	10.5	6.87	0.09	10.06	
16-Aug-93	09:30	26	75.2	63.7	12.5	10.2	60	9	10.5	7.90	0.10	11.54	
16-Aug-93	11:30	27	86.0	71.9	12.5	10.2	60	10	12.1	8.59	0.11	10.82	
16-Aug-93	13:30	27	86.2	71.8	12.5	10.2	60	11	12.1	9.45	0.12	11.92	
17-Aug-93	09:30	26	86.2	71.7	12.5	10.2	60	10	12.1	8.78	0.11	11.09	
17-Aug-93	11:30	26	92.3	74.2	12.8	10.2	60	9	12.5	7.90	0.10	9.63	
17-Aug-93	13:30	27	92.4	74.3	12.9	10.2	60	8	12.6	6.87	0.09	8.37	
18-Aug-93	09:30	26	92.5	74.3	12.8	10.2	60	9	12.6	7.90	0.10	9.61	
18-Aug-93	11:30	27	102.0	82.5	12.9	10.2	60	8	14.2	6.87	0.09	7.39	
18-Aug-93	13:30	28	102.2	82.6	12.8	10.2	60	9	14.2	7.57	0.10	8.11	
19-Aug-93	09:30	26	102.2	82.7	12.9	10.2	60	9	14.2	7.90	0.10	8.47	
19-Aug-93	11:30	27	109.9	84.5	12.9	10.2	60	8	14.6	6.87	0.09	7.18	
19-Aug-93	13:30	28	109.8	84.6	12.8	10.2	60	9	14.6	7.57	0.10	7.89	
21-Aug-93	09:30	26	109.7	84.5	12.7	10.2	60	8	14.6	7.02	0.09	7.32	
21-Aug-93	11:30	26	122.2	96.0	13.4	10.2	60	9	16.8	7.90	0.10	7.16	56.32
21-Aug-93	13:30	28	122.3	96.2	13.5	10.2	60	8	16.9	6.73	0.09	6.09	46.49
22-Aug-93	09:30	26	122.3	96.3	13.5	10.2	60	10	16.9	8.78	0.11	7.93	60.68
22-Aug-93	11:30	27	131.4	101.0	14.5	10.2	60	10	17.8	8.59	0.11	7.43	45.56
22-Aug-93	13:30	28	131.7	101.2	14.5	10.2	60	11	17.8	9.25	0.12	7.98	49.06
23-Aug-93	09:30	26	137.5	104.5	14.5	10.2	60	12	18.5	10.54	0.13	8.76	55.88
									Average	6.546	0.083	17.767	33.336

DATE	TIME	TEMP	H5	H6	H7	H8	H9	H10	Time	Meas.	gradient	Q	Average	K s&f	Kf	Kfilter
			Soil Column		Envelope column			outlet		Vol.water			velocity	H6-H7	H7-H8	H7-H9
		°C	cm	cm	cm	cm	cm	cm	Sec	cc	i1-10	cm^3/min	cm/min	-------	cm/day	------

TEST NO G-112 Permeameter No.7

SOIL thickness = 2.5 cm SOIL weight = 300 g Density = 1.21 g/cm^3

GRAV thickness = 7.5 cm GRAV weight = 870 g Density = 1.61 g/cm^3

FILTER SPECIFICATION = Lawrencepur sand

SOIL SPECIFICATIONS = FDP Drainage IV Bag No 2

31/03/93	9:30	21	6.4	6.3	2.3	2.1	1.9	1.8	60	5	0.5	4.9	0.062	85		
31/03/93	11:30	22	160.8	160.8	29.0	25.0	8.8	1.4	60	252	15.9	242.6	3.073	128	1548.8	1204.9
31/03/93	13:30	23	160.9	160.9	29.2	25.0	8.7	1.4	60	255	16.0	239.7	3.037	126	1457.8	1173.4
01/04/93	9:30	22	6.2	6.2	1.5	1.4	1.0	0.7	60	10	0.6	9.6	0.122	142		1931.6
01/04/93	11:30	22	163.9	163.9	25.4	23.4	9.9	1.4	60	224	16.3	215.6	2.732	108	2753.4	1395.7
01/04/93	13:30	23	163.8	163.8	25.5	23.5	9.9	1.4	60	225	16.2	211.5	2.680	106	2701.2	1360.5
03/04/93	9:30	22	6.3	6.2	2.2	2.1	1.9	1.8	60	4	0.5	3.9	0.049	67		
03/04/93	13:30	22	164.0	164.0	25.8	23.2	9.8	1.4	60	226	16.3	217.5	2.756	109	2136.9	1364.2
04/04/93	9:30	22	6.9	6.9	1.1	1.0	0.9	0.7	300	31	0.6	6.0	0.076	71		
04/04/93	11:30	22	164.8	164.8	8.3	7.6	5.2	1.3	300	152	16.4	29.3	0.371	13	1067.6	947.1
05/04/93	9:30	23	4.9	4.9	1.0	0.9	0.8	0.7	300	35	0.4	6.6	0.083	117		
05/04/93	11:30	23	162.7	162.7	6.5	6.3	4.3	1.3	60	129	16.1	121.3	1.536	54		5531.1
05/04/93	13:30	24	162.8	162.8	6.6	6.3	4.3	1.3	60	114	16.2	104.7	1.327	46		4568.2
06/04/93	9:30	23	6.8	6.8	1.1	1.0	0.9	0.8	300	30	0.6	5.6	0.071	69		
06/04/93	11:30	23	162.2	162.0	6.5	5.9	4.2	1.3	60	124	16.1	116.6	1.477	52	4962.3	5085.6
06/04/93	13:30	24	162.2	162.0	6.5	5.9	4.2	1.3	60	125	16.1	114.8	1.455	51	4887.6	5009.0
07/04/93	9:30	23	5.9	5.9	1.0	1.0	0.9	0.7	300	23	0.5	4.3	0.055	61		
07/04/93	11:30	23	162.2	162.2	6.5	6.0	4.3	1.3	60	123	16.1	115.6	1.465	51	5906.7	5273.9
07/04/93	13:30	24	162.2	162.2	6.5	6.0	4.3	1.3	60	125	16.1	114.8	1.455	51	5865.1	5236.7
08/04/93	9:30	23	5.5	5.5	0.9	0.9	0.9	0.7	300	21	0.5	3.9	0.050	60		
08/04/93	11:30	23	162.0	162.0	6.5	6.0	4.3	1.3	60	123	16.1	115.6	1.465	52	5906.7	5273.9
08/04/93	13:30	24	162.0	162.0	6.4	5.9	4.2	1.3	60	124	16.1	113.9	1.443	51	5818.2	5194.8
10/04/93	9:30	23	5.8	5.8	0.8	0.8	0.8	0.5	300	15	0.5	2.8	0.036	39		
10/04/93	11:30	23	161.3	161.3	5.7	5.2	3.2	1.3	60	18	16.0	16.9	0.214	8	864.4	679.2
10/04/93	13:30	24	161.3	161.3	5.8	5.2	3.2	1.3	60	71	16.0	65.2	0.826	29	2776.2	2516.9
11/04/93	9:30	23	5.9	5.9	0.9	0.9	0.9	0.5	30	6	0.5	11.3	0.143	156		
11/04/93	11:30	23	161.2	161.2	5.9	1.4	3.3	1.3	60	72	16.0	67.7	0.858	30	384.2	2612.2
11/04/93	13:30	24	161.2	161.2	5.9	1.4	3.3	1.3	60	74	16.0	68.0	0.861	30	385.8	2623.2
12/04/93	9:30	24	6.3	6.3	1.3	1.2	1.0	0.9	60	5	0.5	4.6	0.058	64		
12/04/93	11:30	24	162.2	162.2	6.5	5.9	3.7	1.3	60	81	16.1	74.4	0.943	33	3167.2	2666.2
12/04/93	13:30	25	162.3	162.2	6.5	5.9	3.7	1.3	60	83	16.1	74.5	0.944	33	3172.3	2670.6
13/04/93	9:30	24	5.9	5.9	1.4	1.4	1.3	1.0	60	5	0.5	4.6	0.058	71		
13/04/93	11:30	24	162.0	162.0	6.5	5.5	3.5	1.4	30	48	16.1	88.2	1.117	39	2252.2	2949.3
13/04/93	13:30	25	162.0	162.0	6.5	5.5	3.5	1.4	30	49	16.1	88.0	1.115	39	2247.4	2943.0
14/04/93	9:30	24	6.4	6.4	1.3	1.3	1.2	1.0	60	4	0.5	3.7	0.047	50		
14/04/93	11:30	25	162.2	162.2	6.7	5.6	3.7	1.4	60	92	16.1	82.6	1.047	37	1918.0	2762.8
										Average		76.97	0.98	65	2961	3041

