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RECLAMATION OF PHOSPHATIC CLAY WASTE PONDS BY CAPPING

Volume 3: Evaluation of the use of Geotextiles for Capping Phosphatic Waste Clay Ponds

Prepared by University of Florida,

Department of Civil Engineering

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Reclamation of Phosphatic Clay Waste Ponds by Capping - Final Report

Volume 3: Evaluation of the Use of Geotextiles for Capping Phosphatic Waste Clay Ponds

Research Project: FIPR 82-02-030

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TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

Evaluation of the Use of Geotextiles for Capping Phosphatic Waste Clay Ponds

CHAPTER I: INTRODUCTION, OBJECTIVES AND SCOPE

INTRODUCTION

In 1983 Florida's phosphate mines produced over 33.4 million metric tons of phosphate rock, the primary source of phosphorus, which is a mineral essential to all types of plant and animal life on earth. This quantity represents approximately 80% of the nation's demand and 20% of the world's demand. However, it is estimated that this production generates on the order of 54 million gallons per day of waste clays at 3 to 6% solids by weight. These clays are stored in settling ponds surrounded by earthen dams as high as 60 feet above the surrounding terrain. Over 300 miles of earth dams surrounding over 75,000 acres of active or inactive settling ponds exist in the state today. The waste clays are impounded approximately 60% below ground and 40% above ground, as approximately 55 to 70% of the mined volume is used for settling ponds.

The large above ground dams are required because the volume of the waste clays after settling for a year or so (18 to 20% solids) far exceeds the volume of the excavated materials. The settling ponds serve three basic functions:

1. Dewatering the waste clays for process water reuse.
2. Serving as a reservoir system to minimize groundwater use from deep wells.
3. Allowing for ultimate consolidation of the waste clays.

Above ground storage could be effectively minimized if the waste clays could be consolidated to an average solids content greater than 30 percent. However, due to the poor settling characteristics of the clays, self-weight consolidation to a solids content of 30% can take as long as 10 to 20 years. Due to the increasing value of land and the poor aesthetic features of high above ground earthen dams, the turnaround time between mining and land reclamation must be decreased.

Reclamation of phosphate mined lands is now governed under the regulations of Chapter 16C-16 of the Florida Administrative Code. The intent of these regulations is summarized in the following rule adopted by the Department of Natural Resources (DNR):

> Since storage of clay wastes for long periods of time interferes with expeditious reclamation and since above ground storage of clays takes otherwise useful land out of production and raises potential health and safety problems, below grade storage and rapid reclamation techniques are encouraged.

There are basically two approaches to increasing the dewatering rate of phosphatic waste clays; the beneficiation process can be altered such that waste clays at low solids contents are not produced or the consolidation rate, and, hence, the dewatering rate can be increased. The focus of this research is on examining economical methods of increasing the consolidation rate of waste clays.

One method of increasing the consolidation rate of waste clays is to provide a sand or a sand/clay surcharge. However, the low bearing capacity of the clays renders placement of such a surcharge difficult.

A possible method of placement is to support the surcharge material on a geotextile which is placed directly on top of the waste clay surface. The geotextile will initially function as a separator between the waste clays and the surcharge material, preventing the surcharge from "sinking" into the waste clays. The geotextile will then act as a filter, providing a permeable path for the water which is "squeezed" out of the waste clays during the consolidation process but preventing migration of the solid clay particles into the surcharge material. Some tensile reinforcement will result, thus increasing the bearing capacity of the waste clays. However, if the geotextile clogs over a period of time, it will become a relatively impermeable layer inhibiting the passage of water and, thus, the consolidation process. The geotextile would thus be useless.

The first step in evaluating a method for long-term field use is often to test it on a small-scale basis in the laboratory. This report presents an evaluation of the use of geotextiles for capping, and, thus, to enhance the consolidation process, of phosphatic waste clay ponds based on laboratory results.

Statement of Problem

The basic problem that has resulted in the need for this research is that, due to state regulations requiring a reduction in the turnaround time between mining and land reclamation, methods of increasing the consolidation rate of phosphatic waste clays must be developed. This report presents an evaluation of the use of geotextiles for capping phosphatic waste clay settling ponds.

Due to the low bearing capacity of the waste clays at low solids contents, any sand or sand/clay cap placed directly on the settling pond surface will merely result in displacement of the clays and settlement of the capping material below the clay surface. Theoretically, placement of a geotextile over the clay surface will act as a separator and filter, providing a drainage path for water "squeezed" out of the clay during consolidation, providing a barrier to migration of solid clay particles into the capping material, and preventing the capping material from "sinking" into the waste clays. Additionally, some added tensile reinforcement should result, increasing the bearing capacity of the waste clay/geotextile system and, thus, the amount of surcharge that can be placed on the clay surface to induce consolidation. However, the geotextile may become clogged after a period of time and, thus, ineffective in permitting consolidation.

Objectives

The basic objective of this research was to evaluate the use of geotextiles for capping phosphatic waste clay ponds and, thus, to enhance the consolidation process of these materials, for the purpose of reducing the turnaround time between mining and land reclamation. Specific objectives included:

1. To determine the effectiveness of several geotextiles in preventing the migration of solid clay particles across the geotextiles with the waste clay slurry initially at a solids content in the range of 17-19 percent.
2. To determine the long term filtration/permeability characteristics of several geotextiles under a relatively

constant total head, i.e., to determine if the geotextiles will clog over a period of time.

3. To determine the geotextile(s) that are most effective in terms of long-term filtration/permeability characteristics.
4. To determine any correlations which may exist between geotextile properties and long-term filtration/ permeability characteristics.
5. To determine criteria for the selection of a geotextile for use in capping phosphatic waste clay ponds.

Scope of Work

This research involved the testing of 20 different geotextiles for long term filtration/permeability characteristics. This testing was performed in six groups of four geotextiles, with one group of four tested twice due to unreliable results that were obtained the first time they were tested.

A system was designed and constructed for performing the permeability tests such that four geotextiles could be tested simultaneously. Waste clays at initial solids contents ranging from 17 to 19% were placed in the system and allowed to consolidate against the bottom of the geotextiles under the application of an approximate 21 inch water head difference and air pressure ranging from 3 to 4 psi, resulting in total head differences ranging from 8.6 to 10.9 feet of water. Flow rates versus time were determined for each of the geotextiles that were tested. Total heads were measured adjacent to and 1 inch below the bottom of the geotextiles for the final two test groups. The flow rate and clogging indicator (to be defined later) versus time results were plotted to provide an indication of the long-term behavior of each geotextile. Additionally, the thickness and equivalent opening size of the geotextiles were analyzed to determine the effects on geotextile performance.

At the conclusion of each group of tests, samples of the waste clays were obtained adjacent to each geotextile to determine the final solids content. Additionally, scanning electron microphotographs (SEM'S) were obtained of several of the geotextiles before and after testing in order to examine clogging within the geotextiles.

All of the above results were then utilized to compare the long term filtration/permeability characteristics for the tested geotextiles in order to develop a recommendation for selecting a geotextile for use in field testing applications. This, in turn, may lead to large-scale field use for capping phosphatic waste clay ponds.

CHAPTER II: BACKGROUND

PHOSPHATE MINING

Mining Process

The phosphate of the Bone Valley Formation in central Florida generally exists in a sand-clay-phosphate pebble matrix. The phosphate must be separated from the sand and clay to be marketable. Initially the overburden sands and the aluminum phosphate zone of the Bone Valley Formation are removed by draglines in an open pit strip mining operation. This material is stockpiled on one side of the pit. The calcium phosphate zone of the Bone Valley Formation is then removed and placed in a previously excavated pit. This material is slurried with high pressure water jets to a solids content of 25 to 40%. This slurry is pumped through a pipeline to the benefication plant. Upon arrival at the plant the slurry goes through a washer and separator to remove the +16 mesh phosphate pebbles. Through additional processing, quartz and appatite sand particles and phosphate particles of the 16 to 150 mesh range are separated from the slurry, which now consists of -150 mesh waste clay "slimes". The waste clays are pumped at 3 to 6% solids to earthen dam settlement ponds and present the major disposal problem of the phosphate mining process. The 16 to 150 mesh material goes through further processing (flotation) to separate the phosphate particles from the sand particles. A generalized flow chart of the entire benefication process is presented in Figure 1.

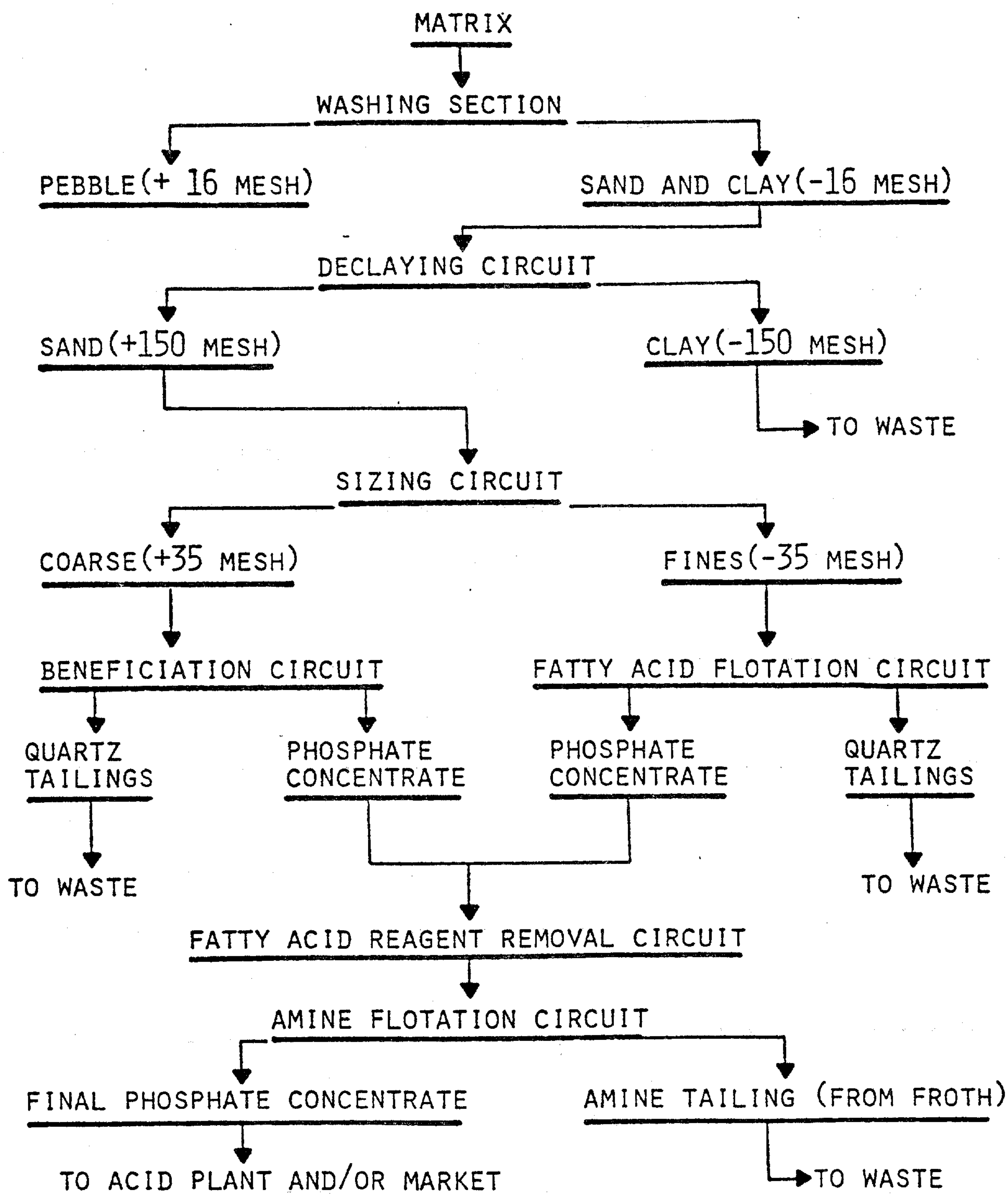


Figure 1: Generalized Phosphate Beneficiation Flow Diagram
(After Bloomquist, 1982)

Waste Clay Properties

As mentioned above, waste clays represent the major disposal problem of the phosphate mining industry. Physical properties of these clays may vary from mine to mine and at different disposal times within the same mine. However, the following data summarizes "typical" values for various properties: (Wissa, et.al., 1982)

- Specific gravity - 2.75 to 2.89, Average 2.81
- Liquid Limit, %, - 280 to 127
- Plasticity Index, %, - 239 to 97
- Activity - 1.6 to 3.9, Average 2.4
- Classification - CH, highly plastic clay

Mineralogical studies were performed Wissa, et. al. (1982) on 12 phosphatic clays. They found that the non-clay minerals detected were: apatite, quartz, dolomite, wavellite, crandallite, and feldspar. These non-clay minerals constituted 35 to 60% by weight of the clays. The apatite content ranged from 7 to 40%, quartz, dolomite and wavellite comprised 6 to 8%, while crandallite and feldspar comprised less than 1%. The clay minerals detected were smectite, illite, palygorskite, kaolinite and interstratified clays. Smectite contents ranged from 6 to 51%, while palygorskite contents ranged from 0 to 35%. Illite contents ranged from 5 to 18%, and kaolinite contents were less than 4%.

These waste clays exhibit poor settling characteristics and, require long periods of time to achieve solids contents in the 30 to 40% range due to self-weight consolidation. Samples taken from the Chistina mine exhibited solids contents ranging from only 36 to 44% approximately 60 years after placement (Bromwell and Oxford, 1977). A major factor in the poor settling characteristics of waste clays is the presence of large quantities of the clay mineral palygorskite. The presence of this mineral inhibits self-weight consolidation of the solid waste clay particles. This mineral is tubular in shape and often arranges itself in a "haystack" structure, resulting in little densification of the clay mass. It has been reported (Lamont et al., 1975; Wissa et al., 1982) that phosphatic clays rich in palygorskite exhibited the poorest settling characteristics.

Another major contributor to the poor settling characteristics is the colloidal size of the clay particles. This results in a high specific surface with the effect that electrostatic forces and Brownian motion tend to oppose the relatively small gravitational forces.

An additional property of phosphatic waste clays that contributes to their poor settling characteristics is the low permeabilities that are exhibited. Permeability controls the rate of consolidation, and, as the solids content increases the permeability decreases even more. Thus, water cannot easily escape. Because of these low permeabilities, as caking occurs on the bottom and sides of the containment dikes, a barrier is formed to inhibit water flow in these directions. Additionally, desiccation at the clay surface also increases the solids content which, in combination with the side and bottom caking, creates relatively impervious boundaries on all sides.

Despite the negative tone set forth in the above discussion, it is known that the 2 to 6% waste clay slurry will consolidate in a period of approximately 3 to 6 months to solid contents in the range of 15 to 19%. This fact leads to the possibility of pumping those materials from the bottom of the settlement ponds and then using some other technique, such as a geotextile in combination with a sand or sand/clay cap, to further consolidate the waste clays to solids contents greater than 15 to 19 percent.

GEOTEXTILES

A geotextile is defined by ASTM as:

> any permeable textile material used with foundation, soil, rock, earth, or any other geotechnical (soil and foundation) engineering related material as an integral part of a man-made project, structure, or system. (Christopher, 1983)

The terms geotextile, filter fabric, plastic filter, cloth fibers, filter cloth, civil engineering fabric, and geotechnical fabric are synonymous throughout the literature. This list may not be all inclusive.

History

Although the use of polymer-type geotextiles for soil stabilization and other geotechnical functions is relatively new, the idea dates back to ancient times. Archaelogical findings in the United Kingdom dating as far back as 2500 BC indicate that some pathways were constructed over logs that were used to stabilize soft ground. The ancient Romans laid woven reed mats over soft, marshy ground before placing stone for roadways. Over the centuries these ancient ideas have developed into the modern day use of geotextiles for similar applications.

Geotextiles have resulted from the development of synthetic polymer chemicals after 1940. The first documented use of a geotextile as a filter was by M. R. Greiser in 1958. He used a synthetic woven fabric for erosion control of his beachfront property in Florida. However, the idea did not catch on quickly. The earliest known publication on the subject is a paper by H. A. Agerschou in 1961 entitled "Synthetic Material Filters in Coastal Protection." The US. Army Corps of Engineers used geotextiles as filters on a few projects in 1962. However, it was not until a report by Robert J. Barrett for Carthage Mills, Inc. in 1965 that a world-wide awareness of some of the uses of geotextiles in Civil Engineering practice was developed.

These initial applications of geotextiles utilized woven geotextiles. The introduction of nonwoven geotextiles in the mid 1970's has greatly expanded the use of geotextiles in Civil Engineering practice. In 1983 the United States and Canada used over 138 million square yards of geotextiles in Civil Engineering applications. However, this is still a developing technology, and more research is required to utilize the numerous different geotextiles on the market today and their extremely variable engineering properties more effectively.

Types of Geotextiles

Geotextiles may generally be divided into three groups based on the general manufacturing process; woven, nonwoven and knitted. The material properties and details of the manufacturing process may vary between geotextiles in different groups and between geotextiles within the same group. Figure 2 shows a flow chart diagram of geotextile types based on the manufacturing process. Geotextiles generally consist of synthetic fibers or filaments of polyvinylidene chloride, nylon, polyester, or polypropylene, although other polymers may be used.