TEST NO G-113 Cylindeer 8

SOIL thickness = 2.54 cm SOIL weight = 300 g Density 1.21 g/cm³

GRAV thickness = 7.5 cm GRAV weight = 907 g Density 1.61 g/cm³

FILTER SPECIFICATION = Lawrencepur sand

SOIL SPECIFICATIONS = FDP Drainage IV Bag No 2

DATE	TIME	TEMP °C	H5 Soil Column cm	H6 cm	H7 Envelope column cm	H8 cm	H9 cm	H10 outlet cm	Time Sec	Meas. Vol.water cc	gradient i1-10	Q cm^3/min	Average velocity cm/min	K s&f H6-H7 -------	Kf H7-H8 cm/day	Kfilter H7-H9 ------
31/03/93	9:30	21	6.0	5.5	1.9	1.8	1.5	1.4	60	7	0.5	6.9	0.087	133		
31/03/93	11:30	22	158.5	158.5	24.0	20.2	10.0	2.3	60	280	15.6	269.5	3.414	139	1811.4	1931.6
31/03/93	13:30	23	158.5	158.5	24.2	20.2	10.0	2.3	60	281	15.6	264.2	3.347	136	1686.8	1866.7
01/04/93	9:30	22	5.9	5.9	1.9	1.9	1.5	1.3	60	9	0.5	8.7	0.110	150		
01/04/93	11:30	22	161.4	161.4	24.7	21.8	13.2	2.0	60	250	15.9	240.6	3.049	122	2119.3	2099.5
01/04/93	13:30	23	161.5	161.5	24.7	21.9	13.3	2.0	60	252	16.0	236.9	3.001	120	2161.0	2085.2
03/04/93	9:30	22	5.9	5.3	1.9	1.8	1.5	1.4	60	6	0.5	5.8	0.073	118		
03/04/93	13:30	22	162.4	162.4	24.5	21.8	13.4	2.0	60	255	16.0	245.4	3.110	123	2321.8	2218.7
04/04/93	9:30	22	6.5	6.5	1.6	1.5	1.4	1.3	300	31	0.5	6.0	0.076	84		
04/04/93	11:30	22	163.5	163.5	9.8	9.4	7.8	2.0	60	174	16.2	167.5	2.122	76		8402.4
05/04/93	9:30	23	4.8	4.8	1.5	1.4	1.4	1.3	300	40	0.4	7.5	0.095	158		
05/04/93	11:30	23	161.5	161.5	8.5	8.3	6.8	1.9	60	152	16.0	142.9	1.810	65		8434.1
05/04/93	13:30	24	161.5	161.5	8.5	8.2	6.7	1.9	60	137	16.0	125.8	1.594	57		7014.9
06/04/93	9:30	23	6.4	6.4	1.6	1.5	1.4	1.3	300	31	0.5	5.8	0.074	84		
06/04/93	11:30	23	160.4	160.4	7.7	6.9	5.5	1.9	60	150	15.9	141.0	1.787	64	4502.1	6431.5
06/04/93	13:30	24	160.4	160.4	7.7	6.8	5.5	1.9	60	152	15.9	139.6	1.769	63	3962.2	6367.9
07/04/93	9:30	23	5.8	5.8	1.7	1.6	1.5	1.4	300	23	0.4	4.3	0.055	73		
07/04/93	11:30	23	160.4	160.4	8.3	7.7	6.0	1.9	60	148	15.9	139.1	1.763	63	5922.7	6069.9
07/04/93	13:30	24	160.5	160.5	8.3	7.7	6.0	1.9	60	149	15.9	136.9	1.734	62	5826.0	5970.8
08/04/93	9:30	23	5.4	5.4	1.5	1.5	1.5	1.4	300	23	0.4	4.3	0.055	77		
08/04/93	11:30	23	160.5	160.5	8.2	7.5	6.0	1.9	60	159	15.9	149.5	1.894	68	5453.9	6817.4
08/04/93	13:30	24	160.5	160.5	8.3	7.5	6.0	1.9	60	162	15.9	148.8	1.885	68	4750.8	6491.7
10/04/93	9:30	23	5.5	5.5	1.5	1.5	1.5	1.4	300	17	0.4	3.2	0.040	55		
10/04/93	11:30	23	159.8	159.8	8.2	8.0	6.0	1.8	60	110	15.8	103.4	1.310	47		4716.5
10/04/93	13:30	24	159.8	159.8	8.2	8.0	6.0	1.8	60	112	15.8	102.9	1.303	47		4692.1
11/04/93	9:30	23	5.5	5.5	1.5	1.5	1.5	1.4	300	19	0.4	3.6	0.045	62		
11/04/93	11:30	23	159.4	159.4	8.8	7.9	5.8	1.9	60	107	15.8	100.6	1.274	46	2854.6	3364.4
11/04/93	13:30	24	159.4	159.4	8.8	7.9	5.8	1.9	60	109	15.8	100.1	1.268	46	2841.3	3348.7
12/04/93	9:30	24	6.3	6.3	1.8	1.8	1.6	1.4	60	6	0.5	5.5	0.070	85		
12/04/93	11:30	24	161.0	161.0	10.3	9.2	6.4	1.8	60	127	15.9	116.7	1.478	54	2708.6	3001.3
12/04/93	13:30	25	161.0	161.0	10.4	9.2	6.4	1.8	60	129	15.9	115.8	1.467	53	2465.2	2905.4
13/04/93	9:30	24	5.7	5.7	1.8	1.8	1.5	1.4	60	5	0.4	4.6	0.058	82		
13/04/93	11:30	24	161.0	161.0	9.7	8.9	6.2	2.0	30	57	15.9	104.7	1.327	48	3343.1	3002.0
13/04/93	13:30	25	161.0	161.0	9.6	8.8	6.2	2.0	30	58	15.9	104.2	1.320	48	3325.2	3073.7
14/04/93	9:30	24	6.3	6.3	1.7	1.7	1.5	1.4	60	5	0.5	4.6	0.058	69		
14/04/93	11:30	25	161.0	161.0	9.8	8.9	6.4	2.0	60	113	15.9	101.5	1.285	47	2879.3	2994.2
											Ave:	99	1	80	3385	4491

DATE	TIME	TEMP	H5	H6	H7	H8	H9	H10	Time	Meas.	gradient	Q	Average	K s&f	Kf	Kfilter
			Soil Column		Envelope column			outlet		Vol.water			velocity	H6-H7	H7-H8	H7-H9
		°C	cm	cm	cm	cm	cm	cm	Sec	cc	i1-10	cm³/min	cm/min	-------	cm/day	------

TEST NO G-114 Permeameter No.9
SOIL thickness = 2.54 cm SOIL weight = 300 g Density = 1.21 g/cm³
GRAV thickness = 7.5 cm GRAV weight = 914 g Density = 1.61 g/cm³
FILTER SPECIFICATION = Lawrencepur sand
SOIL SPECIFICATIONS = FDP Drainage IV Bag No 2