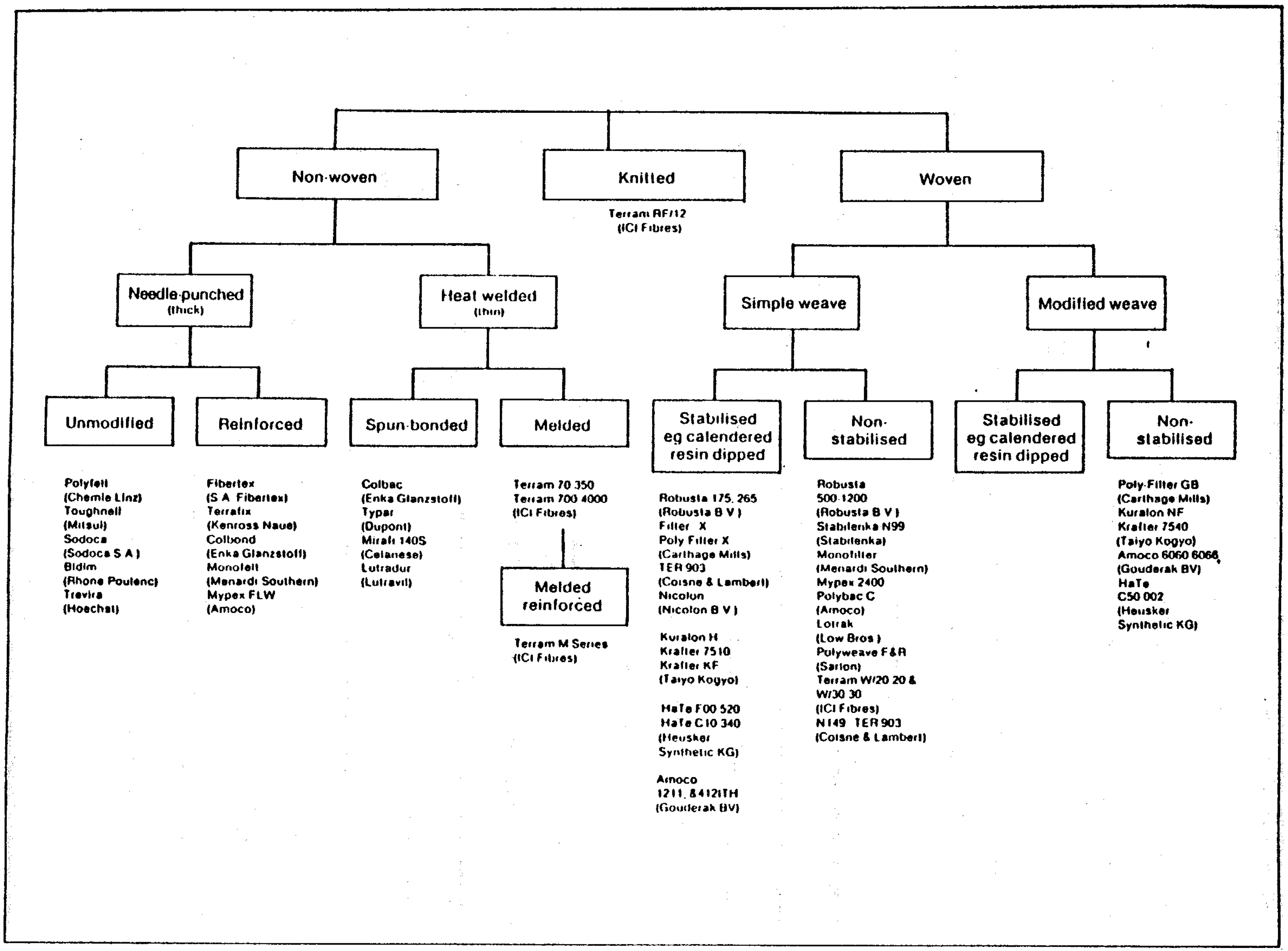


Figure 2: Geotextile Types Based on Manufacturing Process (After Rankilor, 1981)

Woven geotextiles are manufactured by use of a weaving loom. The two directions of the loom are termed the warp (lengthwise) and weft or fill (width, perpendicular to the warp). The warp threads are generally thicker than the weft threads because they must withstand tension in the machine and the up and down action of the reed. The weft threads are placed between the warp threads through the use of a shuttle which is pushed rapidly back and forth. Properties of woven geotextiles may be varied in several ways. These include varying the number of threads per unit length in either or both directions; varying the strength and cross sectional area of the material threads in either direction; varying the weaving pattern, e.g., a warp thread may jump over and under two weft threads or vice versa; and chemically coating the geotextiles to provide stability, to name a few.

Due to the nature of the weaving process, woven geotextiles generally have distinct open areas. Thus, they are heterogeneous materials, containing material threads at some points and openings at other points. The general manufacturing process of woven geotextiles is summarized in Figure 3.

Nonwoven geotextiles can be generally subdivided into two groups based on the manufacturing process; needle-punched and heat bonded. The heat bonded geotextiles are generally thin (two dimensional) and the needle-punched geotextiles are generally thick (three dimensional). The general manufacturing process of spun bonded geotextiles is shown in Figure 4. Molten polymer units are pumped through openings in an extrusion unit. The resulting filaments are drawn together and then deflected to a laying mechanism. The resulting geotextiles are either

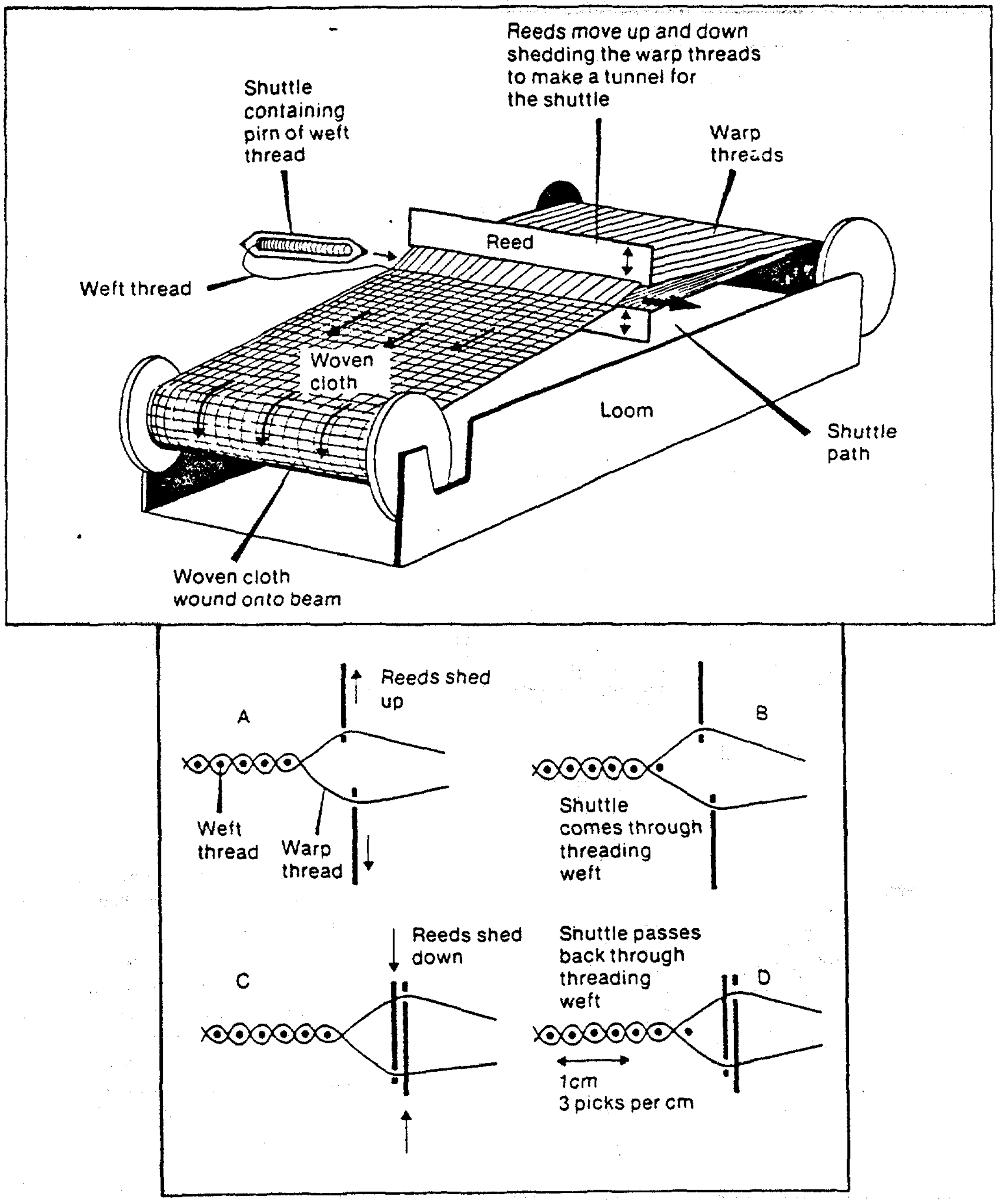
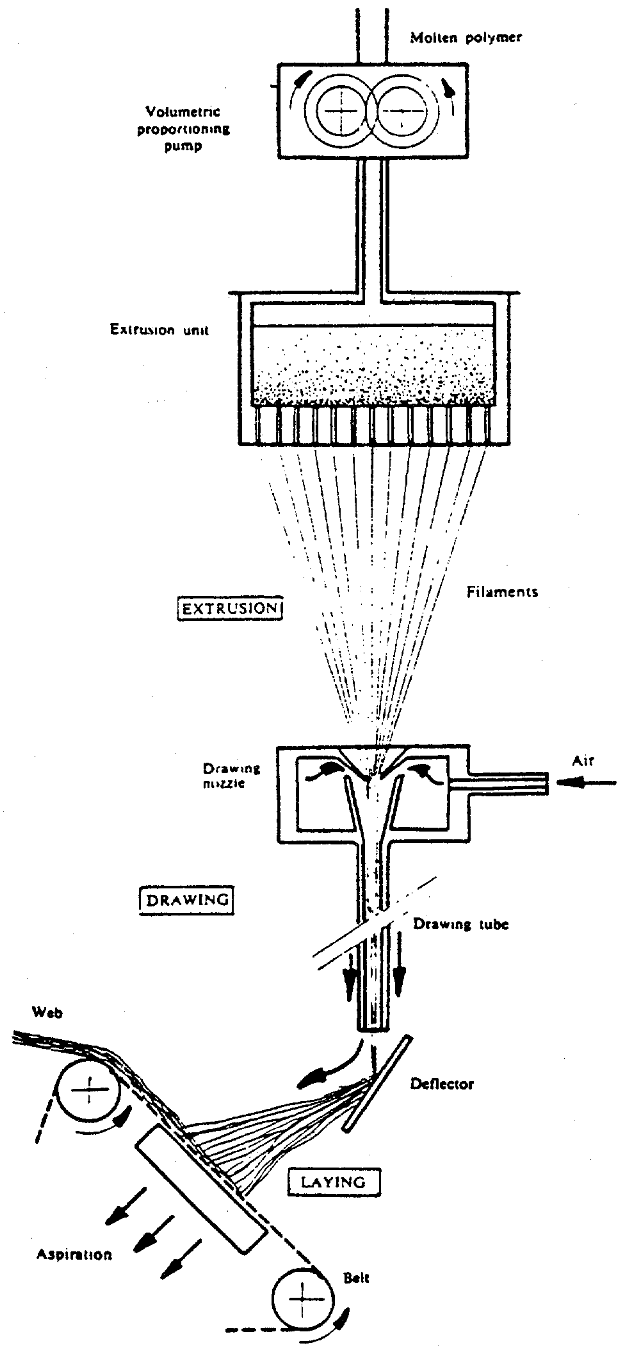


Figure 3: General Manufacturing Process of Woven Geotextiles
(After Rankilor, 1981)



Diagrammatic representation of the manufacture of spun-laid nonwoven fabric

The molten polymer passes through extrusion units, in which a volumetric pump forces it through calibrated holes. Without undergoing any sudden cooling, the filaments thus formed are drawn and then routed to the laying mechanism.

Figure 4: General Manufacturing Process of Spun-Bonded Nonwoven Geotextiles (After Rankilor, 1981)

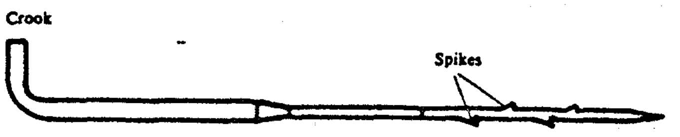
spun-bonded, in which the filaments are comprised totally of the same material (monofilaments), or melded, in which monofilaments consisting of an inner core surrounded by a sheath of a different chemical polymer (heterofilaments) are bonded together by melting the outer sheath of the heterofilament.

The needle-punching process is summarized in Figure 5. Randomly oriented continuous fibers pass through the by means of a belt and are thoroughly intermixed by the up and down movement of barbed needles.

Knitted geotextiles are manufactured such that warp threads lie straight without the over and under pattern of woven geotextiles. Very few knitted geotextiles are available on the market. Therefore, the remainder of this report will primarily consider only woven and nonwoven geotextiles.

The manufacturing process has a tremendous effect on the material properties of the geotextile. In general, woven geotextiles are stronger, less extensible, and less permeable than nonwoven geotextiles (Rankilor, 1981). However, as mentioned previously, slight production alterations can greatly modify these properties.

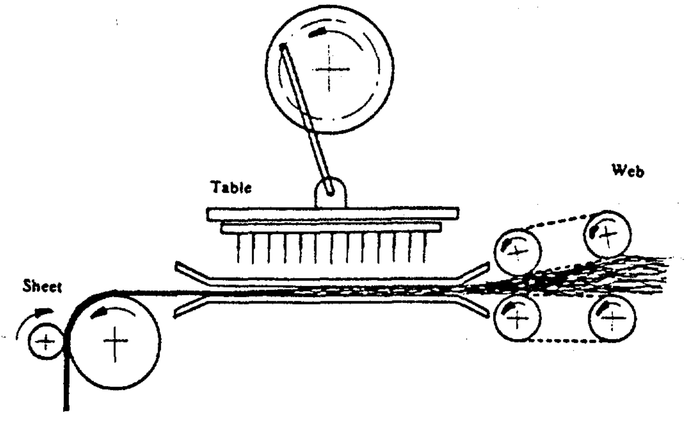
Woven geotextiles tend to exhibit a higher strength and as much as twice the extensibility (Van Leeuwen, 1976) in a direction oriented 45° to the warp and weft directions. However, tears tend to propagate rapidly, even at low stresses. The pore openings are relatively uniform and are quantified by the equivalent opening size (EOS) or the percentage of open area (%OA). The permeability of a woven geotextile is related to the EOS and %OA. The EOS is generally determined from Corps of Engineers test method CWO2215-77. Glass beads of uniform



Needle used for needling

This instrument is in two parts:
— body for fixing on the table;
— active part, with hooks or spikes of different sizes depending on the degree of needling required.

The table is actuated by a reciprocating movement synchronized with the advance of the web



Diagrammatic representation of needling

The web is introduced in the active part of the needling apparatus by means of an endless belt. The needles perforate the web at a certain density, which confers a certain strength on it, and it becomes a "sheet".

Figure 5: General Manufacturing Process of Needle-Punched Nonwoven Geotextiles (After Rankilor, 1981)

diameters are sieved through the geotextile and the smallest size of beads at which less than 5% by weight passes the geotextile is determined. The sieve retaining that size bead is the EOS. The %OA is generally determined by projecting an image of the geotextile on a screen, outlining the open areas, and determining the ratio of the open areas to the total area by use of a planimeter or other measuring means. The procedure is better suited to woven geotextiles than nonwoven.

Nonwoven geotextiles tend to be relatively homogeneous due to the random orientation of the material fibers. Thus, they tend to exhibit rather uniform strength properties in all directions. However, a wide range of pore sizes results from the manufacturing process, thus contributing to the more effective filtration characteristics generally exhibited by nonwoven geotextiles over woven geotextiles. The thin geotextiles tend to exhibit lower strengths, higher extensibility, and be less susceptable to clogging than the thick geotextiles (Rankilor, 1981).

A comparison of the properties of woven and nonwoven geotextiles discussed above is presented in Figure 6. Figures 6a and 6b show the rather uniform opening size of woven geotextiles and the range of pore sizes of nonwoven geotextiles. Figures 6c and 6d show the generally higher strength and lower extensibility properties of woven geotextiles and the relatively uniform directional strength properties of nonwoven geotextiles.

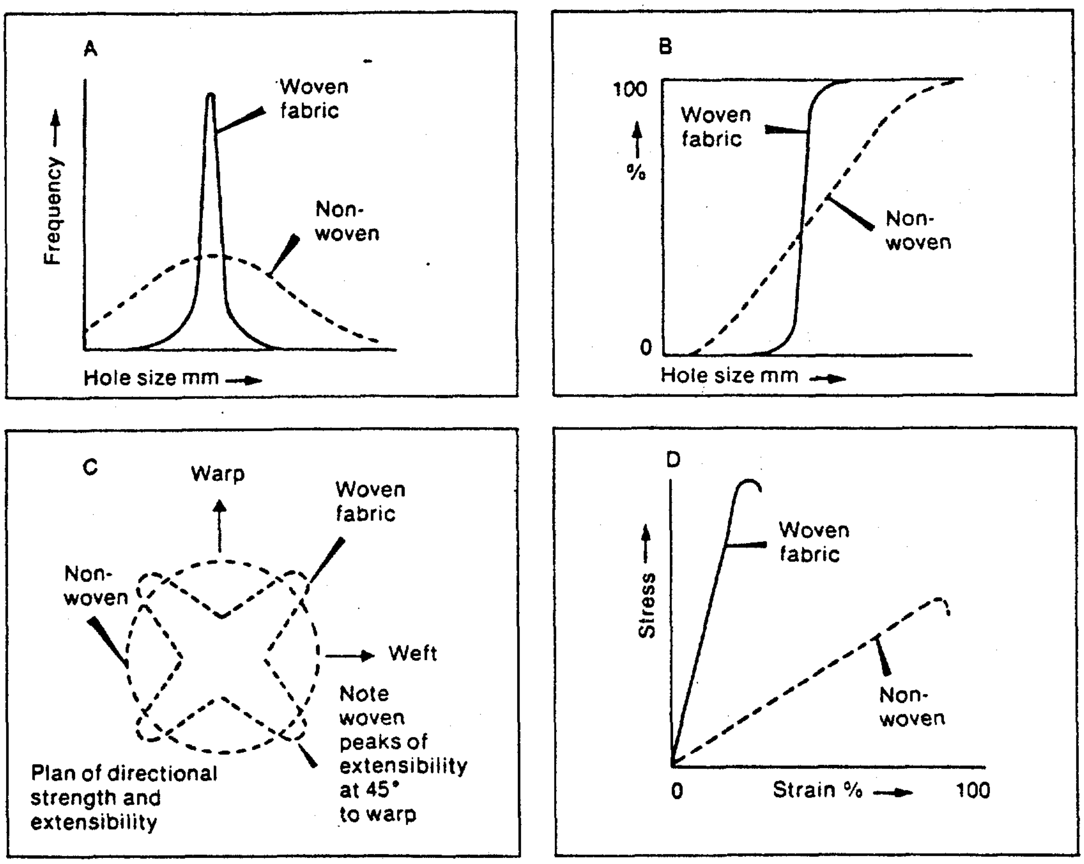


Figure 6: Comparison of Nonwoven and Woven Geotextile Properties (After Rankilor, 1981)

Functions and Applications

According to Rankilor (1981), geotextiles generally perform one or a combination of the following functions in Civil Engineering applications: separation, filtration and drainage, tensile reinforcement, erosion control, and stabilization. Giroud (1980) states that the major functions of geotextiles are drainage or waterproofing, filtration, separation, and reinforcement.

In most applications separation and filtration are found as coexisting functions. When used in conjunction with the capping of waste clay settlement ponds a geotextile would serve initially as a separator, prohibiting the capping material (sand or sand/clay mix) from sinking into and intermixing with the waste clays. Subsequently the geotextile would act in a filtration/drainage capacity. An upward drainage path would be provided allowing pore water to be "squeezed" out of the waste clays, thereby increasing the solids content and thus the strength of the waste clays. Thick, nonwoven geotextiles exhibit an added feature in that drainage can occur "in-the-plane" of the geotextile, i.e., laterally. Thus, the geotextile must be at least as permeable as the underlying waste clays and should remain so for the duration of the clay consolidation process to prevent hydrostatic pressure buildup on the bottom of the geotextile, which could lead to the rupture of the geotextile, in which case it would serve no useful purpose. In addition to the aforementioned separation and drainage/ filtration functions, the geotextile should restrain significant movement of the solid clay particles without clogging. Clogging would cause a hydrostatic pressure buildup on the bottom of the geotextile as discussed above accompanied by a decrease in flow rate across the geotextile. Additionally as the geotextile clogs there would be no drainage path available for water that is "squeezed" out of the clays, resulting in a cessation of the "squeezing" or consolidation process. If the consolidation process terminates before the desired consolidation occurs, the geotextile again would serve no useful function.

Figure 7 illustrates geotextile usage in Civil Engineering applications as discussed above. Figure 7a illustrates the use of a geotextile in drainage applications to convey water from a low permeability clay soil to an outlet in an earth dam. Figure 7b illustrates the use of a coated geotextile as an-impermeable barrier between water and the underlying soil. Figures 7c and dillustrate the use of geotextiles in filtration applications. The geotextile may act as a solid filter as in Figure 7c, preventing fine solid particles from washing into coarser particles, or as a liquid filter as in Figure 7d, allowing water to pass while retaining soil particles. Figure 7e illustrates the use of a geotextile as a separator by preventing two materials from intermixing. Figure 7f illustrates the use of a geotextile for reinforcement, in which the geotextile is placed between two materials to provide greater tensile resistance (e.g., roadway construction over soft soils).

When used in the capping process of phosphatic waste clay settlement ponds, the geotextile would ideally act initially as a separator, preventing the capping material from "sinking" into the soft waste clays. The geotextile would ultimately function as a liquid

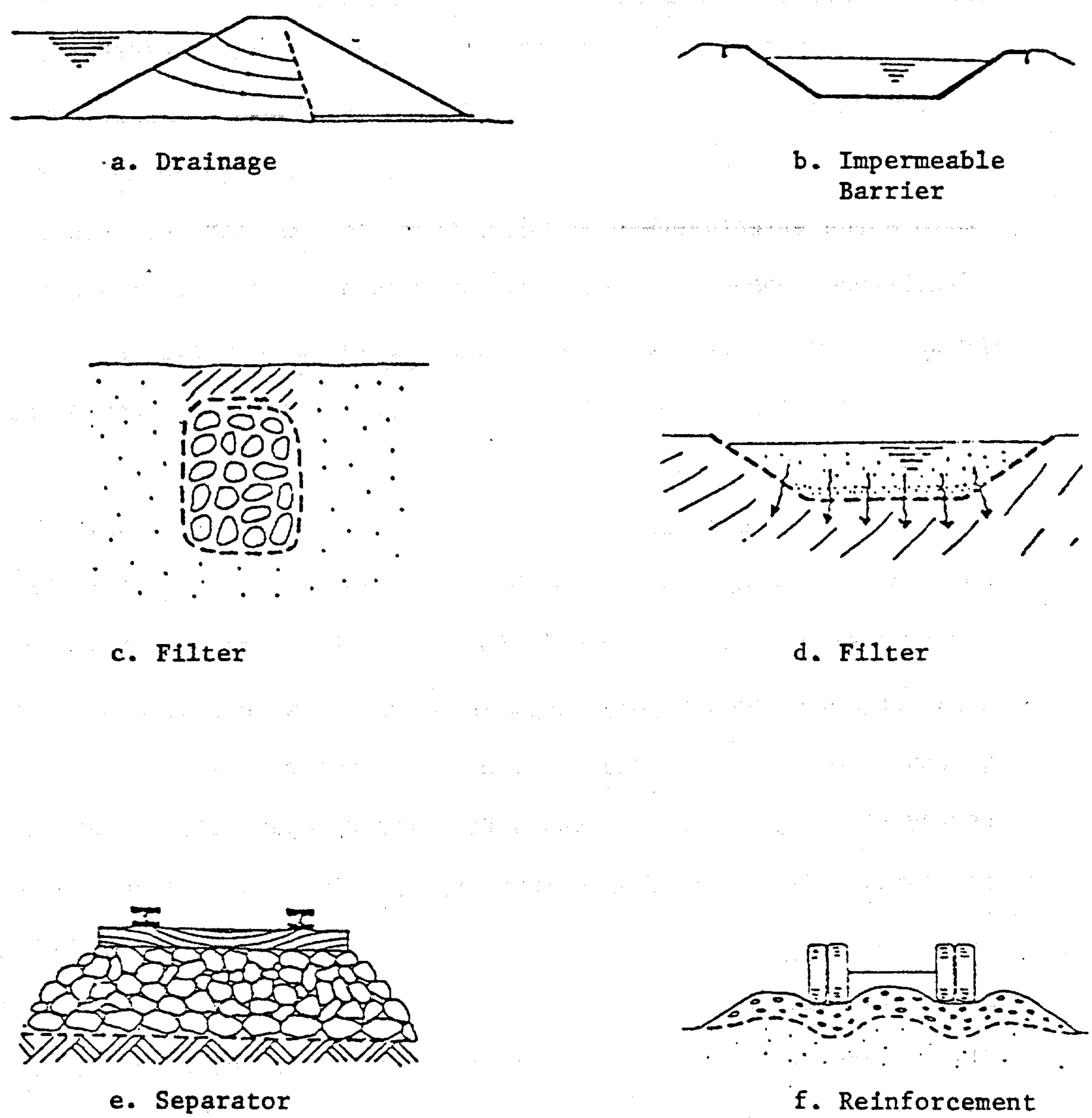


Figure 7: Example of Geotextile Usage in Civil Engineering Applications (After Giroud, 1980)

filter, allowing the passage of water but preventing the solid clay particles from migrating into the capping soils.

Examples of Field Application Over Soft Materials

A review of the literature has revealed limited information concerning field testing of geotextiles. Although several construction projects have incorporated geotextiles in the design in an attempt to improve the effectiveness of the system, in few instances has this effectiveness been evaluated and documented. The following paragraphs present examples of field use of geotextiles placed over soft soils and some of the design and construction problems that were encountered.

A project in Brunswick, Georgia consisted of large containment dike which was constructed of dredged material over very soft foundation materials. The dike was to be 3000 feet in length, 5 feet in height, and 60 feet in width. Three 12 foot wide strips of DuPont Typar 3401, a nonwoven, heat-bonded polypropylene material, were placed along the proposed centerline of the dike, with the outer strips overlapping the center strip by 3 feet on each side. The dredged material was placed by end dumping from single-axle dump trucks. As construction progressed, the embankment began to spread laterally, creating a mud wave which caused the geotextile strips to move. Finally, a complete foundation failure occurred, resulting in damages that were determined to be too excessive to justify repair measures. This failure was a result of faulty design and construction techniques. A proper design would have resulted in the geotextile strips being placed so that they overlapped in a direction perpendicular to the longitudinal axis of the dike, enabling the geotextile strips to resist any lateral movement of the embankment.

At Swan Lake, Mississippi, it was desired to construct a dike over an old oxbow lake filled with a soft clay. Four test embankment sections were constructed, each 400 feet long, 80 feet wide, and 11 feet high. Two of the embankment sections were constructed over a Monsanto nonwoven geotextile (Bidim C-34 and Bidim C-28). The other two embankment sections were constructed without the use of a, geotextile. The geotextiles were oriented perpendicular to the longitudinal axis of the dike test sections and were anchored to the existing ground surface. After the embankment sections were constructed, failure occurred in the form of excessive settlement and cracking in the crest and embankment. This was the result of stretching of the geotextile. It was concluded that the failure was the result of improper geotextile selection.

A highway in Holland was to be constructed over a stratum of soft clay and peat approximately 4.5 meters (14.8 feet) in thickness. A 20 meter long embankment was constructed on a woven geotextile reinforced section. A shallow circular arc failure occurred after partial construction of the embankment. A uniaxial failure of the geotextile occurred at 20% strain. It was postulated that doubling over the geotextile might have prevented the failure (van Leeuwan and Volman, 1976).

At Pinto Pass in Mobile, Alabama, the United States Army Engineer District constructed an 8 foot high, 6000 foot long embankment across soft cohesive soils in order to create a confined dredged material disposal area. A geotextile was placed over the soft material perpendicular to the alignment of the embankment, with the geotextile strips overlapped and sewn together. It was anticipated that the geotextile would act as tensile reinforcement for the embankment. An 800 foot long test section was constructed in the above manner. As a result of this project it was concluded that:

1. a geotextile will enable construction of embankments over soft foundation soils,
2. geotextile elongation should be limited to 5%; otherwise, intolerable embankment displacements may result (Haliburton and Fowler, 1981).

A field test was performed on a 400 foot long section of a logging roadway across low strength muskeg in the Tonguso National Forest in Alaska. The roadway was reinforced with a needlepunched, nonwoven polypropylene geotextile. A granular fill material was end dumped directly on the geotextile and spread with a bulldozer. It was determined that the use of a geotextile reinforcement decreased the embankment fill height required for an adequate roadway section by approximately 30 to 40%, resulting in an approximate 28% savings of rockfill volume (Bell et al. 1977).

IMC and Agrico, two phosphate mining companies in Florida, began a field research project on the subject of waste clay consolidation with respect to land reclamation. These companies were later joined by Mobil. A portion of "this study involved the use of geotextile (Typar) placed between the waste clay surface a surcharge cap. The study showed that the cap must be added in stages, and that the initial stage should be only 1 1/2 to 2 feet in height. One pit that was capped consisted initially of 18% clay solids by weight. The geotextile was anchored at one end of the pit with moist granular material. The original plan was to anchor the geotextile with spray deposited sand tailings and sew additional geotextile sections as tailings were added. However, this procedure resulted in the displacement of the waste clays. It was subsequently decided to place the geotextile over the entire waste clay surface in 15 foot wide strips and to spray sand from three of the pit simultaneously. This attempt was also unsuccessful as the flexible hoses in the sand feeder system wore through the geotextile in one place and the geotextile ripped in another place. A different geotextile reinforced waste clay settling pit was capped using small bulldozers starting from the edge of the pit and working toward the center. This pit was filled with a slurry having a sand/clay ratio of 1.5:1 and after a year the average clay solids content was 26.9 percent. An initial cap approximately 2 feet in height was placed with the entire pit area ultimately covered with a 6 to 8 foot cap. Although advantageous consolidation results have evolved, this method of capping appeared to be economically unfeasable. Finally, another attempt was made at capping the first pit using a Typar geotextile after a vegetative cover root mat proved unsuccessful. A sand/clay capping material was then placed in a ratio of 4.9:1 through three discharge valves along one edge of the pit. The cap was effectively placed and anticipated consolidation results are being achieved. However, it also appears that this method is not economically feasible at the present time.

Previous Laboratory Work on Geotextile/Soil Systems

Although the literature does not reveal any instances of laboratory work performed on phosphatic waste clay/geotextile systems, several researchers have investigated the hydraulic characteristics of various soil/geotextile systems. Those include researchers at the University of Strathclyde in the United Kingdom (McGown and Sweetland, 1973), University of Tennessee (Marks 1975), U. S. Army Corps of Engineers (Calhoun, 1972), Colorado State University (Chen et al., 1980), J. D. Scott (1980), and Haliburton Associates (Wood et al. 1980).

The Corps of Engineers appears to be the first group to document the results of hydraulic testing of soil/geotextile systems. Calhoun (1972) evaluated piping and clogging characteristics of various woven and nonwoven geotextiles using soil systems consisting of sand with different amounts of silt. He utilized a constant head permeability apparatus in which the soil was placed above the geotextile. In order to evaluate geotextile clogging, he developed a Clogging Ratio, which was defined as the hydraulic gradient across the lower 1 inch of soil plus geotextile divided by the hydraulic gradient across the lower 3 inches of soil plus geotextile. A clogging ratio greater than 1 indicated some degree of clogging was taking place. The following piping criteria and clogging/head loss criteria were developed for sand/silt mixtures:

1. for sand/silt mixtures containing 50% or less silt by weight:
   a. 0.147 mm (U. S. Standard Sieve #100) $\leq D_{85}$ (soil) (1)
   b. 4% $\leq$ geotextile Percent Open Area $\leq$ 36%, (2)

2. for sand/silt mixtures containing greater than 50% silt by weight:

   a. $0.147 \text{ mm} \leq \text{EOS (geotextile)} \leq$
      0.212 mm (U. S. Standard Sieve #70) (3)

   b. $4\% \leq$ Fabric Percent Open Area $\leq 10\%$. (4)

Equations 1 and 3 are piping criteria and equations 2 and 4 are head loss/clogging criteria. Additionally, Calhoun recommended nonwoven geotextiles not be used in filtering applications due to their tendencies toward clogging.

McGown and Sweetland (1973) performed testing at the University of Strathclyde to determine filter characteristics of geotextile wrapped drains. They concluded that the geotextile itself does not filter the soil but rather allows an internal filter to develop within the soil. Thus, it was concluded that the opening sizes in the geotextile were not "critically" important. Additionally, by removing the geotextile, piping within the soil took place. This lead to the conclusion that good soil/geotextile contact is important in filtration applications.

The University of Tennessee (Marks, 1975) performed laboratory testing on one geotextile (nonwoven Mirafi, 140) placed against 20 different soil types. The soil types were altered by varying the amounts of silt, kaolinite, and/or montmorillonite that were added to a river sand. The tests were performed over time periods ranging from 21 to 28 days or until a constant flow rate occurred through the soil. A modified version of Calhoun's clogging ratio, termed the Gradient Ratio, was developed by the Corps of Engineers and defined as the hydraulic gradient through the lower 1 inch of soil plus geotextile divided by the hydraulic gradient through the adjacent 2 inches of soil. Calhoun's clogging ratio was determined by dividing the hydraulic gradient through the lower 1 inch of soil plus geotextile by the hydraulic gradient through the lower 3 inches of soil plus geotextile. The Gradient Ratio was determined by Marks to be a "possible" indicator of geotextile plugging or clogging. The increase in the Gradient Ratio with time was dependent on the amount of fines in the soil. It was also concluded that a "filter cake" built up within the soil, similar to the internal filter observed from the University of Strathclyde tests. It is this filter cake which determined the final permeability of the soil/geotextile system, which was less than the permeability of either the original soil or the geotextile. Additionally, piping of the soil through the geotextile was originally observed, but the piping decreased and eventually stopped with the buildup of the filter cake. Figures 8 and 9 show the three major stages in filter cake formation. Letters A, B, and C correspond to the same elapsed testing time in the two figures. Note from Figure 9 that originally the permeability of the system decreased with time as the build-up of the filter cake was occurring. The permeability stabilized as the formation of the filter cake was completed and the soil had formed a "bridge" against the geotextile. The significant conclusion of this testing was that the geotextile (Mirafi 140) was effective in preventing the build-up of excess hydraulic pressures, under-the application of a hydraulic gradient, over a wide range of soil types.

As nonwoven geotextiles became more heavily marketed, the Corps of Engineers performed further testing. It is difficult to measure the percent open area of a nonwoven geotextile since the openings are not as

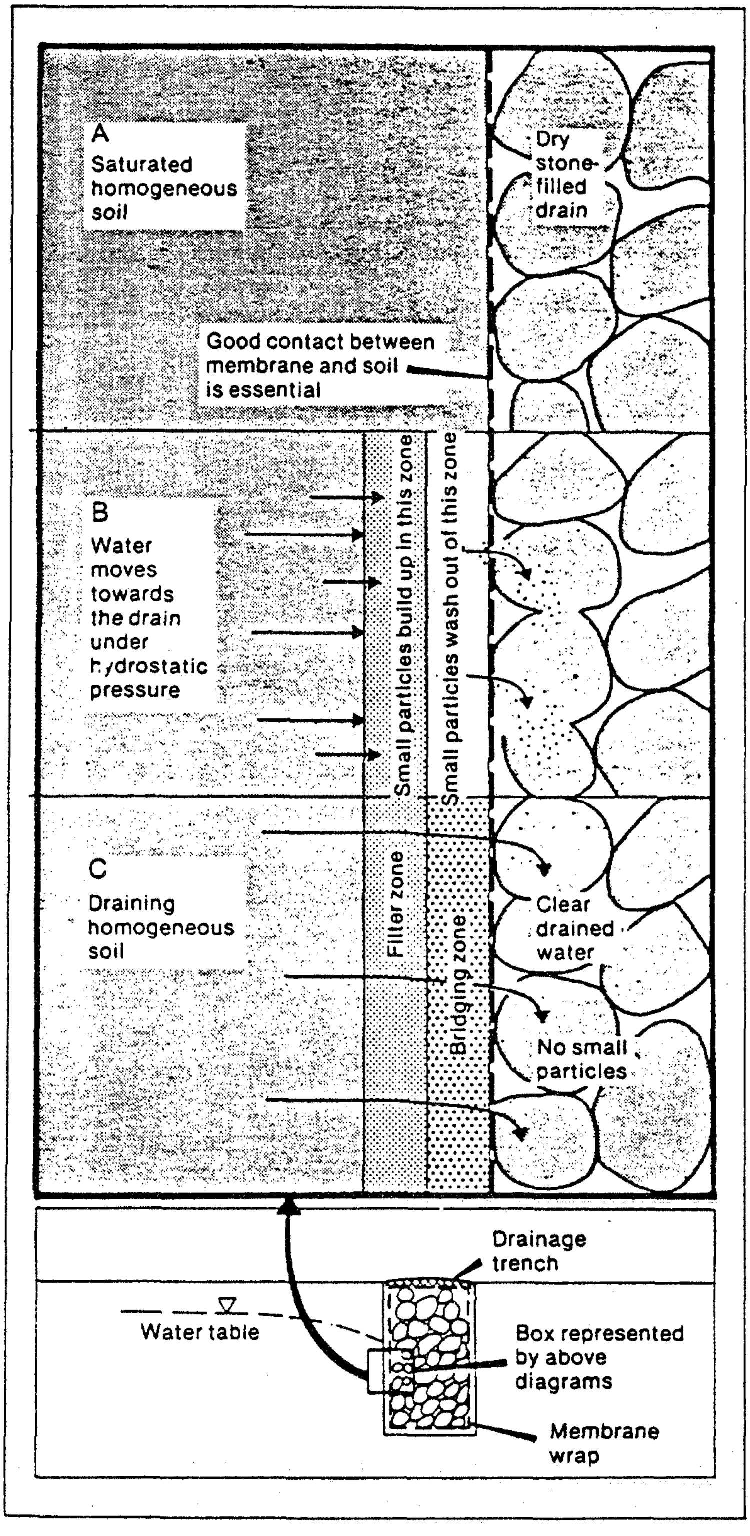


Figure 8: Development of an Internal Soil Filter Behind a Geotextile (After Rankilor, 1981)

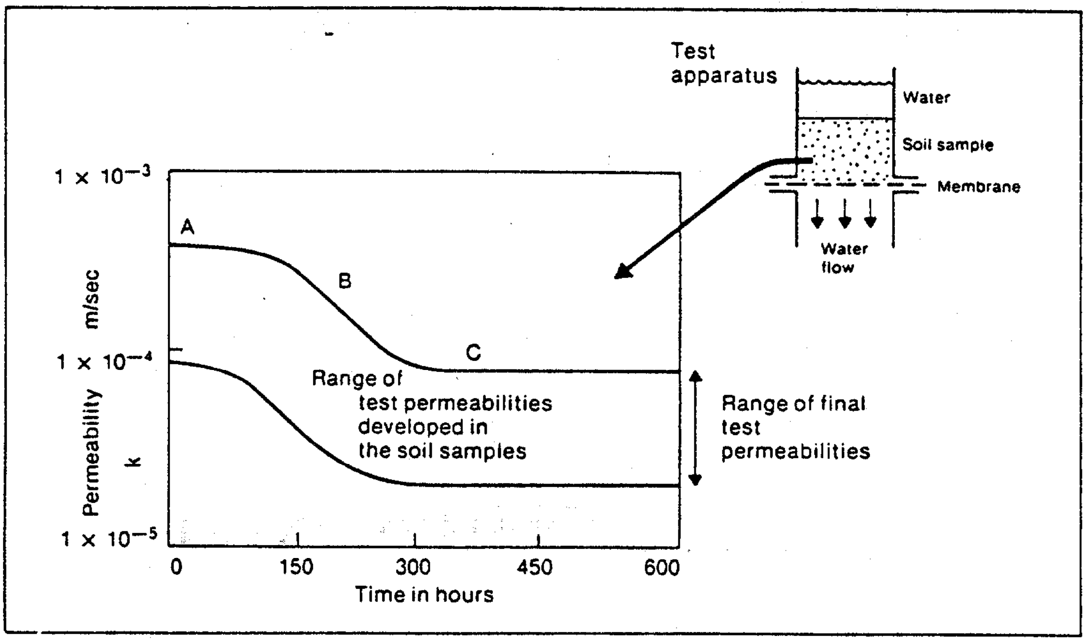


Figure 9: Results of University of Tennessee Permeability Tests on Soil Geotextile Samples (After Marks, 1975)

distinct as those of woven geotextiles, so the Gradient Ratio was used to develop head loss/clogging criteria. This criteria allowed a Gradient Ratio of 3 as acceptable. A Gradient Ratio greater than 3 indicated some degree of geotextile clogging or plugging had occurred. The piping criteria was changed such that the D_{85} of the protected soil must be greater than or equal to the EOS of the geotextile. Geotextiles with an EOS less than the 100 mesh sieve were acceptable, assuming the gradient ratio criteria was met.