31/03/93	9:30	21	6.0	5.4	2.4	2.4	2.0	1.9	60	10	0.4	9.9	0.125	228		
31/03/93	11:30	22	159.5	157.4	41.2	38.8	14.5	2.3	60	332	15.7	319.6	4.049	191	3400.8	1200.9
31/03/93	13:30	23	159.5	157.5	41.2	38.8	14.5	2.3	60	334	15.7	314.0	3.978	187	3341.5	1180.0
01/04/93	9:30	22	5.9	5.5	2.7	2.6	2.0	1.3	60	11	0.5	10.6	0.134	262		1517.7
01/04/93	11:30	22	162.7	162.4	36.4	34.0	15.9	2.2	60	307	16.1	295.5	3.744	163	3144.7	1446.3
01/04/93	13:30	23	162.8	162.5	36.5	34.0	15.8	2.2	60	309	16.1	290.5	3.680	160	2967.8	1408.1
03/04/93	9:30	22	5.8	5.3	2.3	2.3	2.0	1.9	60	9	0.4	8.7	0.110	200		
03/04/93	13:30	22	163.0	163.0	36.5	34.2	15.9	2.2	60	308	16.1	296.5	3.756	162	3292.1	1444.0
04/04/93	9:30	22	6.5	6.5	1.4	1.4	1.3	1.2	300	36	0.5	6.9	0.088	94		
04/04/93	11:30	22	164.0	164.0	13.1	12.2	8.1	1.9	60	223	16.2	214.6	2.719	99	6091.3	4307.4
05/04/93	9:30	23	4.5	4.5	1.3	1.3	1.1	1.0	300	41	0.4	7.7	0.098	167		
05/04/93	11:30	23	159.5	159.5	12.9	11.3	6.8	1.9	60	111	15.8	104.4	1.322	49	1665.8	1716.5
05/04/93	13:30	24	159.6	159.6	12.8	11.5	6.8	1.9	60	169	15.8	155.2	1.967	73	3049.9	2596.0
06/04/93	9:30	23	6.5	6.5	1.4	1.4	1.3	1.2	300	35	0.5	6.6	0.083	89		
06/04/93	11:30	23	160.4	160.4	15.3	15.0	8.0	1.9	60	243	15.9	228.4	2.894	109		3140.0
06/04/93	13:30	24	160.5	160.5	15.4	15.0	8.0	1.9	60	244	15.9	224.1	2.839	107		3039.0
07/04/93	9:30	23	5.5	5.5	1.7	1.7	1.4	1.3	300	31	0.4	5.8	0.074	106		
07/04/93	11:30	23	160.5	160.5	15.2	14.0	7.8	1.9	60	242	15.9	227.5	2.882	109	4842.2	3084.8
07/04/93	13:30	24	160.5	160.5	15.3	14.2	7.8	1.9	60	243	15.9	223.2	2.828	107	5182.6	2986.2
08/04/93	9:30	23	5.3	5.3	1.7	1.5	1.4	1.3	300	29	0.4	5.5	0.069	105		
08/04/93	11:30	23	160.5	160.5	15.0	14.2	7.7	1.9	60	135	15.9	126.9	1.608	60	4051.9	1744.4
08/04/93	13:30	24	160.5	160.5	15.2	14.0	7.8	1.9	60	137	15.9	125.8	1.594	60	2678.4	1706.3
10/04/93	9:30	23	5.4	5.4	1.8	1.7	1.4	1.2	300	34	0.4	6.4	0.081	123		
10/04/93	11:30	23	160.3	160.3	17.4	14.2	7.4	1.7	60	170	15.9	159.8	2.025	78	1275.6	1603.6
10/04/93	13:30	24	160.3	160.3	17.5	14.2	7.4	1.7	60	172	15.9	158.0	2.002	77	1222.8	1569.6
11/04/93	9:30	23	5.5	5.5	1.8	1.7	1.4	1.3	300	35	0.4	6.6	0.083	123		
11/04/93	11:30	23	160.3	160.3	16.0	13.3	7.3	1.9	60	158	15.8	148.5	1.882	71	1405.1	1713.1
11/04/93	13:30	24	160.3	160.3	16.2	13.4	7.3	1.9	60	159	15.8	146.1	1.850	70	1332.2	1646.6
12/04/93	9:30	24	6.0	6.0	1.9	1.9	1.5	1.3	60	7	0.5	6.4	0.081	109		
12/04/93	11:30	24	160.5	160.5	24.8	21.8	9.4	1.7	60	253	15.9	232.4	2.944	119	1978.5	1514.2
12/04/93	13:30	25	160.5	160.5	24.9	21.9	9.5	1.7	60	255	15.9	229.0	2.901	117	1949.2	1491.8
13/04/93	9:30	24	5.5	5.5	2.0	1.9	1.5	1.4	60	7	0.4	6.4	0.081	127		1290.3
13/04/93	11:30	24	161.0	161.0	21.5	17.5	8.0	1.5	30	95	16.0	174.5	2.211	87	1114.4	1297.2
13/04/93	13:30	25	161.0	161.0	21.7	17.5	8.0	1.5	30	97	16.0	174.2	2.207	87	1059.3	1275.7
14/04/93	9:30	24	6.0	6.0	1.9	1.9	1.5	1.4	60	6	0.5	5.5	0.070	93		
14/04/93	11:30	25	161.0	161.0	21.8	17.7	8.2	1.5	60	262	16.0	235.2	2.980	117	1465.4	1735.6
											Ave:	136	2	119	2691	1906

DATE	TIME	TEMP °C	H5 Soil column cm	H6 cm	H7 Envelope column cm	H8 cm	H9 cm	H10 outlet cm	Time Sec	Meas. Vol.water cc	gradient i1-10	Q cm³/min	Average velocit cm/min	Ksoil H6-H7 cm/day	Ks&s H7-H8 cm/day	Ksand H8-H9 cm/day	Ksand-fabric H9-H10 cm/day

Test No GS-1 Perm.No 1
Soil thickness = 5.00 cm Soil = 600 g Density = 1.52 g/cm³
Sand thickness = 5.00 cm Sand = 568 g Density = 1.44 g/cm³
FILTER SPECIFICATION = United Karachi Synthetic + Sand
SOIL SPECIFICATIONS = Loam/Sandy Loam (FES Soils)

26-Sep-93	09:30	25	29.4	29.3	20.2	18.5	18.5	18.5	60	4	1.1	3.6	0.046	27.4	54.0		
26-Sep-93	11:30	26	29.4	29.3	20.2	18.5	18.5	18.5	60	3	1.1	2.6	0.033	20.1	39.6		
26-Sep-93	13:30	26	29.5	29.4	20.2	18.5	18.5	18.5	60	4	1.1	3.5	0.044	26.5	52.8		
27-Sep-93	09:30	25	29.4	29.4	20.4	18.7	18.5	18.5	60	4	1.1	3.6	0.046	27.7	54.0		
27-Sep-93	11:30	26	29.4	29.4	20.4	18.7	18.5	18.5	60	5	1.1	4.4	0.056	33.8	66.0		
27-Sep-93	13:30	26	29.5	29.5	20.5	18.7	18.5	18.5	60	4	1.1	3.5	0.044	27.1	49.8		
28-Sep-93	09:30	25	29.4	29.4	20.4	18.7	18.5	18.5	60	4	1.1	3.6	0.046	27.7	54.0		
28-Sep-93	11:30	26	38.8	38.5	22.6	18.9	18.5	18.5	60	5	2.0	4.4	C.056	19.1	30.3		
28-Sep-93	01:30	26	38.5	38.4	22.8	18.9	18.5	18.5	60	5	2.0	4.4	0.056	19.5	28.8		
29-Sep-93	09:30	25	38.5	38.4	23.0	18.9	18.5	18.5	60	6	2.0	5.4	0.068	24.3	33.6		
29-Sep-93	11:30	26	38.5	38.4	23.0	18.9	18.5	18.5	60	7	2.0	6.1	0.078	27.7	38.3		
29-Sep-93	13:30	26	38.5	38.4	23.0	18.9	18.5	18.5	60	7	2.0	6.1	0.078	27.7	38.3		
30-Sep-93	09:30	25	38.5	38.4	22.5	19.0	18.5	18.5	60	8	2.0	7.2	0.091	31.3	52.4	1074.5	
30-Sep-93	11:30	26	59.0	58.9	26.3	19.3	18.7	18.7	60	14	4.0	12.3	0.156	26.1	44.9	1532.5	
30-Sep-93	13:30	26	59.0	58.9	26.3	19.3	18.7	18.7	60	14	4.0	12.3	0.156	26.1	44.9	1532.5	
02-Oct-93	09:30	26	59.4	59.0	26.0	20.0	18.7	18.7	60	15	4.1	13.2	0.167	27.7	56.1	757.8	
02-Oct-93	11:30	26	59.4	59.0	26.0	20.0	18.7	18.7	60	15	4.1	13.2	0.167	27.7	56.1	757.8	
02-Oct-93	13:30	26	59.5	59.1	26.0	20.0	18.7	18.7	60	15	4.1	13.2	0.167	27.6	56.1	757.8	
03-Oct-93	09:30	25	59.4	59.0	25.9	20.4	18.7	18.7	60	15	4.1	13.5	0.171	28.2	62.5	592.6	
03-Oct-93	11:30	26	212	212	62.4	21.6	19.0	19.0	60	57	19.3	50.0	0.634	23.2	31.3	1439.8	
03-Oct-93	13:30	26	212	212	62.5	21.6	19.0	19.0	60	58	19.3	50.9	0.645	23.6	31.8	1465.1	
04-Oct-93	09:30	25	29	29	22.5	18.9	18.5	18.5	60	4	1.1	3.6	0.046	36.1	25.5		
04-Oct-93	11:30	26	29	29	22.5	18.9	18.5	18.5	60	4	1.1	3.5	0.044	35.3	24.9		
04-Oct-93	13:30	26	29	29	22.7	18.9	18.5	18.5	60	5	1.1	4.4	0.056	45.4	29.5		
05-Oct-93	09:30	25	30	30	22.8	18.9	18.5	18.5	60	5	1.1	4.5	0.057	46.5	29.4		
05-Oct-93	11:30	26	212	212	75.5	21.5	19.2	17.9	60	44	19.4	38.6	0.489	19.6	18.3	1256.4	682.1
05-Oct-93	13:30	26	212	212	75.7	21.5	19.2	17.9	60	45	19.4	39.5	0.501	20.1	18.6	1285.0	697.6
10-Oct-93	11:30	26	29	29	22.9	18.8	18.5	18.5	60	5	1.1	4.4	0.056	46.8	27.3		
10-Oct-93	13:30	26	212	212	75.7	21.6	19.2	17.9	60	47	19.4	41.3	0.523	21.0	19.5	1286.2	728.6
10-Oct-93	09:30	26	29	29	22.4	18.8	18.5	18.5	60	4	1.1	3.5	0.044	36.9	24.9		
											Average	12.7	0.2	28.6	39.8	1144.8	702.7

Test No GS-2 Perm.No 2

Soil thickness= 5.0 cm Soil = 600 g Density = 1.52 g/cm³

Sand thickness= 5.0 cm Sand = 568 g Density = 1.44 g/cm³

FILTER SPECIFICATION = Geotextile Texel 909 Canada + Sand

SOIL SPECIFICATIONS = L/SL (FES Soil)

DATE	TIME	TEMP	H5	H6	H7	H8	H9	H10	Time	Meas.	gradient	Q	Average	Ksoil	Ks&s	Ksand	Ksand-fabric
			Soil column		Envelope column			outlet		Vol.water			velocity	H6-H7	H7-H8	H8-H9	H9-H10
		C	cm	cm	cm	cm	cm	cm	Sec	cc	i1-10	cm^3/min	cm/min	----------		cm/day	----------
26-Sep-93	09:30	25	29	29	20.5	18.7	18.7	18.7	60	4	1.0	3.6	0.046	29.3	51.0		
26-Sep-93	11:30	26	29.1	29.0	20.5	18.7	18.7	18.7	60	4	1.0	3.5	0.044	28.6	49.8		
26-Sep-93	13:30	26	29.1	29.0	20.5	18.7	18.7	18.7	60	3	1.0	2.6	0.033	21.5	37.4		
27-Sep-93	09:30	25	29.2	29.2	20.9	19.2	18.8	18.8	60	4	1.0	3.6	0.046	30.0	54.0		
27-Sep-93	11:30	26	29.2	29.2	20.8	19.2	18.8	18.8	60	4	1.0	3.5	0.044	29.0	56.1		
27-Sep-93	13:30	26	29.3	29.3	20.9	19.2	18.8	18.8	60	4	1.1	3.5	0.044	29.0	52.8		
28-Sep-93	09:30	25	29.2	29.2	20.8	19.2	18.8	18.8	60	4	1.0	3.6	0.046	29.6	57.3		
28-Sep-93	11:30	26	38.5	38.4	23.0	19.1	18.9	18.9	60	5	2.0	4.4	0.056	19.8	28.8		
28-Sep-93	01:30	26	38.4	38.3	23.0	19.2	18.9	18.9	60	5	2.0	4.4	0.056	19.9	29.5		
29-Sep-93	09:30	25	38.5	38.4	24.2	19.2	18.9	18.9	60	6	2.0	5.4	0.068	26.3	27.5		
29-Sep-93	11:30	26	38.5	38.4	24.3	19.2	18.9	18.9	60	7	2.0	6.1	0.078	30.2	30.8		
29-Sep-93	13:30	26	38.5	38.4	24.3	19.2	18.9	18.9	60	7	2.0	6.1	0.078	30.2	30.8		
30-Sep-93	09:30	25	38.5	38.4	24.0	19.2	18.9	18.9	60	8	2.0	7.2	0.091	34.6	38.2		
30-Sep-93	11:30	26	58.9	58.8	28.4	19.5	19.0	19.0	60	14	4.0	12.3	0.156	28.0	35.3	1838.9	
30-Sep-93	13:30	26	58.9	58.8	28.4	19.5	19.0	19.0	60	14	4.0	12.3	0.156	28.0	35.3	1838.9	
02-Oct-93	09:30	26	59.2	59.0	29.4	19.5	19.0	19.0	60	15	4.0	13.2	0.167	30.8	34.0	1970.3	
02-Oct-93	11:30	26	59.2	59.0	29.4	19.5	19.0	19.0	60	15	4.0	13.2	0.167	30.8	34.0	1970.3	
02-Oct-93	13:30	26	59.2	59.0	29.4	19.5	19.0	18.9	60	15	4.0	13.2	0.167	30.8	34.0	1970.3	
03-Oct-93	09:30	25	59.2	59.0	29.4	19.5	19.0	18.9	60	13	4.0	11.7	0.148	27.3	30.1	1746.1	
03-Oct-93	11:30	26	212	212	77	22.1	19.8	19.0	60	55	19.3	48.3	0.612	24.8	22.6	1570.5	1070.4
03-Oct-93	13:30	26	212	212	77	22.1	19.8	19.0	60	56	19.3	49.2	0.623	25.3	23.0	1599.1	1089.9
04-Oct-93	09:30	25	29	29	28	18.5	18.4	18.4	60	5	1.1	4.5	0.057	345.8	11.6		
04-Oct-93	11:30	26	29	29	28	18.5	18.4	18.4	60	5	1.1	4.4	0.056	338.2	11.3		
04-Oct-93	13:30	26	29	29	29	18.5	18.4	18.4	60	6	1.1	5.3	0.067	456.5	13.5		
05-Oct-93	09:30	25	29	29	29	18.5	18.4	18.4	60	6	1.1	5.4	0.068	622.4	13.5		
05-Oct-93	11:30	26	212	212	211	25.0	20.0	18.5	60	67	19.3	58.8	0.745	5097.9	8.1	880.1	695.5
05-Oct-93	13:30	26	212	212	211	25.2	20.0	18.5	60	67	19.3	58.8	0.745	5097.9	8.1	846.2	695.5
10-Oct-93	11:30	26	29	29	29	18.5	18.4	18.4	60	6	1.1	5.3	0.067	730.5	13.1		
10-Oct-93	13:30	26	212	212	211	25.2	20.4	18.5	60	69	19.3	60.6	0.768	4666.8	8.3	944.1	565.4
10-Oct-93	09:30	26	29	29	29	18.6	18.5	18.4	60	4	1.0	3.5	0.044	2434.8	8.9		
											Average	14.6	0.2	679.2	29.6	1561.4	823.3