Colorado State University researchers (Chen et al., 1980) presented a report based on a study performed for E. I. DuPont de Nemours and Company. In this study 5 different soil types were tested. These soil types included various percentages of sand, silt, and clay. Each soil type was with either 6 or 12 different geotextiles. A total of 18 different geotextiles were tested including 15 nonwoven geotextiles and 3 woven geotextiles. The conclusions were from this study:

1. If the soil acts as a filter, the geotextile will not clog under a hydraulic gradient and will function primarily as a separator and as a solid constraint.
2. If the soil is less permeable than the geotextile then the soil controls the hydraulic characteristics of the system. In this situation, different geotextiles will perform the same.
3. If the soil does not act as a filter then the geotextile actually acts as a filter to prevent the passage of soil particles. In this case local clogging could occur if the soil particles form a cake on the surface of the geotextile.

4. The action of bacteria can control the hydraulic characteristics of the soil/geotextile system.

5. It was suggested that the Gradient Ratio used by the Corps of Engineers be used to analyze long term effects of the soil/ geotextile system.

6. The Corps of Engineers design criteria (Calhoun 1972) was generally found to be too conservative. It was suggested that the following piping equation be used rather than Equation 1

$$\frac{\text{EOS (of geotextile)}}{D_{85}\ \text{(of soil)}} < 2 \qquad (5)$$

7. A design criteria was suggested for selecting a geotextile for use as a filter based on the characteristics of the soil. The criteria suggested the following four step procedure.

   a. determine the coefficient of permeability of the soil,

   b. determine the grain size distribution of the soil,

   c. determine if the soil is a self-filter. The soil is considered a self-filter if the following criteria are met:

$$\frac{D_{85}}{D_{50}}, \frac{D_{50}}{D_{35}}, \frac{D_{35}}{D_{15}} < 5 \qquad (6)$$

   where D_{85}, D_{50}, D_{35}, and D_{15} are the soil particle diameters of which 85, 50, 35, and 15% of the soil particles are finer,

   d. select a geotextile with a coefficient of permeability greater than that of the soil. If Equation 5 indicates that the soil is a self-filter, then use the following equation to determine a suitable geotextile:

$$\frac{\text{EOS (of geotextile)}}{D_{85}\text{ (of soil)}} < 2 \qquad (7)$$

If Equation 6 indicates that the soil is not a self-filter, then use Equation 7 along with the following equation:

$$\frac{\text{EOS (of geotextile)}}{D_{15}\text{ (of soil)}} > 2 \qquad (8)$$

Scott (1980) presented the results of several constant flow tests on soil/geotextile systems. He developed a Modified Gradient Ratio, defined as the hydraulic gradient through the "filter zone" divided by the hydraulic gradient through the "undisturbed zone." The filter zone was defined as the bottom portion of the soil/geotextile system where internal soil piping had occurred. The undisturbed zone was defined as the portion of the soil not affected by water flow. These two zones were determined plotting the head loss through various portions of the soil/geotextile system. A Modified Gradient Ratio greater than 1 indicates some degree of geotextile clogging.

Wood et al. (1980) of Haliburton Associates completed a study for Carthage Mills in which filtration and clogging tests of four geotextiles (2 woven and 2 nonwoven) were performed a sand-silt mixture with the silt content ranging from 0 to 30%. The geotextiles were evaluated using the Corps of Engineers gradient ratio. The following conclusions were developed based on the results of these tests:

1. The maximum allowable gradient ratio of 3 recommended by the Corps is reasonable.

2. The gradient ratio was superior to the clogging ratio developed by Calhoun and the modified gradient ratio developed by Scott.

3. No relationship existed between geotextile EOS and clogging behavior.

4. In order to prevent clogging, nonwoven geotextiles should be either needle-punched or have a relatively high % open area.

5. Woven geotextiles with low % open areas have high tendencies toward clogging.

6. For soils containing greater than 25% silt-size particles by weight, a woven geotextile with a relatively high % open area should be used to prevent clogging.

7. In filtration/drainage applications, a woven monofilament geotextile with a moderate % open area performed better than a woven split-type geotextile with a relatively low % open area, a nonwoven heat bonded geotextile, and a nonwoven needle-punched geotextile.

Darcy's Law and flow Rate

The governing equation for laminar water flow through soil is Darcy's Law (developed by Henri Darcy in 1856) which states

$$Q = kiAt = k\frac{\Delta h}{\Delta l}At \qquad (9)$$

where:

Q = total volume of water flow

k = Darcy's coefficient of permeability

i = hydraulic gradient, or head loss per unit length of flow path $\Delta h/\Delta l$

A = cross sectional area perpendicular to the direction of flow

t = time of flow

Δh = total head loss

Δl = distance over which Δh occurs.

The equation can be solved for k, which gives a measure of the ability of the soil to allow the flow of water through its voids. Thus, all other values (i.e., i, A, and t) being constant, the higher the value of k, the greater volume of water that is capable of passing through the soil voids. In terms of cohesive soils, the flow of water through the soil voids under some surcharge load results in consolidation.

The introduction of a geotextile into the seepage system presents some difficulty in determining a value of k because it is difficult to measure the hydraulic gradient, or, more specifically, the length over which a certain head loss occurs. However, realistically the coefficient of permeability of a geotextile does not hold as much importance as the flow rate (or total flow) through or across the geotextile. The value of the flow rate versus the coefficient of permeability can be understood when one considers that two unique geotextiles of different thicknesses (i.e., different values of Δl) can exhibit identical flow rates but, all other variables (Δh, A, and t) held constant, the coefficient of permeability will be less for the geotextile with the smaller thickness. Thus, the use of the coefficient of permeability to evaluate geotextile performance would indicate that the thicker geotextile exhibited superior characteristics when, in reality, both geotextiles exhibited identical performance characteristics in relation to the ultimate consolidation of the waste clays.

Therefore, it seems more appropriate to compare Q/t (flow rates) or $k/\Delta l$.

By monitoring the flow rate across geotextile, a determination can be made concerning the long term effectiveness of the geotextile to allow the passage of water. A decrease in flow rate could be an indication of either geotextile plugging or clogging. Plugging is defined as a decrease in the flow of water across a geotextile with time due to a partial blockage of geotextile pores. Clogging is defined as the blockage of geotextile pores to such an extent that the geotextile is essentially useless as a filter. Geotextile clogging or plugging can occur either by single soil particles larger than the geotextile openings blocking the pores or by smaller clay-size particles smaller than the geotextile openings becoming entrapped within the pores. Both mechanisms result in an inhibition to the flow of water across the geotextile and a buildup of hydrostatic pressure on the bottom of the geotextile, thus potentially rupturing the geotextile. If rupturing occurs, the geotextile would not be performing the necessary separation function.

CHAPTER III: MATERIALS, EQUIPMENT, AND TEST PROCEDURES

As is often the case, with new untested methods, the testing apparatus and procedures were-modified during the course of the research as experience was gained with the test apparatus and test procedures. The original test apparatus was constructed such that only the volume of flow across each geotextile was measured. The addition of the mamometer board to the system during the later tests enabled the measurement of total heads at different points within the system and, thus, the development of a parameter termed the "Clogging Indicator," modified from the Gradient Ratio, Modified Gradient Ratio, and Clogging Ratio developed by others as discussed in Chapter II.

MATERIALS AND EQUIPMENT

Permeameter Test Apparatus

The permeameter test apparatus was constructed such that four geotextiles could be tested simultaneously. The apparatus consisted of four permeameters, a central supply tank, associated plumbing, and a specially fabricated wooden support table. A plan view of the assembly is shown in Figure 10, which also indicates the permeameter numbering system. The system was developed so that water flowed through the geotextile from the bottom to the top in order to model the actual field conditions as closely as possible. Thus, the waste clays consolidated against the bottom of the geotextile. This assured that the consolidation of waste clays against the geotextile was due to the hydraulic gradient and was not affected by gravity, i.e., self-weight consolidation.

The permeameters, central supply tank, and associated plumbing were constructed primarily of schedule 40 PVC materials, which were chosen due to their versatility, relatively low cost and applicability to the test methodology. The plumbing consisted of lengths of 1 1/4 inch pipe, tees, elbows, reducer bushings, couplings, male adapters, and Matz gate valves. The central, supply tank consisted of a length of 12 inch diameter PVC pipe capped on both ends. The bottom cap was provided with two flow outlets to which the plumbing was attached. The outlets allowed the waste clays and water to flow through the plumbing to the permeameter locations. The system was designed such that the flow path from the central supply to each permeameter was essentially both in shape both in shape and distance. A flexible air pressure line was threaded into the top cap of the central supply tank such that a pressure head could be applied to the system. The applied pressure was controlled by using the pressure gage and regulator shown in Figure 11. The original system was modified to include a sight tube installed to the front of the central supply tank such that the water level in the tank could be monitored during testing. When the water level had fallen below the sight tube the air pressure was temporarily removed from the system and, by disconnecting the air pressure line, water was added through the top cap to refill the supply tank.

Permeameters

Each permeameter was constructed using a 6 inch PVC coupling, a 6 inch to 3 inch PVC reducer bushing, and an approximate 8 to 9 inch square sample of a geotextile. As shown in Figure 12, the geotextile was draped over the reducer bushing and the coupling was forced over the

Figure 10: Plan View of Permeameter Test Aparatus.

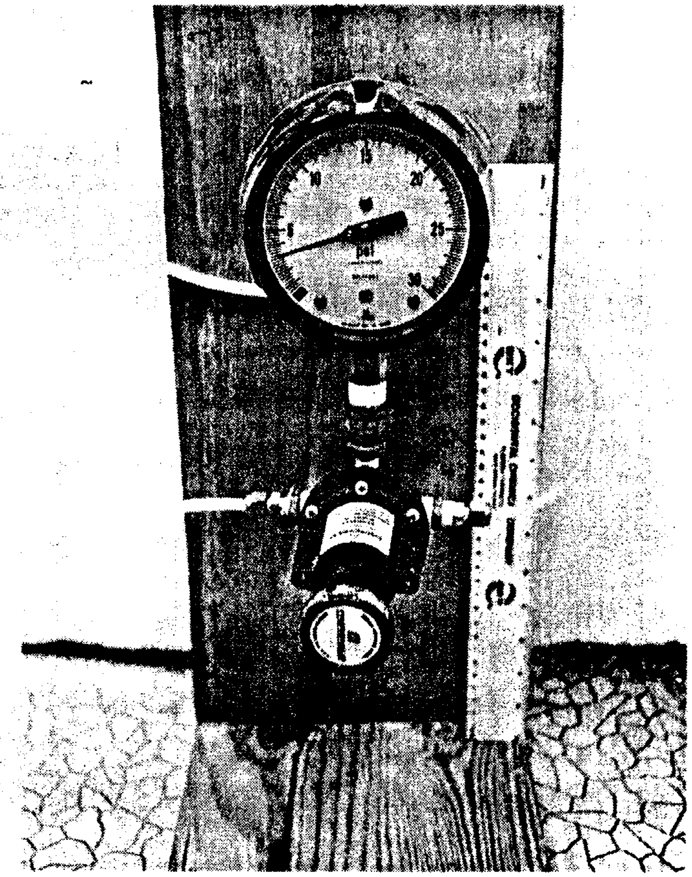


Figure 11: Pressure Gage and Regulator Used to Control Air Pressure Applied to the System.

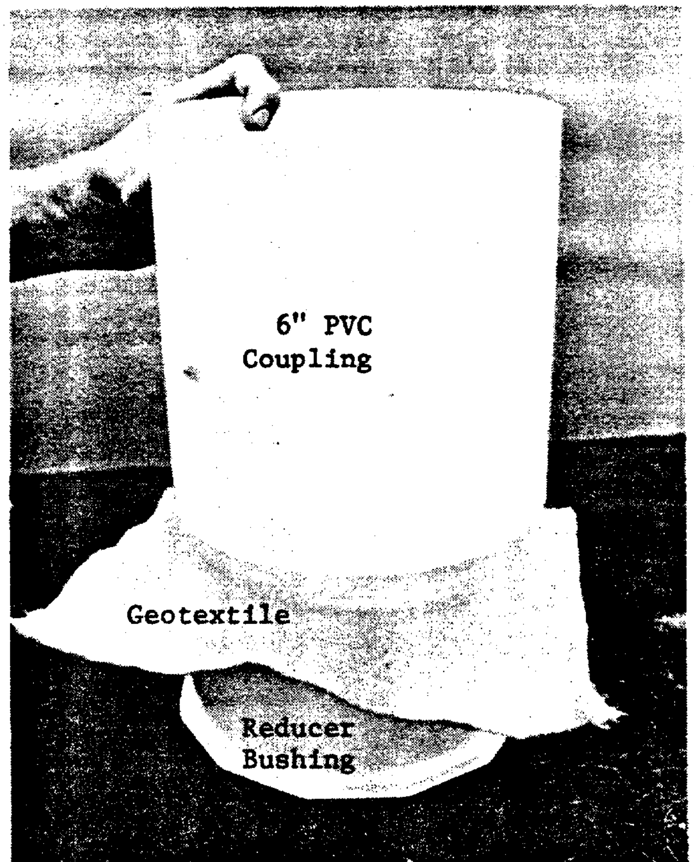


Figure 12: Construction of a Permeameter

bushing as far as possible by applying several blows of a heavy weight to the top. The geotextile was trimmed at intervals during this process, which continued until the coupling was forced down as far as possible. Leakage through the bottom of the permeameter was prevented by applying a PVC bead weld in the small annular space between the bottom of the coupling and the bushing. An outflow fitting was threaded into the permeameter at an approximate height of 16.5 cm (arbitrarily chosen) above the support table. A short piece of flexible tubing was connected to the fitting such that the water outflow was directed into containers. A 3 inch to 1 1/4 inch PVC threaded bushing was fitted to the bottom of the permeameter to connect it to the associated plumbing.

A manometer board, described in the following section, was connected to the system during the final two test groups such that total heads at different points within each permeameter could be measured. Thus, the permeameters in the final two test groups were provided with two threaded outlets such that manometer tubes could be connected. These outlets were located adjacent to the bottom of the geotextile and 1 inch (center to center) below this level. A valve was ultimately placed between each permeameter and manometer tubes so that the pressure head could be "locked" into each tube during periods in which the air pressure was removed and water was added to the supply tank.

Evaporation from the permeameters was controlled by placing a square piece of plywood on top. No attempt was made to measure or account for any of this evaporation that may have occurred. It was felt that this evaporation, though not completely eliminated, was minimal and had no effect on the final test results. Evaporation from the outflow collection containers was ultimately controlled by placing a plastic bag over each container and sealing the bag at the bottom. A slit was made in the top of each bag such that the end of the flexible hose leading from each permeameter could be placed inside in order to direct the water outflow into the containers. Evaporation from a fifth container, covered with a plastic bag as discussed above, was monitored for the duration of the tests and evaporation corrections were applied to the test results at each time interval. Detailed evaporation monitoring procedures and assumptions for each test group are discussed in the test procedures section of this chapter.

Manometer Board

A manometer board was added to the system during the final two test groups so that total heads at two different points within each permeameter assembly could be measured. The manometer board consisted of eight 1/8 inch diameter pressure tubes connected to a peg board and leading to the permeameters. The location of the manometer tube connections to each permeameter are discussed in the preceding section. Metersticks were attached to the right and left side of the peg board to enable the measurement of total heads. The top of the support table was taken as the datum. The manometer board was set up to measure a maximum total head of 257 centimeters (8.4 feet) of water. This is equivalent to approximately 4.8 feet of surcharge material placed at a density of 110 pcf. As mentioned previously, when the air pressure was removed from the system the total head in the manometer tubes could be locked into the system by closing the valves that were located adjacent to the outside of the permeameters.

Figures 13 and 14 show the testing apparatus as it appeared during the course of testing. Figure 13 is a close-up view of the flow system, support table, and pressure regulator. Figure 14 shows the entire system, including the manometer board, after all of the modifications had been made. A schematic diagram of the test apparatus is shown in Figure 15.

Geotextiles Tested

Geotextiles on the market today come in a variety of types, based primarily on the manufacturing process, and exhibit a wide range of properties. The tested geotextiles were selected to generally cover the range of properties exhibited. Table 1 presents a summary of the physical and material properties of the geotextiles that were tested. This information was obtained from literature supplied by the manufacturers. Table 2 presents a list of companies that supplied geotextile samples for testing. However, this report will not identify the geotextiles that were tested with the company that supplied them. The intent this report is to compare geotextiles of different types and properties and not to compare different manufacturers. A far greater number of geotextiles were supplied than were tested and companies not listed in Table 2 may manufacture or supply equal products.