Test No GS-3 Perm.No 3
Soil thickness = 5.0 cm Soil = 600 g Density = 1.52 g/cm³
Sand thickness = 5.0 cm Sand = 568 g Density = 1.44 g/cm³
FILTER SPECIFICATION = Geotextile Polyfelt TS 22 Austria + Sand
SOIL SPECIFICATIONS = L/SL (FES Soil)

DATE	TIME	TEMP	H5	H6	H7	H8	H9	H10	Time	Meas.	gradient	Q	Average	Ksoil	Ks&s	Ksand	Ksand-fabric
			Soil column		Envelope column			outlet		Vol.water			velocity	H6-H7	H7-H8	H8-H9	H9-H10
		C	cm	cm	cm	cm	cm	cm	Sec	cc	i1-10	cm³/min	cm/min	---------	cm/day --------		
26-Sep-93	09:30	25	29.9	29.8	20.0	18.8	18.8	18.8	60	4	1.1	3.6	0.046	25.4	76.4		
26-Sep-93	11:30	26	29.9	29.8	20.0	18.8	18.8	18.8	60	5	1.1	4.4	0.056	31.1	93.4		
26-Sep-93	13:30	26	29.9	29.8	20.0	18.8	18.8	18.8	60	4	1.1	3.5	0.044	24.8	74.8		
27-Sep-93	09:30	25	28.9	28.9	20.2	18.8	18.5	18.5	60	5	1.0	4.5	0.057	35.8	81.9		
27-Sep-93	11:30	26	28.9	28.9	20.2	18.8	18.5	18.5	60	5	1.0	4.4	0.056	35.0	80.1		
27-Sep-93	13:30	26	28.9	28.9	20.2	18.8	18.5	18.5	60	5	1.0	4.4	0.056	35.0	80.1		
28-Sep-93	09:30	25	28.9	28.9	20.2	18.8	18.5	18.5	60	5	1.0	4.5	0.057	35.8	81.9		
28-Sep-93	11:30	26	38.3	38.3	21.9	18.9	18.5	18.5	60	6	2.0	5.3	0.067	22.3	44.9		
28-Sep-93	01:30	26	38.0	38.0	21.9	19.0	18.5	18.5	60	6	2.0	5.3	0.067	22.7	46.4	788.1	
29-Sep-93	09:30	25	38.2	38.2	22.4	19.0	18.5	18.5	60	7	2.0	6.3	0.080	27.6	47.2	940.2	
29-Sep-93	11:30	26	38.2	38.2	22.4	19.0	18.5	18.5	60	7	2.0	6.1	0.078	27.0	46.2	919.5	
29-Sep-93	13:30	26	38.2	38.2	22.4	19.0	18.5	18.5	60	7	2.0	6.1	0.078	27.0	46.2	919.5	
30-Sep-93	09:30	25	38.3	38.3	22.0	19.0	18.5	18.5	60	8	2.0	7.2	0.091	30.5	61.2	1074.5	
30-Sep-93	11:30	26	58.7	58.5	24.7	19.4	18.7	18.5	60	13	4.0	11.4	0.145	23.4	55.0	1219.7	
30-Sep-93	13:30	26	58.7	58.5	24.7	19.4	18.7	18.5	60	13	4.0	11.4	0.145	23.4	55.0	1219.7	
02-Oct-93	09:30	26	58.9	58.9	25.2	19.4	18.7	18.5	60	14	4.0	12.3	0.156	25.3	54.1	1313.5	
02-Oct-93	11:30	26	58.9	58.9	25.2	19.4	18.7	18.5	60	14	4.0	12.3	0.156	25.3	54.1	1313.5	
02-Oct-93	13:30	26	58.9	58.9	25.2	19.4	18.7	18.5	60	14	4.0	12.3	0.156	25.3	54.1	1313.5	
03-Oct-93	09:30	25	58.9	58.9	25.2	19.5	18.8	18.6	60	13	4.0	11.7	0.148	24.0	52.3	1247.2	
03-Oct-93	11:30	26	212	212	79	22.3	18.9	18.8	60	50	19.3	43.9	0.556	22.9	19.7	965.8	
03-Oct-93	13:30	26	212	212	79	22.4	18.8	18.9	60	52	19.3	45.7	0.578	23.9	20.5	948.7	
04-Oct-93	09:30	25	29	29	28	18.9	18.5	18.5	60	4	1.0	3.6	0.046	498.0	9.7		
04-Oct-93	11:30	26	29	29	29	18.9	18.5	18.5	60	4	1.0	3.5	0.044	608.7	9.3		
04-Oct-93	13:30	26	29	29	29	18.9	18.5	18.5	60	5	1.0	4.4	0.056	760.9	11.7		
05-Oct-93	09:30	25	29	29	29	18.9	18.5	18.5	60	5	1.0	4.5	0.057	1037.4	11.8		
05-Oct-93	11:30	26	212	212	209	23.3	20.0	18.7	60	45	19.3	39.5	0.501	913.1	5.4	895.6	435.3
05-Oct-93	13:30	26	212	212	209	23.3	20.0	18.7	60	46	19.3	40.4	0.512	933.4	5.6	915.5	444.9
10-Oct-93	11:30	26	29	29	29	18.9	18.5	18.5	60	6	1.0	5.3	0.067	1217.4	14.0		
10-Oct-93	13:30	26	212	212	209	23.4	20.2	18.7	60	46	19.3	40.4	0.512	875.0	5.6	944.1	385.6
10-Oct-93	09:30	26	29	29	28	18.9	18.5	18.5	60	5	1.0	4.4	0.056	1521.8	11.9		
											Average	12.4	0.2	298.0	43.7	1058.7	421.9

Test No SG-4 Permeameter No.1

Soil thickness = 5.0 cm Weight = 600 g Density 1.52 g/cm^3

Sand thickness = 5.0 cm Weight = 550 g Density 1.39 g/cm^3

FILTER SPECIFICATION = United Karachi Synthetic + Fine Sand

SOIL SPECIFICATIONS = Loam/Sandy Loam (FES Soils)