Waste Clays

The phosphatic waste clay slurry used in the testing was primarily obtained from settlement ponds near Bartow, Florida in the Central Florida Phosphate District as discussed previously. The physical

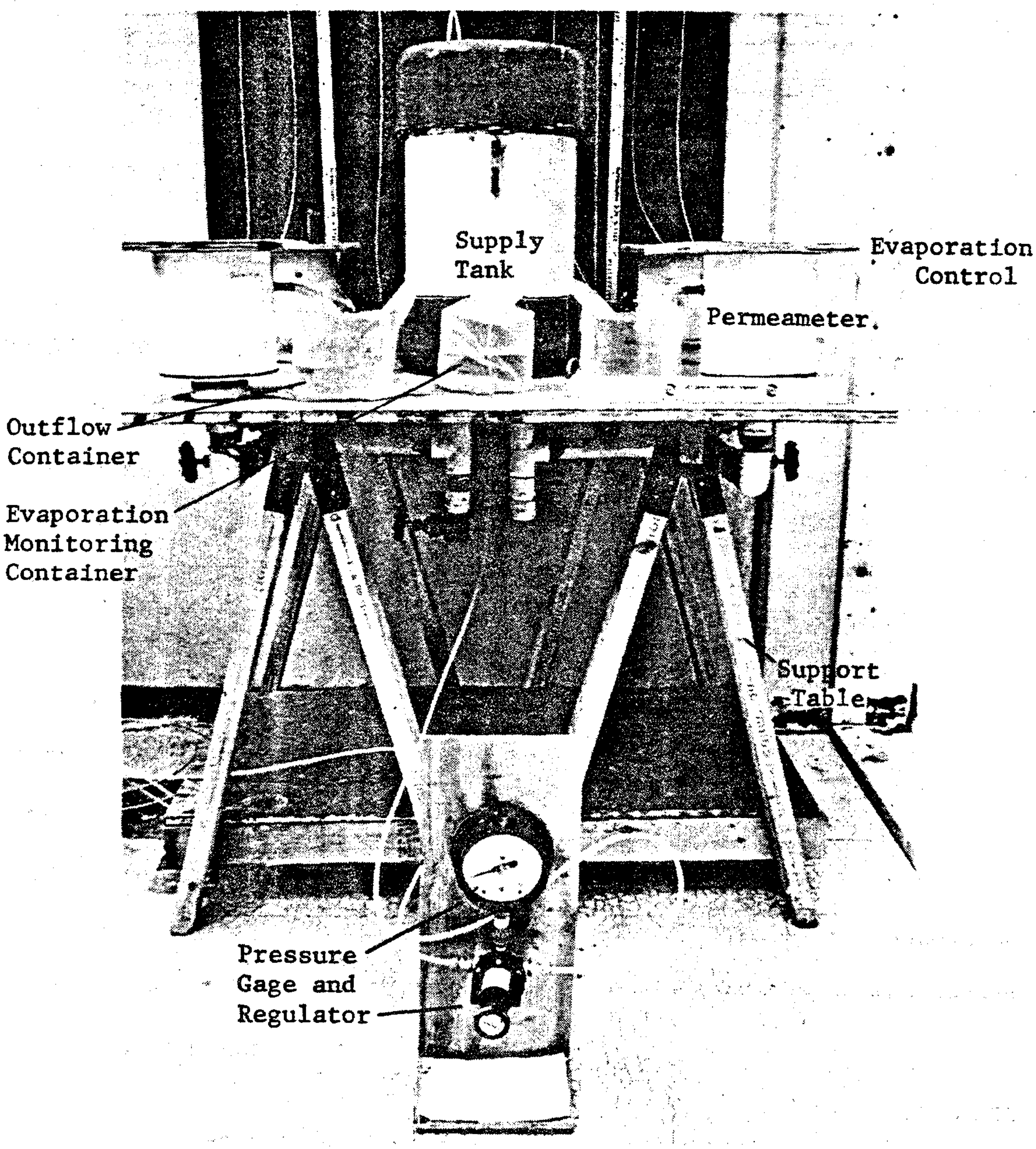


Figure 13: Flow Rate Test Apparatus

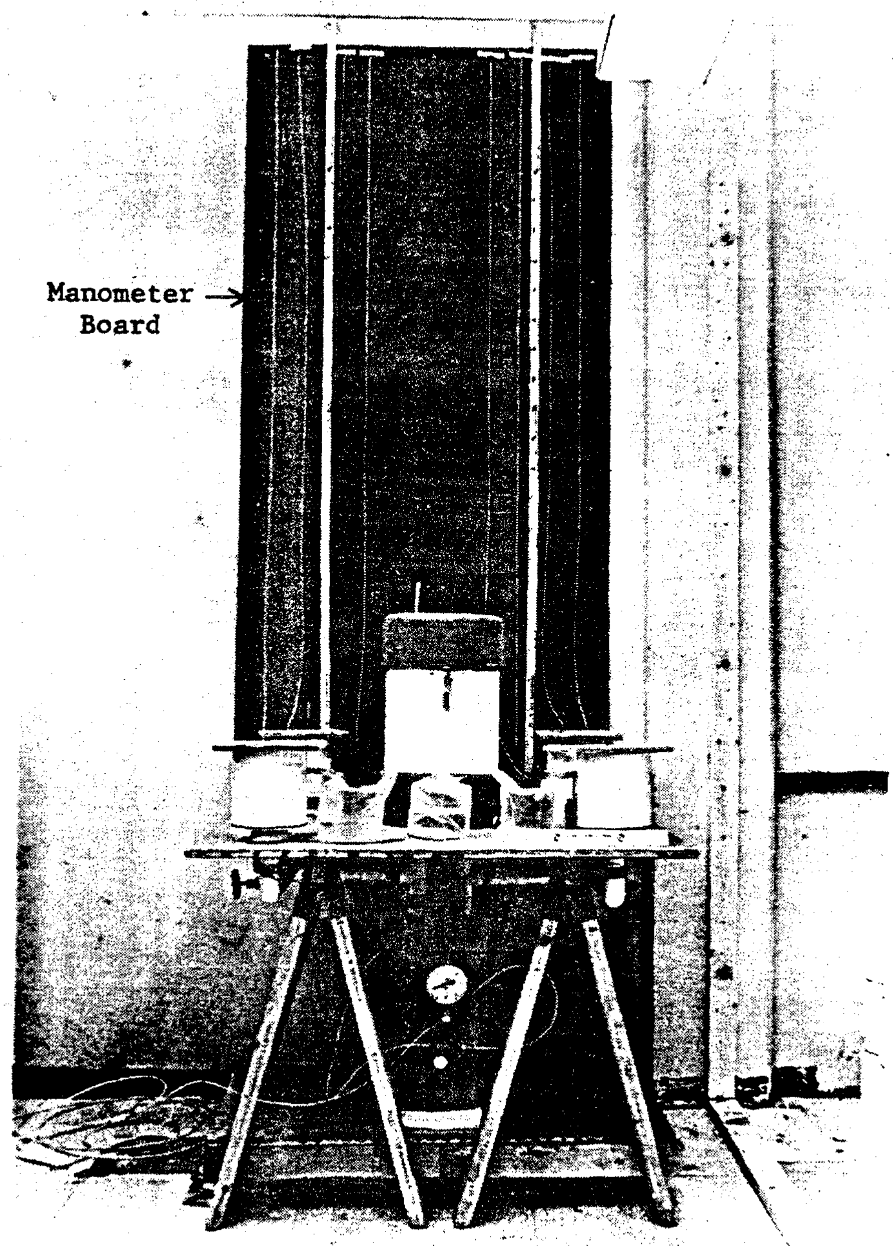


Figure 14: Flow Rate Test Apparatus with Manometers

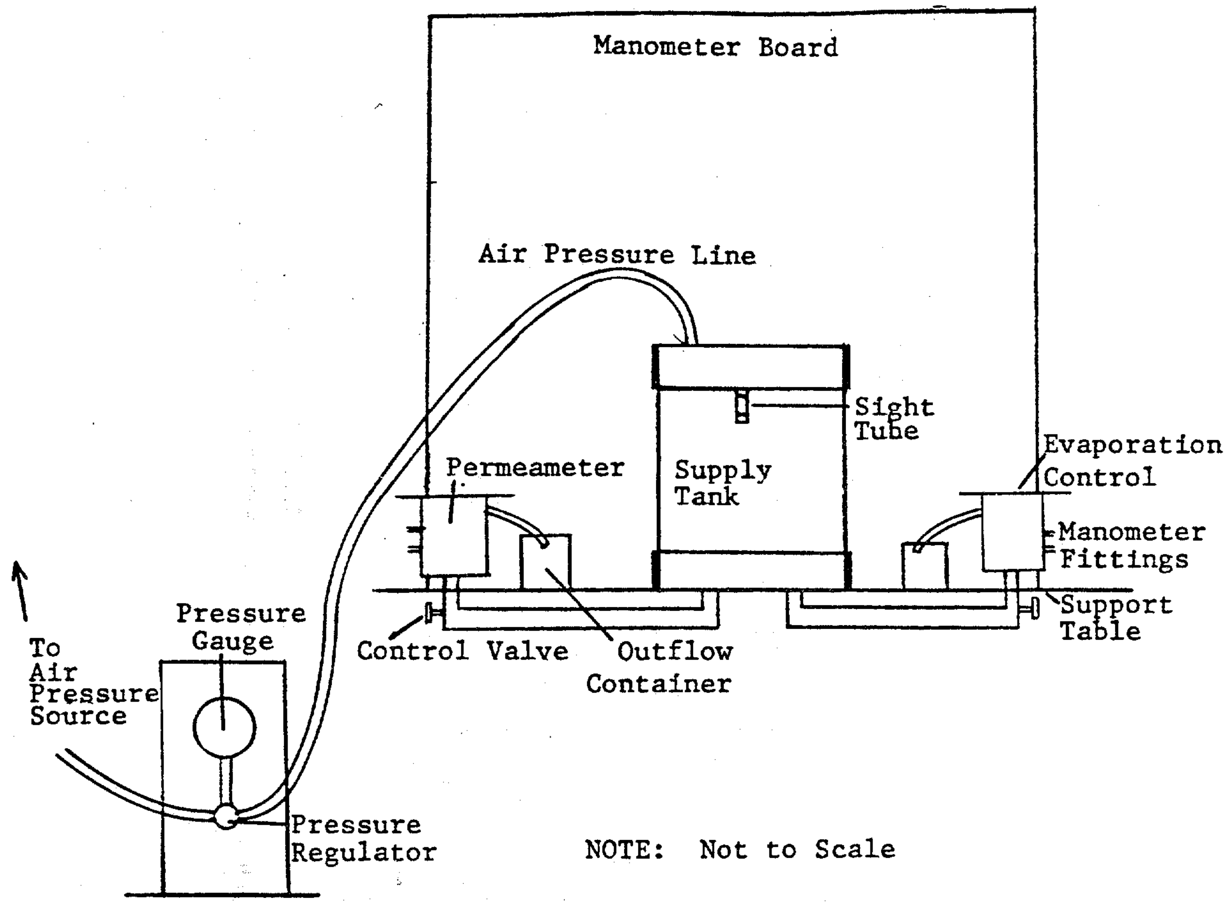


Figure 15: Schematic Diagram of Flow Rate Test Apparatus

TABLE 1. PHYSICAL AND MATERIAL PROPERTIES OF GEOTEXTILES THAT WERE TESTED

GEOTEXTILE DESIGNATION	DESCRIPTION	TYPE	K[a] (cm/sec)	EQUIVALENT[b] OPENING SIZE	THICKNESS (mils)	% OPEN AREA
A1-FWPP-50-40/70	Black Woven Polypropylene	Woven	0.01	40/70	50	-
A2-AWPP-18-70/30	Black Woven Polypropylene	Woven	-	30/70	18	1
A3-JNPP-55-70/100	White Nonwoven Needle-punched Polypropylene	Nonwoven	0.1	70/100	55	-
A4-JNPP-90-60/100	Gray Nonwoven Needle-punched Polypropylene	Nonwoven	0.22	60/100	90	-
B1-ENPP-18-140/170	Gray Nonwoven Heatbonded Polypropylene, Continuous Filaments	Nonwoven	0.014	140/170	18	-
B2-DNPP-110-80/100	White Nonwoven Spunbonded Needlepunched Polypropylene, Continuous Filament	Nonewoven	0.3	80/100	110	-
B3-AWPP-18-70/100	Woven Polypropylene	Woven	0.2	70/100	18	4
B4-HNPE-10-70/100	White Nonwoven Spunbonded Nylon, Reinforced with Black Polyester Netting	Nonwoven	-	70/100	10	-

TABLE 1. CONTINUED

GEOTEXTILE DESIGNATION	DESCRIPTION	TYPE	K^a (cm/sec)	EQUIVALENT[b] OPENING SIZE	THICKNESS (mils)	% OPEN AREA
C1-GW-X-X		Woven	-	-	-	-
C2-FWPP-50-50/100	Yellow Woven Polypropylene	Woven	0.01	50/100	50	-
C3-AWPP-30-30/70	Yellow and Black Woven Polypropylene	Woven	-	30/70	30	2
C4-ANPP-45-70	Nonwoven Polypropylene Fibers	Nonwoven	0.2	70	45	0
D1-CWPV-16-100	Green Woven Polyvinylidene Chloride Monofilament Yams	Woven	0.48	100	16	4.5
D2-BWX-100-30	Woven Polypropylene	Woven	0.35	30	100	6-12
D3-KNPE-190-100	Gray Nonwoven Needlepunched Polyester Continuous Filament	Nonwoven	0.3	100	190	-
D4-IWPE-90-50	White Woven Polyester Yarn	Woven	0.1	50	90	-
E1-GW-X-X		Woven	-	-	-	-
E2-FWPP-50-50/100	Yellow Woven Polypropylene	Woven	0.01	50/100	50	-
E3-ANPP-45-70	Nonwoven Polypropylene Fibers	Nonwoven	0.2	70	45	0

TABLE 1. CONTINUED

GEOTEXTILE DESIGNATION	DESCRIPTION	TYPE	K[a] (cm/sec)	EQUIVALENT[b] OPENING SIZE	THICKNESS (mils)	% OPEN AREA
E4-AWPP-30-30/70	Yellow and Black Woven Polypropylene	Woven	-	30/70	30	2
F1-KNPE-75-50	Gray Nonwoven Needlepunched Polyester Continuous Filament	Nonwoven	0.3	50	75	-
F2-KNPE-90-70	Gray Nonwoven Needlepunched Polyester Continuous Filament	Nonwoven	0.3	70	90	-
F3-INPE-102-170	Nonwoven Polyester Filaments	Nonwoven	0.4	100	102	-
F4-ENPP-15-70/100	Gray Nonwoven Spunbonded Polypropylene	Nonwoven	0.3	70/100	15	-

a. Darcy's Coefficient of Permeability
b. CW02215-77; Corps of Engineers Test Method

TABLE 2. LIST OF COMPANIES THAT SUPPLIED GEOTEXTILE SAMPLES FOR TESTING

Amoco Fabrics Company
Carthage Mills
Chicopee
Crown Zellerbach
E. I. Dupont de Nemours & Company, Inc.
Exxon Chemical Americas
Gibraltar Industries
Mercantile Development, Inc.
Mirafi, Inc.
Nicolon Corporation
Phillips Fabrics Corporation
Quline Corporation

properties and characteristics of the waste clays are discussed in Chapter II.

The waste clays can be rapidly consolidated to about 12 to 18% solids using flocculants or can undergo self-weight consolidation to about 15 to 18% solids in a period of approximately 3 to 6 months. Thus, the slurry was placed in the test apparatus at solids contents of approximately 17 to 19%. The slurry was obtained from the settlement pond and transported to the University of Florida laboratory in plastic lined 55 gallon drums, Prior to testing a portion of the slurry was transferred to a large stainless steel container and prepared to the above solids contents by either adding and thoroughly mixing water to the slurry or allowing the slurry to dry out. When the desired solids content was attained, the slurry was placed in the system and testing was performed as described in the following Test Procedures section.

TEST PROCEDURES

General Procedures

The test procedures that were used were a modified version of the procedures used by Haliburton Associates. The system was designed such that water flowed through the geotextile from bottom to top in order to more closely model the field conditions. The testing procedures were modified slightly from test to test as experience was obtained concerning the performance of the system. The final test procedures are described below. Any deviations from these procedures during any specific test are discussed in subsequent sections of this report.

Each test group consisted of four different geotextiles. An approximate 8 to 9 inch square sample of each geotextile was cut for use in constructing each permeameter as described previously. After each permeameter was sealed to prevent leakage, it was connected to the test apparatus. Teflon tape was used to prevent leakage through the PVC connections. The manometer tubes were then connected at the appropriate locations by means of a brass connection that was threaded into the side of each permeameter. A small piece of geotextile was glued to the end of each connection so that the waste clay slurry would not flow into manometer tubes.

The slurry was then introduced into the system at solids contents ranging from 17 to 19 percent. The slurry was forced into the two outflow pipes at the bottom of the supply tank. In order to achieve as much consistency in the testing procedures as possible, a mark was made on the inside of the supply tank to indicate the initial test level of the slurry. The supply tank was filled with tap water to a level approximately three inches below the top of the tank. A bead of silicone sealant was then placed around the perimeter of the top of the supply tank and the end cap was forced over the tank. The tank was completely filled with water through the small opening in the top of the end cap and the air pressure line was connected to the top end cap.

Four cast acrylic outflow containers were enclosed in sealed clear plastic bags that had a small hole cut in the top to enable insertion of the flexible outflow tubing from the permeameters. A fifth container was filled approximately 1/2 to 2/3 with tap water and sealed inside of a clear plastic bag with a small hole cut in the top for insertion of a short length of clear flexible tubing. This fifth container was used to monitor evaporation from the outflow containers during the course of the test

The system was then ready for testing. The initial weights, of the evaporation monitoring container with its plastic bag and water and the four empty outflow containers with plastic bags were obtained. An air pressure of 3 psi was applied to the system. As water began flow through each of the geotextiles the valves controlling the flow to each geotextile were closed. The permeameters were filled to the outflow points with water and any excess water was allowed to flow into the outflow containers. With the valves remaining closed, the containers were emptied and dried. Plywood squares were placed over the permeameters to control, evaporation. The valves controlling flow through the geotextiles were opened and the tests were considered to have begun at this point, corresponding to time zero.

At periodic time intervals the five Plexiglas containers were weighed. The difference in the weight of the evaporation monitoring container between, consecutive weighings was added to the weight of water in each container to determine the amount of water passing each geotextile. Additionally, water level were taken in each of the manometer tubes at identical time intervals. During the weighings a container was placed under the permeameter outflow tubes in order to catch any outflow of water that occurred. Any outflow was poured into the original container and accounted for in subsequent weighing. This process was continued until the flow rates had essentially stabilized. The tests were generally performed for time periods ranging from approximately 600 to 1000 hours. When an individual outflow container was nearly full it was weighed according to the procedures of the previous paragraph, emptied and wiped dry, placed adjacent to the appropriate permeameter, and the testing continued as discussed previously.

When the water level reached the bottom of the sight tube in the supply tank, the manometer valves were closed and the air pressure temporarily removed from the system. Closing the manometer valves "locked" the water head into the tubes. The air pressure line was disconnected from the system and tap water was added through the opening in the top end cap until the supply tank was filled. The air pressure line was then reconnected to the system, the air pressure reapplied and the manometer valves opened. Testing proceeded as before. The times at which the air pressure was temporarily removed from and then reapplied to the system were noted. The resulting time interval was not applied to the elapsed time of the test.

When an individual test was completed the manometers were diconnected from the permeameters and the permeameters removed from the system. The slurry in each permeameter was sampled using a modified syringe. The tip of the syringe had been removed so that a sample could be obtained. Three samples (top-adjacent to the geotextile, middle, and bottom) of the slurry in the syringe were placed in preweighed aluminum tins for solids content determinations. Each sample and tin was weighed, placed in an oven for 24 hours, and weighed again. The solids content was determined as the weight of solids divided by the total weight of slurry.

After the solids content samples were obtained the system was flushed out by threading an adapter into each permeater location individually, opening and closing appropriate valves, placing a garden hose over the end of the adapter, and forcing the slurry out with water pressure. The system was then reassembled. The above procedures were utilized to test a total of six groups of four geotextiles.

INDIVIDUAL TEST GROUPS

Test Group A

This test group consisted of two woven geotextiles and two nonwoven geotextiles. The slurry was placed in the system at 17.0% solids. Initially only two of the permeameter valves were opened. An initial air pressure of 2 psi was applied to the system for approximately 2.5 hours. This pressure was not sufficient to cause the slurry to flow through the system; therefore, the pressure was increased to 4 psi for approximately 10 minutes. This pressure was sufficient to cause the slurry flow and consolidate against the bottom of the geotextiles. However, water flowed through the geotextiles at a rate that would have rapidly exceeded the holding capacity of the outflow containers. Thus, the pressure was decreased to 3 psi for the remainder of the test. After a time period of approximately 21 hours the remaining permeameter valves were opened, allowing the flow of water to the respective permeameters.

The testing was begun with no attempt to control evaporation from either the permeameters or the outflow containers. However, after a period of time, it was evident that evaporation was significant and should be controlled. Therefore, plastic bags were placed over the outflow containers and the testing proceeded as before. At the end of test group C, evaporation monitoring was performed and the results were applied to each of the first three test groups. The evaporation monitoring techniques are presented in greater detail in the Evaporation Monitoring section of this report.

The test group A tests were performed for total elapsed times ranging from 624 to 641 hours. No attempt was made to refill the system with water during the course of testing. This was reflected in the final flow rates for the geotextiles and was accounted for in determining stabilized flow rates as discussed in Chapter IV of this report.

Test Group B

Test Group B consisted of two nonwoven and two woven geotextiles. The slurry was placed in the system at 19.2% solids. Permeameter valves 1, 2, and 3 were opened simultaneously. Initially permeameter 4 suffered a leak. Therefore the leak was fixed and the corresponding valve was opened at a later time. An air pressure of 4 psi was applied to the system in order to cause the slurry to flow.

Evaporation was controlled at the beginning of the test for each permeameter. Evaporation corrections were based on the evaporation monitoring that was performed at the completion of test group C.

The test group B tests were performed for total elapsed times ranging from 600 to 718 hours. As in test group A, the supply tank was not refilled with water during the course of the test. This was accounted for in determining stabilized flow rates, as discussed in Chapter IV.

Test Group C

Test group C consisted of three woven geotextiles and one nonwoven geotextile. The slurry was placed in the system at 19.1% solids. The four permeameter valves, were opened simultaneously. Initially permeameter 2 suffered a leak; however, testing proceeded and the leak eventually stopped. An air pressure of 4 psi was applied to the system in order to cause the slurry to flow.

Evaporation was controlled at the start of the test for each permeameter. Evaporation monitoring was performed at the conclusion of testing and applied to each of test groups A, B, and C as discussed in the Evaporation Monitoring section of this Chapter.

The test group C tests were performed for a total elapsed time of 551 hours. Testing was temporarily halted after 241 hours, the supply tank top removed, the supply tank filled with water, the top replaced and resealed and testing restarted. This was the first test group in which water was added to the system during the course of testing.

Test Group D

Test group D consisted of 3 woven geotextiles and 1 nonwoven geotextile. The slurry was placed in the system at 19.1% solids. Permeameter valves 1, 2, and 3 were, opened simultaneously. Permeameter valve 4 was opened 5 minutes later. An air pressure of 3 psi was applied to the system in order to cause the slurry to flow.

Evaporation was controlled at the beginning of the test and measured during the test according to the procedures discussed in the Evaporation Monitoring section. The tests were performed for total elapsed times, ranging from 114 to 1030 hours. Permeameter 1 was tested for an elapsed time of only 114 hours because the PVC plumbing leading to the permeameter broke during testing and could not be fixed while the test was in progress.

The system was refilled with water after a time period of 114 hours, when the water level in the system had reached a level at the bottom of the sight tube on the supply tank. This was the first test group in which the sight tube was utilized. Additionally, this test was temporarily discontinued after an elapsed testing time of 122 hours in order to secure the top onto the supply tank, as it had broken loose during testing.

Test Group E

Test group E consisted of three woven geotextiles and one nonwoven geotextile, which were the same geotextiles that were tested in test group C. The slurry was placed in the system at 16.9% solids. The four permeameter valves were opened simultaneously. However, only the geotextiles corresponding to permeameters 2 and 3 were able to be tested, as discussed in the Discussion and Analysis chapter on this report. An air pressure of 3 psi was applied to the system in order to cause the slurry to flow.

Evaporation was controlled at the beginning of the test and measured during the test according to the procedures and assumptions discussed in the Evaporation Monitoring section of this chapter. The tests were performed for a total elapsed testing time of 663 hours.

Testing was temporarily stopped and the system was refilled with water after elapsed testing times of 92, 361, and 548 hours, when the water level in the system had reached a level at the bottom of the sight tube on the supply tank. Additionally, manometer tubes were inserted into the sides of the permeameters in order to measure the total head at two different points within each permeameter as described in the Materials and Equipment section of this report.

Test Group F

Test group F consisted of four nonwoven geotextiles. The slurry was placed in the system at 17.0% solids. The four permeameter valves were open simultaneously. An air pressure of 3 psi was applied to the system in order to cause the slurry to flow.

Evaporation was controlled at the beginning of the test and measured during the test according to the procedures and assumptions discussed in the following Evaporation Monitoring section of this report. The tests were performed for a total elapsed testing time of 743 hours. Testing was temporarily stopped and the system was refilled with water after an elapsed testing time of 291 hours. As in test group E, manometer tubes were inserted into the sides of the permeameters in order to measure the total head at two different points within each permeameter.

Evaporation Monitoring

The testing was originally begun without attempting to measure or control evaporation, assuming that evaporation would have negligible effects on the test results. However, during the course of test group A, it was realized that evaporation was significant and had to be controlled. At the conclusion of test group C evaporation was monitored and the results used to estimate the evaporation that had occurred for test groups A, B, and C. These estimates were based on the following assumptions:

1. the evaporation was equal from all of the containers that had approximately the same surface area,
2. the evaporation rate from the containers was constant with time,
3. the assumed constant evaporation rate was the same for each of the three test groups.

Although these assumptions are only approximate, it is felt that they do not invalidate the test results. The above assumptions hold only for test groups A, B, and C. The evaporation monitoring techniques for these test groups are discussed in the following paragraph.

Test group A was begun with no evaporation control from the outflow containers during the initial 96 hours of testing. The outflow containers consisted of 6 inch diameter cast acrylic containers for permeameters 1, 2, and 3 and a coffee can for permeameter 4. At the end of test group C, four cast acrylic containers and a coffee can were weighed empty and then partially filled with an arbitrary amount of water. An initial weight of the partially filled containers was obtained. Subsequent weights were obtained at arbitrary time intervals to determine the amount of water that had evaporated. Linear regression analyses were performed using an HP-15C calculator, using the weight of water evaporated and elapsed time as the input variables. One analysis was performed using the results from the four Plexiglas containers and one analysis performed using the results from the coffee can. The resulting equations were modified to indicate no evaporation at time zero. The results were used to determine the evaporation from the outflow containers during the initial 96 hours of testing. Similar procedures were followed to estimate the evaporation from the outflow containers for the remainder of test group A and for the duration of test groups B and C, with the exception that a plastic bag similar to those used during actual testing was placed over each container.

Prior to the start of test group D the procedures were modified so that evaporation was monitored simultaneous to testing. The initial empty weight of one cast acrylic container and plastic bag was determined. The container was then partially filled with water. At the beginning of the test the partially filled container was covered with a plastic bag and weighed in a similar manner to the outflow containers. The container was then weighed each time the outflow containers were weighed and the difference of the obtained weight from the previous weight was assumed to be the evaporation from each outflow container. Thus, the assumptions that the evaporation was constant with time and the same for each test were eliminated. The only assumption using these procedures was that the evaporation was the same from each container.

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CHAPTER IV: ANALYSIS AND DISCUSSION OF TEST RESULTS

METHODS OF ANALYSIS

The testing consisted of a total of six groups of four geotextiles; thus, a total of 24 tests were performed. Of these, two of the woven geotextiles allowed excessive piping of the waste clay slurry upon application of the air pressure and were not able to be tested. These geotextiles corresponded to permeameters 1 and 4 of test group E. Additionally, the PVC plumbing broke during the course of testing of test group D; therefore, a stabilized flow rate was not able to be obtained for permeameter 1, although the initial flow rate was determined. Thus, a total of 22 initial flow rates and 21 stabilized flow rates were determined and compared. Test groups C and E tested the same four geotextiles for reasons as discussed in later sections of this report.

Darcy's law states that Q = kiAt. The total flow (Q) was measured directly at each time interval and the flow rate (Q/t) was determined by dividing the total flow by the elapsed time (t). The area (A) was the same for each geotextile tested. The hydraulic gradient (i) for the tests was relatively constant since 3 or 4 psi of air pressure was applied to the system for each test. The coefficient of permeability (k) was the only variable for each geotextile that affected the flow rate. Thus, the flow rate results for each geotextile can be compared.

A plot of flow rate versus time was prepared for each geotextile tested. These plots are shown in Figures A-1 through A-22 in Appendix A. A typical plot is shown in Figure 16. The flow rate at a given time

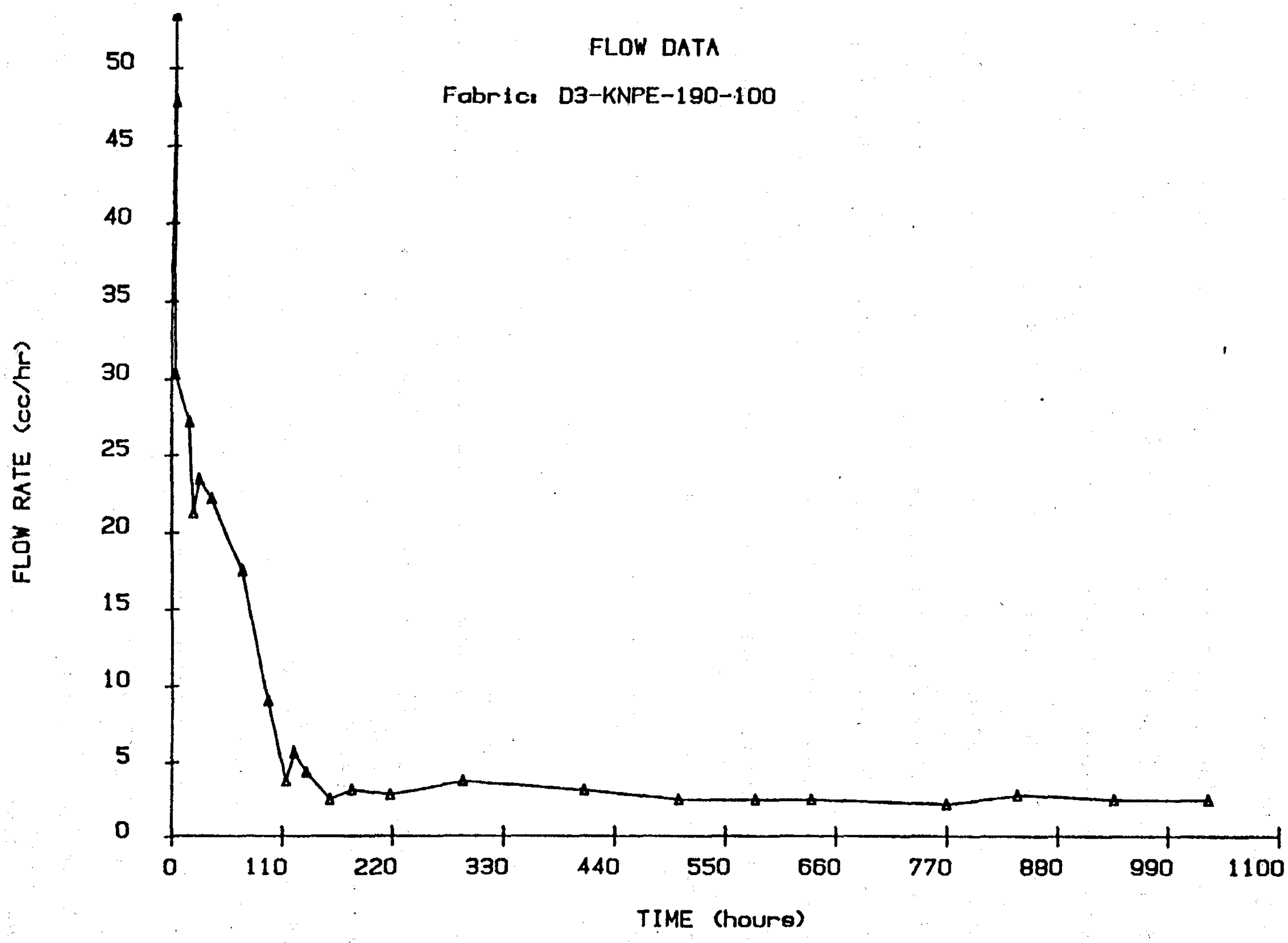

Figure 16: Example Plot of Flow Rate Versus Time

was determined by dividing the difference between successive cumulative flow readings (corrected for evaporation) by the elapsed time between the readings. The initial flow rate was determined as the cumulative flow (cc/hr) that had occurred after an approximate time period of 24 hours. The stabilized flow rate was determined from the by taking an average flow rate over the time period during which the flow rate appeared to stabilize. Since test groups A and B were performed without adding water to the system during the course of testing, the stabilized flow rates were determined as the rate at which stabilization appeared to first occur from the flow rate versus time plots. This procedure is justified by the flow rate results for test groups D, E, and F, as will be discussed in a subsequent section of this chapter.

Various geotextile properties and characteristics were analyzed to determine their effect on the performance of the soil/geotextile system. These included type of geotextile, type of polymer used in the manufacturing process, and the EOS and thickness of the geotextile. Other variables during the testing included total testing time, initial slurry solids content, and initial applied air pressure. Tables 3 and 4 present a summary of the test results. Figures 17 and 18 show plots of Equivalent Opening Size versus Initial Flow Rate and Stabilized Flow Rate, respectively. Figures 19 and 20 show plots of Thickness versus Initial Flow Rate and Stabilized Flow Rate, respectively.

An attempt was made to relate geotextile performance/clogging behavior to head loss data, similar to the procedures used by the U. S. Army Corps of Engineers; the Engineering Research Center, Civil

TABLE 3. SUMMARY OF TEST RESULTS FOR EACH GEOTEXTILE TESTED

GEOTEXTILE DESIGNATION	THICKNESS (inches)	EOS (in x 10^{-3})	OPEN AREA (%)	TOTAL TESTING TIME (hr)	INITIAL FLOW RATE (cc/hr)	STABILIZED FLOW RATE (cc/hr)	INITIAL CLOGGING INDICATOR	FINAL CLOGGING INDICATOR	INITIAL SOLIDS CONTENT (%)	FINAL SOLIDS CONTENT (%)
A1-FWPP-50-40/170	.050	8.3-16.5	-	641	25.7	2.5	-	-	17.0	29.5
A2-AWPP-18-70/30	.018	8.3-23	1	430	26.8	1.7	-	-	17.0	28.7
A3-JNPP-55-70/100	.055	5.9-8.3	-	624	26.0	4.5	-	-	17.0	30.9
A4-JNPP-90-80/100	.090	5.9-7.0	-	624	24.3	6.4	-	-	17.0	29.6
B1-ENPP-18-140/170	.018	3.5-4.1	-	600	20.1	6.8	-	-	19.2	30.2
B2-DNPP-110-80/100	.110	5.9-7.0	-	718	13.4	5.9	0	0	19.2	29.9
B3-AWPP-18-70/100	.018	5.9-8.3	4	718	20.1	7.6	-	-	19.2	29.9
B4-HNPE-10-70/100	.010	5.9-8.3	-	714	14.7	2.6	-	-	19.2	30.0
C1-GW-X-X	-	-	-	551	8.3	0.3	-	-	19.1	29.4
C2-FWPP-50-50/100	.050	5.9-11.7	-	551	6.6	0.1	-	-	19.1	28.8
C3-AWPP-30-30/70	.030	8.3-23	2	551	7.1	0.7	-	-	19.1	28.7
C4-ANPP-45-70	.045	8.3	0	551	10.8	0.6	-	-	19.1	28.7
D1-CWPV-16-100	.016	5.9	4-5	114	48.6	-	-	-	19.1	-
D2-BWPP-100-30	.100	23	6-12	1030	34.7	3.3	-	-	19.1	32.8
D3-KNPE-190-100	.190	5.9	-	1030	31.0	2.8	-	-	19.1	32.2
D4-IWPE-90-50	.090	11.7	-	1030	35.3	3.1	-	-	19.1	33.5
E1-GW-X-X	-	-	-	-	-	-	-	-	16.9	-
E2-FWPP-50-50/100	.050	5.9-11.7	-	663	35.4	15.1	3.2	3.0	16.9	33.0
E3-ANPP-45-70	.045	8.3	0	663	54.8	27.9	0.14	0.08	16.9	32.0
E4-AWPP-30-30/70	.030	8.3-23	2	-	-	-	-	-	16.9	-
F1-KNPE-75-50	.075	11.7	-	744	34.5	13.1	10.3	1.5	17.0	-
F2-KNPE-90-70	.090	8.3	-	744	35.2	5.2	-4.1	-3.8	17.0	-
F3-INPE-102-170	.102	8.3	-	744	35.4	13.0	2.4	1.4	17.0	-
F4-ENPP-15-70/100	.015	5.9-8.3	0	744	37.4	5.2	-0.6	-2.5	17.0	-

TABLE 4. TABLE SHOWING AVERAGE INITIAL AND STABILIZED FLOW RATES FOR DIFFERENT GEOTEXTILE AND POLYMER FIBER TYPES

TYPE	AVERAGE INITIAL FLOW RATE (cc/hr)	AVERAGE STABILIZED FLOW RATE (cc/hr)	FINAL SOLIDS CONTENT (%)
Overall	30.7	7.4	30.9
Nonwoven	29.7	8.4	30.7
Polypropylene	29.3	9.3	30.5
Polyester	30.2	7.3	31.1
Woven	32.4	5.6	31.2
Polypropylene	28.5	6.0	30.8
Polyester	35.3	3.1	33.5
Polyvinylidene Chloride	48.6	-	-
Polypropylene	29.0	7.8	30.6
Polyester	31.0	6.6	31.9
Polyvinylidene Chloride	48.6	-	-

Note: These values do not include test group C results.