DATE	TIME	TEMP	H5	H6	H7	H8	H9	H10	Time	Meas. Vol.water	gradient	Q	Average velocity	Ksoil H6-H7	K S&S H7-H8	Ksand H8-H9	Ksand-fabric H9-H10
			Soil column			Envelope column		outlet									
		C	cm	cm	cm	cm	cm	cm	Sec	cc	i1-10	cm^3/min	cm/min	------cm/day	----------		
10-Oct-93	09:30	25	21.9	21.9	18.5	18.0	17.9	17.9	300	3	0.4	0.5	0.007	11.0	27.5		
10-Oct-93	11:30	26	21.9	21.9	18.5	18.0	17.9	17.9	300	4	0.4	0.7	0.009	14.3	35.9		
10-Oct-93	13:30	26	21.9	21.9	18.5	18.0	17.9	17.9	300	3	0.4	0.5	0.007	10.7	26.9		
11-Oct-93	09:30	25	22.0	22.0	18.5	18.0	17.9	17.9	300	6	0.4	1.1	0.014	21.3	55.0		
11-Oct-93	11:30	26	32.0	32.0	21.0	18.4	18.0	17.9	60	4	1.4	3.5	0.044	22.1	34.5		
11-Oct-93	13:30	26	32.0	32.0	21.3	18.4	18.0	17.9	60	4	1.4	3.5	0.044	22.8	30.9		
12-Oct-93	09:30	25	38.7	38.7	23.2	18.5	18.0	17.9	60	5	2.1	4.5	0.057	20.1	24.4		
12-Oct-93	11:30	26	38.7	38.7	23.2	18.6	18.0	17.9	60	6	2.1	5.3	0.067	23.6	29.3	656.8	
12-Oct-93	13:30	26	38.7	38.7	23.2	18.6	18.0	17.9	60	5	2.1	4.4	0.056	19.6	24.4	547.3	
13-Oct-93	09:30	25	50.0	50.0	21.0	19.2	18.2	18.0	60	5	3.2	4.5	0.057	10.7	63.7	335.8	
13-Oct-93	11:30	25	50.0	50.0	21.0	19.2	18.2	18.0	60	6	3.2	5.4	0.068	12.9	76.4	403.0	
13-Oct-93	13:30	26	49.5	49.5	25.7	19.5	18.2	18.0	60	10	3.2	8.8	0.111	25.6	36.2	505.2	
14-Oct-93	09:30	25	60.4	60.4	32.5	20.0	18.3	18.0	60	14	4.2	12.6	0.159	31.2	25.7	553.1	
14-Oct-93	11:30	26	60.4	60.4	32.6	20.0	18.3	18.0	60	15	4.2	13.2	0.167	32.8	26.7	579.5	
14-Oct-93	13:30	26	62.0	62.0	27.0	20.0	18.4	18.0	60	11	4.4	9.7	0.122	19.1	35.2	451.5	
18-Oct-93	09:30	25	70.0	70.0	29.0	20.2	18.4	18.0	60	13	5.2	11.7	0.148	19.7	33.9	485.0	
18-Oct-93	11:30	25	70.0	70.0	29.2	20.2	18.4	18.0	60	14	5.2	12.6	0.159	21.4	35.7	522.3	
18-Oct-93	13:30	26	70.0	70.0	29.2	20.2	18.4	18.0	60	15	5.2	13.2	0.167	22.4	37.4	547.3	
19-Oct-93	09:30	25	80.6	80.6	31.0	20.2	18.3	18.0	60	17	6.3	15.3	0.193	21.3	36.1	600.9	
19-Oct-93	11:30	25	80.6	80.6	31.2	20.2	18.4	18.0	60	16	6.3	14.4	0.182	20.2	33.4	597.0	
19-Oct-93	13:30	26	91.5	91.5	33.5	19.8	18.4	18.0	60	10	7.4	8.8	0.111	10.5	16.4	469.1	
20-Oct-93	09:30	23	200.5	200.5	57.8	22.5	18.7	18.0	60	26	18.3	24.4	0.310	11.9	17.7	481.1	
20-Oct-93	11:30	23	200.5	200.5	57.8	22.5	18.7	18.0	60	25	18.3	23.5	0.298	11.4	17.0	462.6	765.7
20-Oct-93	13:30	24	22.4	22.4	19.0	18.0	17.9	17.8	60	1	0.5	0.9	0.012	18.7	23.5		
21-Oct-93	09:30	23	200.5	200.5	60.5	22.0	18.8	18.2	60	23	18.2	21.6	0.274	10.7	14.3	505.4	821.8
21-Oct-93	11:30	23	200.5	200.5	60.5	22.0	18.8	18.2	60	22	18.2	20.7	0.262	10.2	13.7	483.4	786.1
21-Oct-93	13:30	24	22.5	22.5	19.0	18.0	17.9	17.8	60	1	0.5	0.9	0.012	18.2	23.5		
23-Oct-93	09:30	23	200.5	200.5	60.7	22.2	18.9	18.2	60	24	18.2	22.6	0.286	11.2	15.0	511.4	735.0
23-Oct-93	11:30	23	200.5	200.5	60.7	22.2	18.9	18.2	60	24	18.2	22.6	0.286	11.2	15.0	511.4	735.0
23-Oct-93	13:30	24	21.9	21.9	18.6	18.0	17.9	17.8	60	2	0.4	1.8	0.023	38.6	78.2		
24-Oct-93	09:30	23	200.5	200.5	60.7	22.2	18.9	18.2	60	22	18.2	20.7	0.262	10.3	13.7	468.8	673.8
24-Oct-93	11:30	23	200.5	200.5	60.7	22.0	18.9	18.2	60	22	18.2	20.7	0.262	10.3	13.6	499.0	673.8
24-Oct-93	13:30	24	22.0	22.0	18.5	18.0	17.9	17.8	60	2	0.4	1.8	0.023	36.4	93.8		
25-Oct-93	09:30	23	200.5	200.5	61.2	22.3	19.0	18.2	60	23	18.2	21.6	0.274	10.8	14.2	490.1	616.4
25-Oct-93	11:30	23	200.5	200.5	61.2	22.3	19.0	18.2	60	22	18.2	20.7	0.262	10.3	13.6	468.8	589.6
25-Oct-93	13:30	24	22.5	22.5	18.5	18.0	17.9	17.8	60	2	0.5	1.8	0.023	31.8	93.8		
26-Oct-93	09:30	23	200.5	200.5	61.0	22.4	19.0	18.2	60	25	18.2	23.5	0.298	11.7	15.6	517.0	670.0
26-Oct-93	11:30	23	200.5	200.5	61.0	22.4	19.0	18.2	60	25	18.2	23.5	0.298	11.7	15.6	517.0	670.0
26-Oct-93	13:30	24	21.8	21.8	18.6	18.0	17.9	17.8	60	2	0.4	1.8	0.023	39.8	78.2		
27-Oct-93	09:30	23	200.5	200.5	60.9	22.2	18.9	18.2	60	23	18.2	21.6	0.274	10.7	14.3	490.1	704.4
27-Oct-93	11:30	23	200.5	200.5	60.9	22.2	18.9	18.2	60	22	18.2	20.7	0.262	10.3	13.6	468.8	673.8
27-Oct-93	13:30	24	22.4	22.4	18.8	18.0	17.9	17.8	60	2	0.5	1.8	0.023	35.4	58.7		
28-Oct-93	09:30	23	200.5	200.5	61.5	22.5	19.0	18.2	60	21	18.2	19.7	0.250	9.8	12.9	421.9	562.8
30-Oct-93	11:30	23	200.5	200.5	61.7	22.4	19.2	18.2	60	21	18.2	19.7	0.250	9.9	12.8	461.5	450.2
											Average	11.8	0.15	18.3	32.4	498.5	658.2

DATE	TIME	TEMP	H5	H6	H7	H8	H9	H10	Time	Meas. Vol.water	gradient	Q	Average velocity	Ksoil H6-H7	K S&S H7-H8	Ksand H8-H9	Ksand-fabric H9-H10
			Soil column		Envelope column		outlet										
		C	cm	cm	cm	cm	cm	cm	Sec	cc	i1-10	cm³/min	cm/min	------cm/day---------			

Test No SG-5 Perm.No 2

Soil thickness = 5.0 cm Soil wt. = 600 g Density = 1.52 g/cm³

Sand thickness = 5.0 cm Sand wt. = 520 g Density = 1.32 g/cm³

FILTER SPECIFICATION = Geotextile Texel 909 Canada + Fine Sand

SOIL SPECIFICATIONS = L/SL (FES Soil)