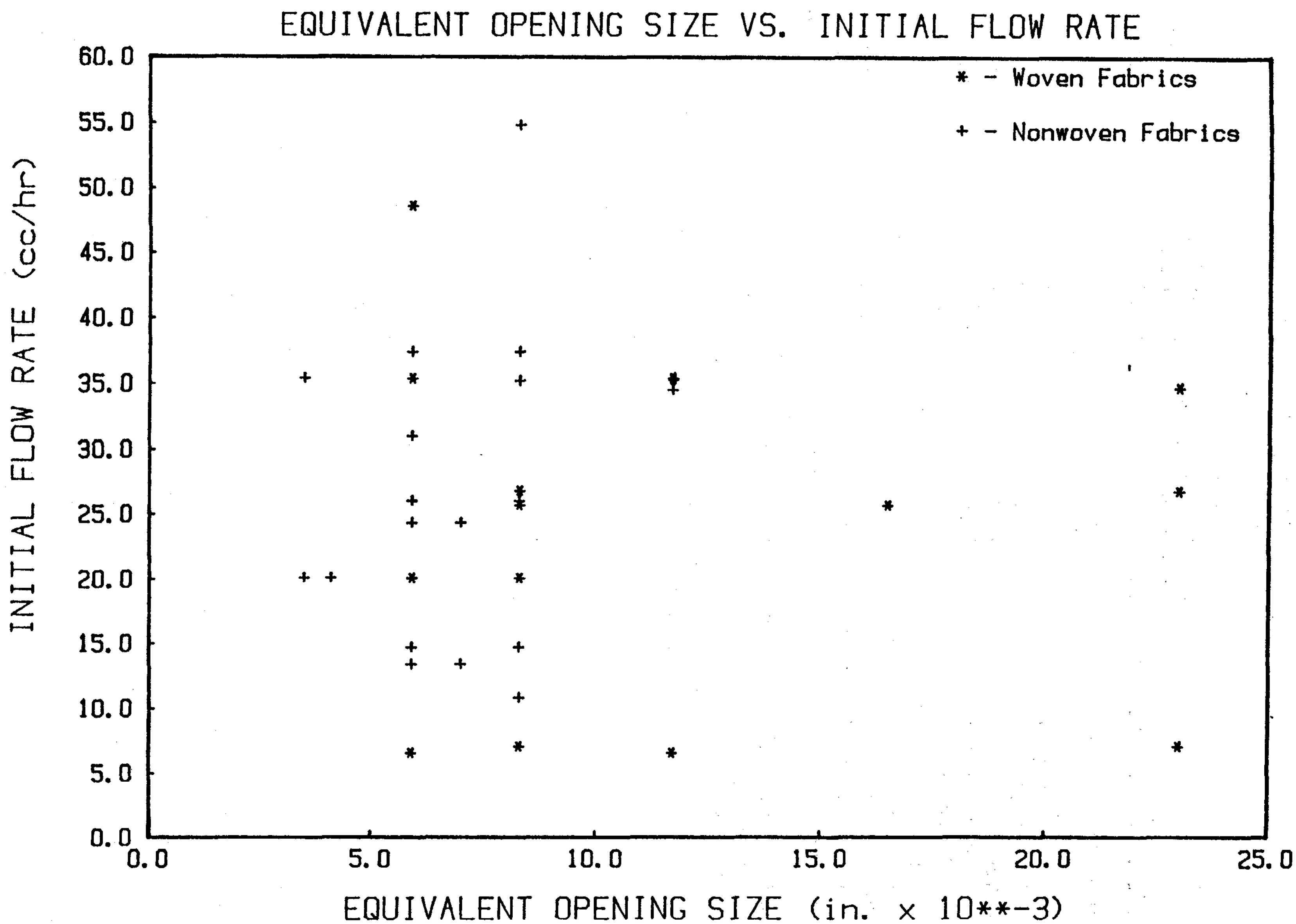

Figure 17: Equivalent Opening Size Versus Initial Flow Rate for Woven and Nonwoven Geotextiles

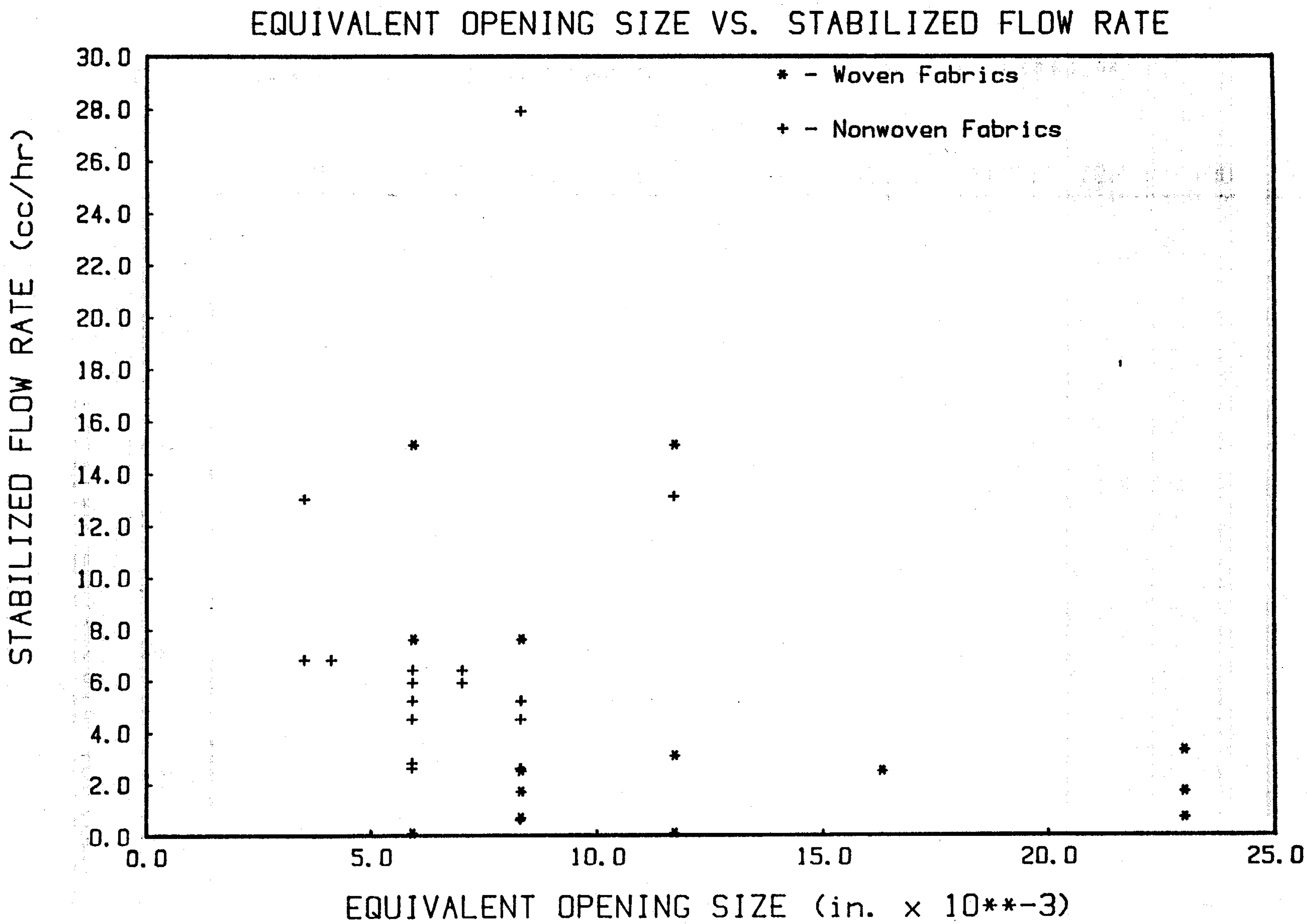

Figure 18: Equivalent Opening Size Versus Stabilized Flow Rate for Woven and Nonwoven Geotextiles

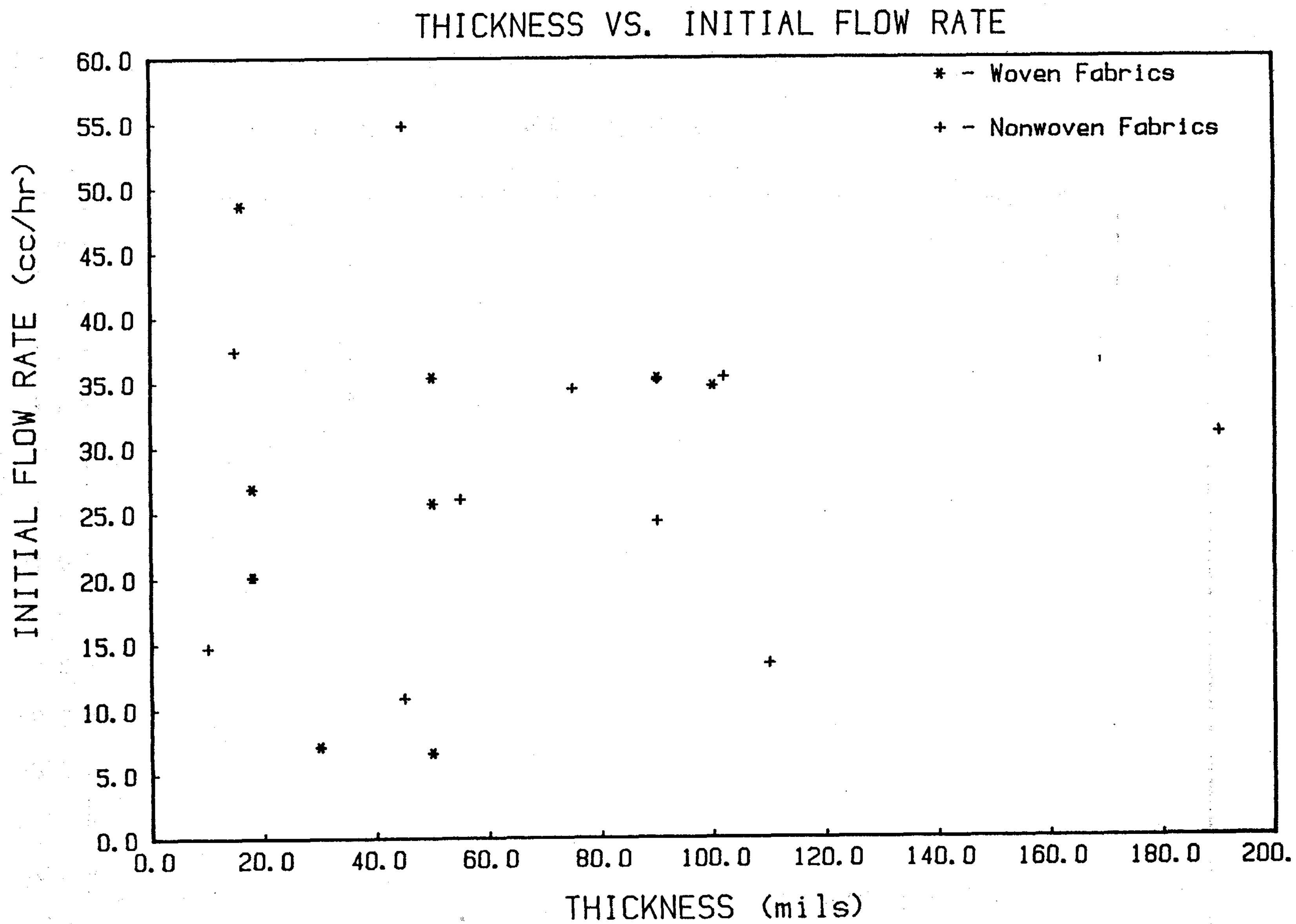

Figure 19: Thickness Versus Initial Flow Rate for Woven and Nonwoven Geotextiles

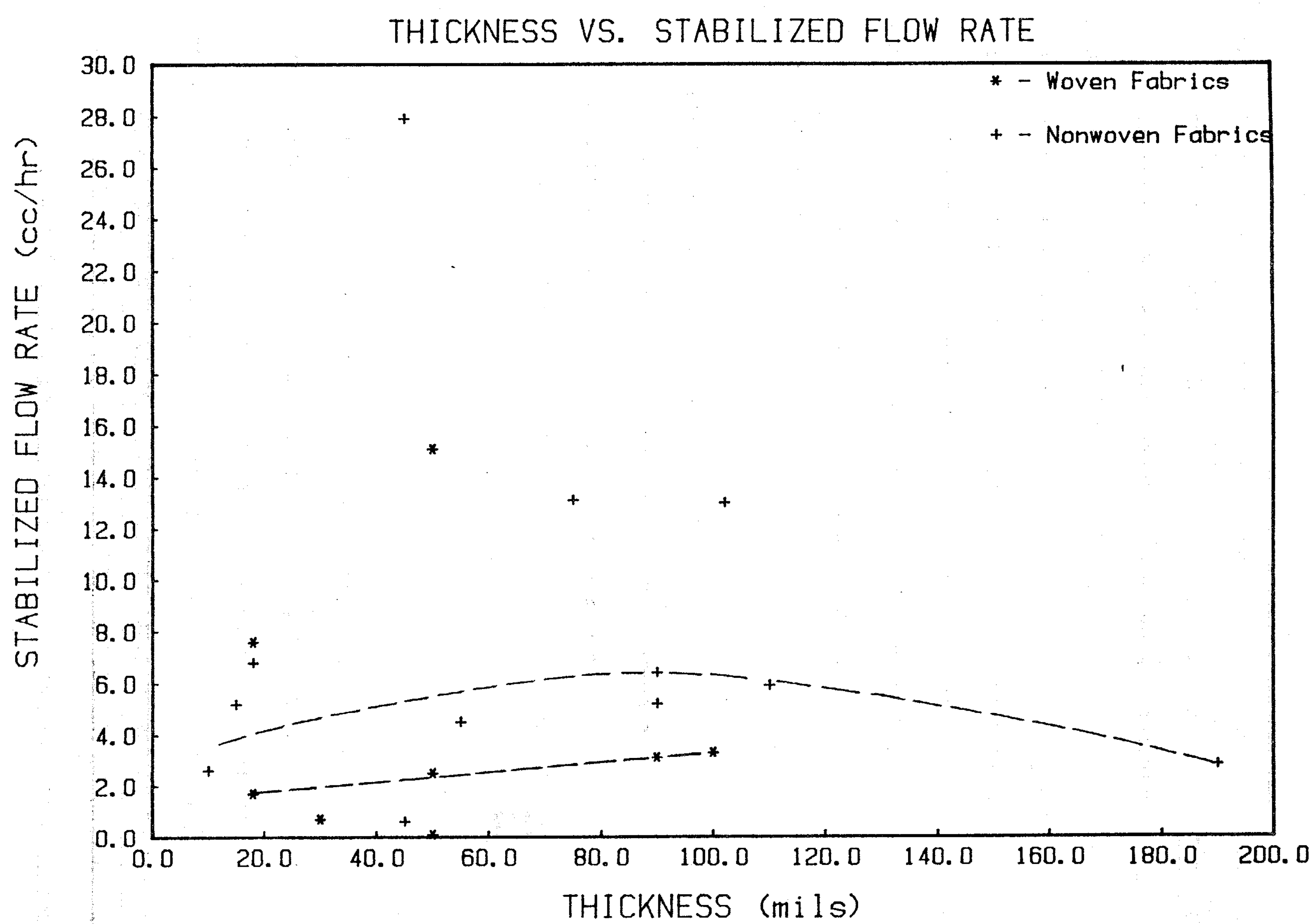

Figure 20: Thickness Versus Stabilized Flow Rate for Woven and Nonwoven Geotextiles

Engineering Department, Colorado State University, and by Haliburton and Associates. A clogging indicator (CI) was determined by dividing the hydraulic gradient (I_f) across geotextile plus 1/2 the diameter of the brass fitting by the hydraulic gradient (I_1) across the adjacent one inch of slurry. The clogging indicator results are summarized in Table 3. Plots of Clogging Indicator versus Time are presented in Figures B-1 through B-6 in Appendix B. A typical plot is shown in Figure 21. In a further attempt to determine clogging characteristics, scanning electron microphotographs (SEMs) were taken of several) representative geotextiles. The SEMs are shown in Figures C-1 through C-7 in Appendix C.

At the completion of testing, the final solids contents of the slurry at various depths beneath the geotextile were determined according to the procedures presented in Chapter III. The initial solids contents and the final solids contents adjacent to each geotextile are presented in Table 5.