DATE	TIME	TEMP	H5	H6	H7	H8	H9	H10	Time	Meas. Vol.water	gradient	Q	Average velocity	Ksoil	K S&S	Ksand	Ksand-fabric
10-Oct-93	09:30	25	21.8	21.8	18.0	18.0	17.2	17.2	300	2	0.5	0.4	0.005	6.6		33.6	
10-Oct-93	11:30	26	21.8	21.8	18.0	18.0	17.2	17.2	300	2	0.5	0.4	0.004	6.4		32.8	
10-Oct-93	13:30	26	21.8	21.8	18.0	18.0	17.2	17.2	300	3	0.5	0.5	0.007	9.6		49.3	
11-Oct-93	09:30	25	21.9	21.9	18.5	17.7	17.4	17.4	300	5	0.5	0.9	0.011	18.3	28.7		
11-Oct-93	11:30	26	32.0	32.0	21.9	18.2	17.5	17.5	60	5	1.5	4.4	0.056	30.1	30.3	469.1	
11-Oct-93	13:30	26	32.0	32.0	21.9	18.2	17.5	17.5	60	5	1.5	4.4	0.056	30.1	30.3	469.1	
12-Oct-93	09:30	25	38.7	38.7	23.9	22.2	17.5	17.5	60	4	2.1	3.6	0.046	16.8	54.0	57.2	
12-Oct-93	11:30	26	38.7	38.7	23.9	22.0	17.6	17.5	60	5	2.1	4.4	0.056	20.6	59.0	74.6	
12-Oct-93	13:30	26	38.7	38.7	23.9	22.0	17.6	17.5	60	6	2.1	5.3	0.067	24.7	70.8	89.6	
13-Oct-93	09:30	25	50.0	50.0	27.6	22.0	17.8	17.6	60	5	3.2	4.5	0.057	13.9	20.5	80.0	
13-Oct-93	11:30	25	50.0	50.0	27.7	22.0	17.9	17.6	60	6	3.2	5.4	0.068	16.7	24.1	98.3	
13-Oct-93	13:30	26	49.5	49.5	26.5	22.0	17.9	17.6	60	9	3.2	7.9	0.100	23.8	44.9	144.2	
14-Oct-93	09:30	25	60.4	60.4	28.4	22.5	18.2	17.6	60	13	4.3	11.7	0.148	25.3	50.5	203.0	345.0
14-Oct-93	11:30	26	60.4	60.4	28.5	22.7	18.2	17.6	60	13	4.3	11.4	0.145	24.8	50.3	189.7	337.4
14-Oct-93	13:30	26	62.0	62.0	30.3	19.6	18.0	17.5	60	10	4.5	8.8	0.111	19.2	21.0	410.5	311.4
18-Oct-93	09:30	25	70.0	70.0	33.5	19.6	18.0	17.5	60	12	5.3	10.8	0.137	20.5	19.8	503.7	382.1
18-Oct-93	11:30	25	70.0	70.0	33.6	19.7	18.0	17.6	60	13	5.2	11.7	0.148	22.2	21.4	513.6	
18-Oct-93	13:30	26	70.0	70.0	33.7	19.8	18.0	17.7	60	13	5.2	11.4	0.145	21.8	21.0	474.3	
19-Oct-93	09:30	25	80.5	80.5	36.4	19.9	18.0	17.7	60	15	6.3	13.5	0.171	21.2	20.8	530.2	
19-Oct-93	11:30	25	80.5	80.5	36.5	19.9	18.0	17.7	60	14	6.3	12.6	0.159	19.8	19.3	494.9	
19-Oct-93	13:30	26	91.4	91.4	41.0	19.7	18.0	17.7	60	11	7.4	9.7	0.122	13.3	11.6	425.0	
20-Oct-93	09:30	23	200.5	200.5	73.3	22.5	18.5	17.8	60	25	18.3	23.5	0.298	12.8	11.8	439.5	595.4
20-Oct-93	11:30	23	200.5	200.5	73.6	22.5	18.5	17.8	60	26	18.3	24.4	0.310	13.4	12.2	457.1	619.2
20-Oct-93	13:30	24	22.4	22.4	19.0	17.8	17.5	17.5	60	2	0.5	1.8	0.023	37.5	39.1		
21-Oct-93	09:30	23	200.5	200.5	72.0	22.0	18.5	17.7	60	24	18.3	22.6	0.286	12.2	11.5	482.2	500.1
21-Oct-93	11:30	23	200.5	200.5	72.0	22.0	18.5	17.7	60	24	18.3	22.6	0.286	12.2	11.5	482.2	500.1
21-Oct-93	13:30	24	22.5	22.5	18.9	17.8	17.5	17.5	60	2	0.5	1.8	0.023	35.4	42.7		
23-Oct-93	09:30	23	200.5	200.5	72.2	22.0	18.5	17.7	60	23	18.3	21.6	0.274	11.7	11.0	462.1	479.3
23-Oct-93	11:30	23	200.5	200.5	72.2	22.0	18.5	17.7	60	22	18.3	20.7	0.262	11.2	10.5	442.0	458.4
23-Oct-93	13:30	24	23	23	19	18	18	18	60	2	0.5	1.8	0.023	35.4	39.1		
24-Oct-93	09:30	23	201	201	73	22	19	18	60	22	18.3	20.7	0.262	11.2	10.5	418.1	458.4
24-Oct-93	11:30	23	201	201	73	22	19	18	60	22	18.3	20.7	0.262	11.2	10.5	418.1	458.4
24-Oct-93	13:30	24	22	22	19	18	18	18	60	2	0.5	1.8	0.023	36.4	42.7		
25-Oct-93	09:30	23	201	201	73	22	19	18	60	23	18.3	21.6	0.274	11.7	11.0	425.6	426.0
25-Oct-93	11:30	23	201	201	73	22	19	18	60	22	18.3	20.7	0.262	11.2	10.5	407.1	407.5
25-Oct-93	13:30	24	22	22	19	18	18	17	60	2	0.5	1.8	0.023	34.4	46.9		
26-Oct-93	09:30	23	201	201	73	22	19	18	60	20	18.3	18.8	0.238	10.2	9.5	401.8	333.4
26-Oct-93	11:30	23	201	201	73	22	19	18	60	22	18.3	20.7	0.262	11.2	10.5	442.0	366.8
26-Oct-93	13:30	24	22	22	19	18	17	17	60	3	0.5	2.8	0.035	53.1	78.2		
27-Oct-93	09:30	23	200	200	73	23	19	18	60	21	18.3	19.7	0.250	10.8	10.0	388.6	318.3
27-Oct-93	11:30	23	200	200	73	23	19	18	60	22	18.3	20.7	0.262	11.3	10.4	418.1	333.4
27-Oct-93	13:30	24	22	22	19	18	17	17	60	3	0.5	2.8	0.035	56.2	70.4		
28-Oct-93	09:30	23	200	200	73	23	19	18	60	23	18.3	21.6	0.274	11.8	11.0	425.6	319.5
30-Oct-93	11:30	23	201	201	73	23	19	18	60	22	18.3	20.7	0.262	11.3	10.4	429.7	305.6
											Average	11.6	0.15	20.4	27.5	345.7	403.7

Test No SG-6 Perm.No 3
Soil thickness = 5.0 cm Soil wt = 600 g Density = 1.52 g/cm³
Sand thickness = 5.0 cm Sand wt = 530 g Density = 1.34 g/cm³
FILTER SPECIFICATION = Geotextile Polyfelt TS 22 Austria + Fine Sand
SOIL SPECIFICATIONS = L/SL (FES Soil)

DATE	TIME	TEMP C	H5 (Soil column) cm	H6 (Soil column) cm	H7 (Envelope column) cm	H8 (Envelope column) cm	H9 (Envelope column) cm	H10 (outlet) cm	Time Sec	Meas. Vol.water cc	gradient i1-10	Q cm³/min	Average velocity cm/min	Ksoil H6-H7 cm/day	K S&S H7-H8 cm/day	Ksand H8-H9 cm/day	Ksand-fabric H9-H10 cm/day
10-Oct-93	09:30	25	22	22	18	18	17	17	300	2	0.4	0.4	0.005	7.3	11.5		
10-Oct-93	11:30	26	22	22	18	18	17	17	300	2	0.4	0.4	0.004	7.2	11.2		
10-Oct-93	13:30	26	22	22	18	18	17	17	300	2	0.4	0.4	0.004	7.2	11.2		
11-Oct-93	09:30	25	22	22	19	17	17	17	300	6	0.5	1.1	0.014	23.3	21.2		
11-Oct-93	11:30	26	32	32	23	18	18	17	60	5	1.5	4.4	0.056	35.8	20.8		
11-Oct-93	13:30	26	32	32	23	18	18	17	60	5	1.5	4.4	0.056	35.8	20.8		
12-Oct-93	09:30	25	39	39	27	18	18	18	60	5	2.1	4.5	0.057	26.2	13.0		
12-Oct-93	11:30	26	39	39	27	18	18	18	60	6	2.1	5.3	0.067	31.2	15.5	788.1	
12-Oct-93	13:30	26	39	39	27	18	18	18	60	6	2.1	5.3	0.067	31.2	15.5	788.1	
13-Oct-93	09:30	25	50	50	32	19	18	18	60	6	3.2	5.4	0.068	21.2	10.3	403.0	
13-Oct-93	11:30	25	50	50	32	19	18	18	60	6	3.2	5.4	0.068	21.2	10.3	403.0	
13-Oct-93	13:30	26	49	49	33	19	18	18	60	7	3.2	6.1	0.078	25.4	11.5	459.7	
14-Oct-93	09:30	25	60	60	34	19	18	18	60	11	4.3	9.9	0.125	26.1	17.0	527.7	
14-Oct-93	11:30	26	60	60	34	20	18	18	60	10	4.3	8.8	0.111	23.3	15.2	437.8	
14-Oct-93	13:30	26	62	62	28	20	18	18	60	10	4.5	8.8	0.111	17.9	26.4	437.8	251.5
18-Oct-93	09:30	25	70	70	35	20	18	18	60	10	5.2	9.0	0.114	18.0	14.5	479.7	183.7
18-Oct-93	11:30	25	70	70	36	20	18	18	60	11	5.2	9.9	0.125	19.9	15.9	527.7	202.1
18-Oct-93	13:30	26	70	70	36	20	18	18	60	11	5.3	9.7	0.122	19.4	15.5	516.0	197.6
19-Oct-93	09:30	25	81	81	49	20	18	18	60	13	6.3	11.7	0.148	25.4	10.4	513.6	238.8
19-Oct-93	11:30	25	81	81	49	20	18	18	60	12	6.3	10.8	0.137	23.6	9.5	503.7	220.4
19-Oct-93	13:30	26	91	91	41	20	18	18	60	11	7.4	9.7	0.122	13.3	11.6	425.0	
20-Oct-93	09:30	23	201	201	60	24	20	17	60	23	18.3	21.6	0.274	10.6	15.4	385.1	147.5
20-Oct-93	11:30	23	200.5	200.5	59.7	23.8	19.5	17.4	60	24	18.3	22.6	0.286	11.1	16.1	392.5	153.9
20-Oct-93	13:30	24	22.4	22.4	17.8	17.4	17.4	17.2	60	1	0.5	0.9	0.012	13.8	58.7		
21-Oct-93	09:30	23	200.5	200.5	71.2	22.8	19.4	17.4	60	23	18.3	21.6	0.274	11.6	11.4	475.7	154.8
21-Oct-93	11:30	23	200.5	200.5	71.2	22.8	19.4	17.4	60	24	18.3	22.6	0.286	12.1	11.9	496.4	161.6
21-Oct-93	13:30	24	22.5	22.5	17.7	17.4	17.4	17.2	60	1	0.5	0.9	0.012	13.3	78.2		
23-Oct-93	09:30	23	200.5	200.5	71.5	22.9	19.5	17.4	60	24	18.3	22.6	0.286	12.1	11.9	496.4	153.9
23-Oct-93	11:30	23	200.5	200.5	71.5	22.9	19.5	17.4	60	23	18.3	21.6	0.274	11.6	11.4	475.7	147.5
23-Oct-93	13:30	24	22.2	22.2	17.7	17.5	17.5	17.2	60	1	0.5	0.9	0.012	14.2	117.3		
24-Oct-93	09:30	23	200.5	200.5	71.6	22.8	19.5	17.4	60	22	18.3	20.7	0.262	11.1	10.8	468.8	141.0
24-Oct-93	11:30	23	200.5	200.5	71.6	22.8	19.5	17.4	60	22	18.3	20.7	0.262	11.1	10.8	468.8	141.0
24-Oct-93	13:30	24	22.3	22.3	17.8	17.5	17.5	17.2	60	1	0.5	0.9	0.012	14.2	78.2		
25-Oct-93	09:30	23	200.5	200.5	71.5	22.9	19.5	17.4	60	21	18.3	19.7	0.250	10.6	10.4	434.3	134.6
25-Oct-93	11:30	23	200.5	200.5	71.6	22.9	19.5	17.4	60	22	18.3	20.7	0.262	11.1	10.8	455.0	141.0
25-Oct-93	13:30	24	22.5	22.5	17.9	17.4	17.4	17.2	60	1	0.5	0.9	0.012	13.8	46.9		
26-Oct-93	09:30	23	200.5	200.5	71.8	23.0	19.5	17.4	60	23	18.3	21.6	0.274	11.6	11.3	462.1	147.5
26-Oct-93	11:30	23	200.5	200.5	71.8	23.0	19.5	17.4	60	24	18.3	22.6	0.286	12.2	11.8	482.2	153.9
26-Oct-93	13:30	24	22.4	22.4	17.7	17.4	17.4	17.2	60	2	0.5	1.8	0.023	27.1	156.4		
27-Oct-93	09:30	23	200.5	200.5	71.8	23.2	19.5	17.4	60	20	18.3	18.8	0.238	10.1	9.9	380.1	128.2
27-Oct-93	11:30	23	200.5	200.5	71.8	23.2	19.5	17.4	60	21	18.3	19.7	0.250	10.6	10.4	399.1	134.6
27-Oct-93	13:30	24	21.9	29.9	17.7	17.4	17.4	17.2	60	2	0.5	1.8	0.023	10.4	156.4		
28-Oct-93	09:30	23	200.5	200.5	72.1	23.4	19.6	17.4	60	23	18.3	21.6	0.274	11.7	11.3	425.6	140.8
											Average	10.9	0.14	17.1	29.5	475.4	163.7

Appendix B

Table B-1 Synthetic envelope materials tested in the laboratory*

Type of Material	Manufacturer Address	Supplier
Local Olympia Synthetic-3	Olympia Carpet, 23-Davis Road, Lahore Pakistan	Olympia Carpet, 23-Davis Road,Lahore Pakistan
Ts-22	Polyfelt, St.Peter Str.25,P.O.Box 675, Ph:(732) 5983-0, Austria	National Engineers, 90-Bank Square Market, Model Town, Lahore, Pakistan. Ph: 042 858185,857332
Local Nayyer Carpets	Nayyer Carpets, 83-A Shadman-II, Lahore, Pakistan Ph:042 416176,7571346	National Engineers, 90-Bank Square Market, Model Town, Lahore, Pakistan. Ph: 042 858185,85733212
Texel 909	Texel Canada 485, rue des Erables, St - Elzear, Comte Beauce Nord Quebec, Canada. Ph:(418) 387-5910	R.S.Broughton Macdonald Campus 21 111 Lakeshore Rd. Ste-Anne de Bellevue Quebec, Canada
Texel 912	Texel Canada 485, rue des Erables, St - Elzear, Comte Beauce Nord Quebec, Canada Ph:(418) 387-5910	R.S.Broughton Macdonald Campus 21 111 Lakeshore Rd. Ste-Anne de Bellevue Quebec, Canada
United Karachi	United Carpet E/15-A Sindh Industries, Trading Estate, Karachi Pakistan Ph:021-294315-316	United Carpet E/15-A Sindh Industries, Trading Estate, Karachi Pakistan Ph:021-294315-316

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