FLOW RATE DATA

General

Six groups of four geotextiles were tested. However, due to excessive initial piping of the slurry solids through two of the woven geotextiles during test group E upon initial application of the air pressure, these geotextiles were unable to be tested. This resulted in a total of 22 tested geotextiles. Additionally, due to equipment malfunction during test group D, one woven geotextile was unable to be monitored for the duration of the test. Thus, 21 geotextiles were

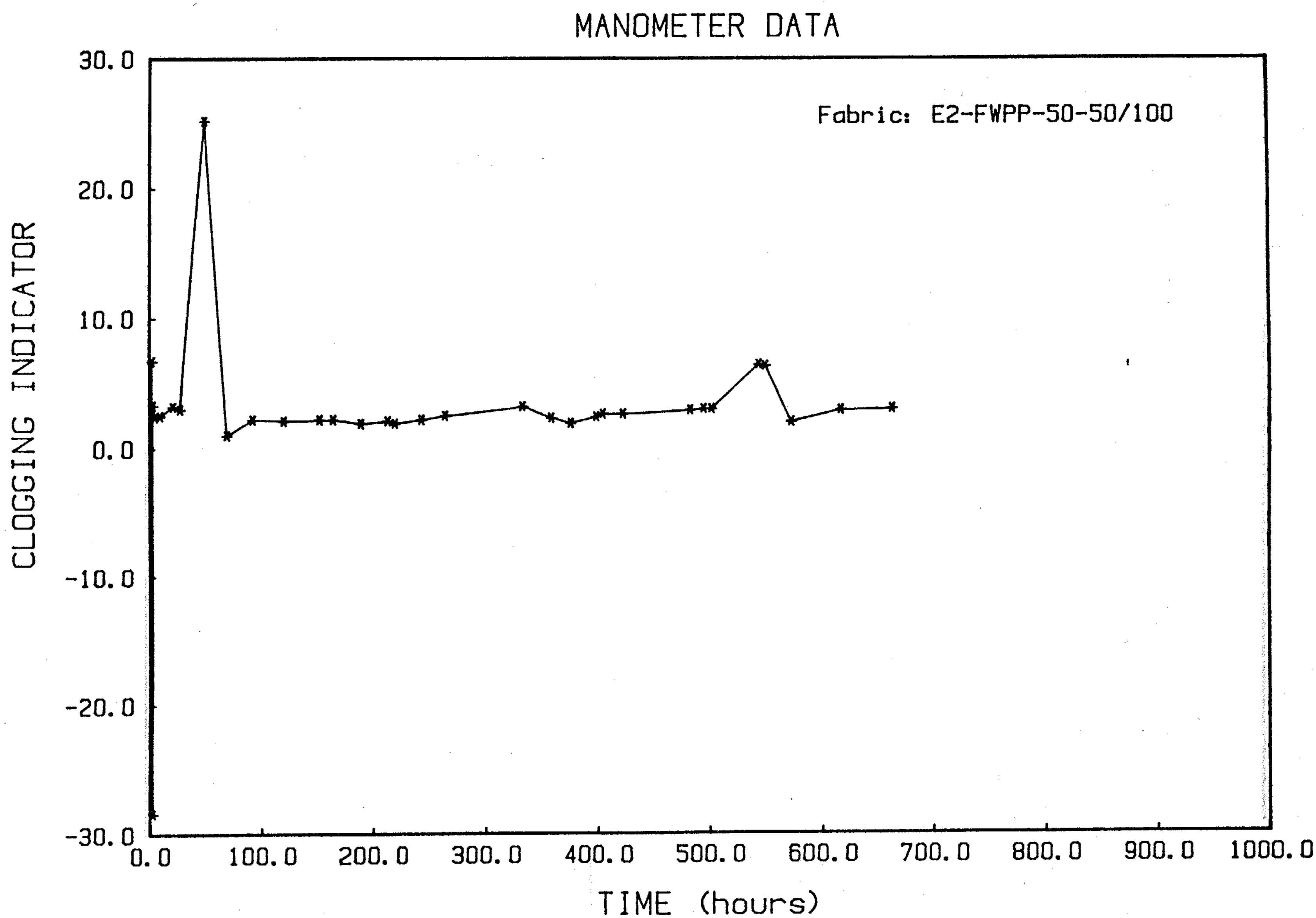

Figure 21: Example Plot of Clogging Indicator Versus Time

TABLE 5. Summary of Solids Content Data

Geotextile	SOLIDS CONTENT, %			
	Before Testing	After Testing		
		Top[a]	Middle[b]	Bottom[c]
A1-FWPP-50-40/70	17.0	29.5	26.6	26.0
A2-AWPP-18-70/30	17.0	28.7	26.9	28.4
A3-JNPP-55-70/100	17.0	30.9	27.7	25.1
A4-JNPP-90-60/100	17.0	29.6	26.9	25.7
B1-ENPP-18-140/170	19.2	30.2	23.9	23.2
B2-DNPP-110-80/100	19.2	29.9	25.9	24.0
B3-AWPP-18-70/100	19.2	29.9	26.0	24.8
B4-HNPE-10-70/100	19.2	30.0	26.9	24.8
C1-GW-X-X	19.1	29.4	23.6	20.7
C2-FWPP-50-50/100	19.1	28.8	23.6	22.8
C3-AWPP-30-30/70	19.1	28.7	22.0	21.8
C4-ANPP-45-70	19.1	28.7	22.2	22.2
D1-CWPV-16-100	19.1	--	--	--
D2-BWX-100-30	19.1	32.8	28.9	26.1
D3-KNPE-190-100	19.1	32.2	28.3	28.2
D4-IWPE-90-50	19.1	33.5	28.7	25.8
E1-GW-X-X	16.9	--	--	--
E2-FWPP-50-50/100	16.9	33.0	26.3	17.6
E3-ANPP-45-70	16.9	32.0	24.5	18.7
E4-AWPP-30-30/70	16.9	--	--	--
F1-KNPE-75-50	17.0	--	--	--
F2-KNPE-90-70	17.0	--	--	--
F3-INPE-102-170	17.0	--	--	--
F4-ENPP-15-70/100	17.0	--	--	--

a) Top of Permeameter - adjacent to geotextile
b) Middle of Permeameter
c) Bottom of Permeameter

monitored for the duration of testing. Of these, test groups C and E consisted of samples of the same four geotextiles. As shown in Table 3, the results from test group C seem unreasonably low and are felt to be nonrepresentative results as will be discussed later. Thus, comparisons of long-term performance characteristics were generally based on the results of 17 geotextile tests. However, the test group C results were used to obtain some useful conclusions concerning the test apparatus and procedures.

Figure 16 shows typical flow rate versus time results for a selected test. This figure shows the results of a group D test of a relatively thick nonwoven geotextile of polyester filaments with a thickness of 190 mils. (.190 in) and an EOS of 100 (U. S. Standard Sieve Number). The figure shows an initial rapid decrease in the flow rate which levels off at an elapsed time of approximately 150 hours and then remains relatively constant with time. As seen from Figures A-1 through A-22 this is a typical response. However, there was a large variation in the initial and stabilized flow rates for different geotextile/slurry systems, with initial flow rates varying from 13.4 to 54.8 cc/hr (not including the test group C results) and the stabilized flow rates varying from 1.7 to 27.9 cc/hr (again, not including test group C results).

A decrease in flow rate with time could result from;

1. clogging or plugging of the geotextile pores with solid clay particles, resulting in a decrease in permeability of the geotextile and, thus, flow rate across the geotextile,

2. consolidation of the slurry against the bottom of the geotextile, resulting in a decrease in permeability of the slurry and, thus, flow rate across the geotextile,

or

3. a combination of 1 and 2.

Geotextile clogging results from solid clay particles becoming trapped within the geotextile fibers, completely blocking pore openings. Plugging is partial geotextile clogging or partial blocking of the pore openings. Clogging would result in a virtually impermeable system since there would be no path available to water flow, thus, the system would be virtually useless for its intended function. Geotextile plugging results in partial pore blockage, decreasing the number of paths available to water flow. This is analagous to a decrease in void ratio of a solid body. Plugging would result in a more tortuous and longer flow path, thereby increasing the time for an individual water molecule to flow across the geotextile and decreasing the flow rate through the system. This would result in a decrease in the serviceability of the system but would not necessarily render the system useless for its intended function.

Geotextile clogging or plugging results in a decreased flow rate through the system due to a decrease in the permeability of the geotextile. Consolidation of the slurry against the bottom of the geotextile increases the solids content of the slurry, thereby decreasing the void ratio and, thus, the permeability, corresponding to a resulting decrease in the flow rate through the system. Thus, a decrease in flow rate could be the result of action within the geotextile, the slurry, or a combination of the two.

Test Groups A and B

Test groups A and B were performed without adding water to the system during the tests. Thus, a gradual decrease in flow rate was noted such that the value approached zero for each geotextile. The results are shown in Figures A-1 through A-8 in Appendix A. The initial flow rates varied from 13.4 cc/hr to 26.8 cc/hr. Since the flow rates approached a value of zero because water was not added to the system during the tests, the results of test groups D, E, and F were used to develop a method to determine stabilized flow rates for the group A and B tests. These values likely would have been observed had water been added to the system during the tests. By examining the flow rate, versus time plots for test groups D, E, and F, it was noted that the flow rates had generally stabilized after elapsed times ranging from approximately 75 to 140 hours, which was generally before water was added to the system. Therefore, the stabilized flow rates for the group A and B tests were determined by noting the first sign of stabilization within this general time range and the results are felt to be valid.

Test Group C

The results of the group C tests, which are shown in Figures A-9 through A-12 in Appendix A, are not consistent with the remainder of the test results. These tests showed erratic flow rate versus time responses, indicating that the slurry or some other factor within the system was likely controlling in response. It is possible that slurry contained "clumps" of relatively impermeable clay particles that were clogging the plumbing pipes and not allowing the flow of water through the system. Each geotextile showed an initial flow rate (after approximately 2 hours) comparable to the initial flow rates of the remainder of the geotextiles. However, a rapid decrease in the flow rates was noted until essentially a no flow condition occurred. However, upon adding more water to the system, the flow rates increased suddenly to approach the initial values but were accompanied by a rapid drop to again approach zero. The initial flow rates for the group C tests varied from 6.6 to 10.8 cc/hr and the stabilized flow rates varied from 0.1 to 0.7 cc/hr. Although presented as a portion of this report, the test group C results are considered to be meaningless with the exception that they indicate that the slurry or other factors within the system can control the flow rate. Therefore, these same four geotextiles were tested in test group E.

Test Group D

The test group D results are shown in Figures A-13 through A-16 in Appendix A. Water was added to the system after an elapsed time of 114 hours. The figures indicate an initial rapid decrease until the flow rates had essentially stabilized, similar to the results of test groups A and B. With the exception of permeameter 1, which was broken during the refilling process, each of the permeameters showed a slight increase in flow rates upon the addition of water to the system, indicating that the test was not a true constant head test. However, the flow rates did not increase significantly and they stabilized shortly after the addition of water, indicating that the tests could essentially be treated as constant head tests.

The initial flow rates ranged from 31.0 to 48.6 cc/hr and the stabilized flow rates ranged from 2.8 to 3.3 cc/hr. These results were similar to the results obtained in the group A and B tests, further indications that the group C test results are unreliable. The results for permeameter 1 (as shown in Figure A-13) indicate that the flow rate had not stabilized when the plumbing was broken after a time period of 114 hours; therefore, it was not possible to obtain a stabilized flow rate. The remainder of the test results indicated that stabilization had essentially occurred after time periods ranging from 134 to 158 hours. The group D tests for permeameters 2, 3, and 4 were performed for total elapsed times of 1030 hours. The flow rates after an elapsed time of 1030 hours were essentially the same as the flow rates upon initial stabilization as discussed above. Water was not added to the system during the intervening time period. This indicates that once an approximate stabilized flow rate had occurred, the results were not significantly affected by the water level drop that occurred within the supply tank and, thus, the test could essentially be treated and analyzed as a constant head test.

Test Group E

Test group E included two woven geotextiles that allowed initial piping of the slurry and thus could not be tested. The results for the two nonwoven geotextiles that were tested are shown in Figures A-17 and A-18 As with the previous tests, these tests initially showed a rapid decrease in flow rate before stabilizing after times ranging from approximately 92 to 152 hours. The initial flow rates ranged from 35.4

to 54.8 cc/hr and the stabilized flow rates ranged from 15.1 to 27.9 cc/hr.

Water was added to the system after elapsed times of 92, 359 and 550 hours. The geotextile corresponding to permeameter 2 showed no significant flow rate effects from adding water after elapsed times of 92 and 550 hours. However, a significant increase in flow rate noted when water was added after 359 hours of testing. The geotextile corresponding to permeameter 3 showed a slight increase in flow rate when water was added after 92 hours and somewhat more significant increases when water was added after 359 and 550 hours. These results indicate that the system was significantly disturbed when water was added after 359 hours but that the addition of water to the system had minor effects on the flow rates after 92 and 550 hours. Thus, these results also appear to indicate that the test can essentially be treated as a constant head test.

The geotextile corresponding to permeameter 2 showed an initial rapid decrease in flow rate followed by a gradual stabilization after a time period of approximately 152 hours. When water was added to the system after 359 hours, a rapid increase in flow rate occurred, followed by an erratic response over the subsequent approximate 200 hours, in turn followed by a rapid stabilization for the remainder of the test. It is interesting to note that the flow rate stabilized at essentially the same value as previously, indicating the validity of the stabilized value under the applied conditions.

Test Group F

The test group F results are presented in Figures A-19 through A-22 in Appendix A. These results show the rapid initial decrease in flow rate and subsequent stabilization as was generally noted in the previous tests. The stabilization time generally ranged from 41 hours to 316 hours, although the geotextiles corresponding to permeameters 1, 2, and 3 showed slightly erratic responses for some time period after stabilization had occurred. However, the geotextile corresponding to permeameter 4 showed an almost "ideal" response, exhibiting an almost constant flow rate after a time period of 188 hours as shown in Figure A-21 The initial flow rates ranged from 34.5 to 37.4 cc/hr and the stabilized flow rates ranged from 5.2 to 13.1 cc/hr. Water was added to the system after an elapsed time of 290 hours. The geotextiles generally showed only a slight increase in flow rate upon addition of water to the system, showing that the test may essentially be evaluated as a constant head test.

General Discussion of Results

As discussed above, all of the geotextiles showed an initial rapid decrease in flow rate generally followed by a stabilization after elapsed times ranging from 41 hours to 316 hours for the test groups in which water was added to the system during testing. Most of the stabilization times ranged from 92 to 158 hours. These observations were used to obtain stabilized flow rates for the group A and B tests, during which water was not added to the system. The above results also indicate that the tests could have been performed for a shorter period of time in order to obtain stabilized flow rates. A testing time of 200 hours seems reasonable, unless erratic flow rate results indicate that a longer time period is required for an individual geotextile or group of geotextiles.

The majority of the test results indicated a slight increase in flow rate upon the addition of water to the system. The 3 psi of air pressure that was applied to the system during most of the tests is equivalent to 6.9 feet of water head. An additional water head of approximately 1.7 feet (above the permeameter outflow levels) was applied at the beginning of the tests in order to fill the supply tank. Thus, a total head difference of approximately 8.6 feet of water (equivalent to 4.8 feet of surcharge placed at a dry density of 110 pcf) was applied at the beginning of the test to initiate water flow through the system. After the sight tube was added to the supply tank in order to monitor the water level within the tank, water was added when the water level was at the bottom of the sight tube, corresponding to a drop in water head of approximately 0.5 feet, or approximately 6% of the initial total head difference at the beginning of the test. According to Darcy's Law, this should result in only a 6% decrease in the flow rate, which is rather insignificant. The test results indicated that generally minor increases in flow rate were exhibited when water was added to the system which leads to the conclusion that the test results can essentially be evaluated and analyzed as constant head tests.

The test group C results do not appear consistent with the remainder of the test results, as the initial and final flow rates were significantly less for the group C tests than for the remainder of the tests. This indicates that there were some inconsistencies during these tests within the testing system or the testing procedures that were not exhibited in the remainder of the tests. However, there was no obvious deviation in the testing procedures or in the system setup. There did not appear to be a difference in the slurry that was used for testing. However, since there were no significant leaks in the system, (although minor leaks were noted and fixed during testing) and since the permeability, and, thus, flow rate, of any system is controlled by the least permeable portion of the system, it is concluded that the slurry likely clotted or clogged within the PVC plumbing of the system, acting as a relatively impermeable barrier to water flow. Upon adding water to the supply tank during testing, it is felt that there was enough disturbance within the system to rearrange the clots or clogs temporarily to allow water to flow, possibly between a small annular space between the clogged slurry and the PVC plumbing. However, within a short time the clots had rearranged themselves to again provide a relatively impermeable barrier to water flow. Thus, it is concluded that the slurry was controlling the flow rate through the system by means other than consolidation against the bottom of the geotextile and that the results are inconsistent with the remaining test results and should not be used for comparative or conclusive purposes.

Effects of Geotextile Properties

Two physical geotextile properties which were analyzed for possible effects on the system flow rate were the thickness and the Equivalent Opening Size (EOS). Roth could be logically considered as factors in the clogging/plugging characteristics of geotextiles under the test conditions, especially for the nowoven geotextiles. It would seem reasonable that the thicker nonwoven geotextiles would result in a more tortuous flow path for both water molecules and solid particles than would the thinner nonwoven and the woven geotextiles, resulting in a greater probability that a solid particle would become entrapped within the geotextile. As the number of entrapped solid particles increases, the "void ratio" of the geotextile decreases, resulting in a decrease in the permeability of the geotextile and, thus, the flow rate. A smaller EOS is analogous to a smaller void ratio, or area available for water flow, which would result in a lower flow rate under a constant hydraulic gradient.

Figures 17 and 18 show plots of EOS versus Initial Flow Rate and EOS versus Stabilized Flow Rate for both nonwoven and woven geotextiles. As seen in the figures, eight of the nonwoven geotextiles (not including the test group C geotextile) exhibited an average EOS within the range of 5.9-8.3 x 10^{-3} inch (U. S. Standard Sieve Numbers 70-100). Large variations in initial and stabilized flow rates were noted for these geotextiles, with initial rates ranging from 13.4 cc/hr to 54.8 cc/hr and stabilized flow rates ranging from 2.6 to 27.9 cc/hr. Thus these results fail to show any apparent correlation between geotextile EOS and the initial or stabilized flow rates for either the nonwoven or woven geotextiles. Thus, the decrease in flow rates are likely due to other factors, such as geotextile thickness, slurry consolidation, bacterial growth, nonhomogeneous soils resulting from test preparation procedures, or some combination of these or other factors.

Figures 19 and 20 show plots of geotextile thickness versus initial and stabilized flow rates for both woven and nonwoven geotextiles. Figure 19 shows considerable scatter in the initial flow rate results for the woven geotextiles. There appears to be no correlation between initial flow rate and thickness for woven geotextiles. At first glance there appears to also be considerable scatter in the stabilized flow rate results for woven geotextiles. However, a closer look at Figure 20 indicates that four of the data points lie on an approximate straight line, which indicates that a correlation may exist. No woven geotextiles were tested that had a thickness greater than 100 mils; however, there appears to be very few woven geotextiles on the market having a thickness greater than 100 mils. Thus, if a woven geotextile is used under field applications, the lab results indicate that a thickness in the range of 90-100 mils will provide the best results.

The nonwoven geotextiles also exhibited scatter in the initial flow rate versus thickness results. However, the results of Figure 19 indicate that the initial flow rate appears to peak at a thickness in the range of 80 to 110 mils. There is also some scatter in the stabilized flow rate versus thickness results for the nonwoven geotextiles as shown in Figure 20. However, there appears to be a peak in the results at a thickness in the range of 70-110 mils. Thus, as a first approximation, the lab tests indicate that nonwoven geotextiles with a thickness in the range of 70-110 mils provide the best long term filtration characteristics. However, it is suggested that further investigations of nonwoven geotextiles within this thickness range be performed in order to determine if this apparent optimum thickness in combination with other properties (e.g., EOS, polymer type, etc.) provide some optimum correlations. Of the five nonwoven. geotextiles tested within this thickness range, the EOS varied from 3.5 to 11.7 x 10^{-3} inches (U. S. Standard Sieve Numbers 160~50). These geotextiles included three manufactured of polyester filaments and two of polypropylene filaments. The highest stabilized flow rates were exhibited by two polyester geotextiles with EOS values at the extremes of the above range. However, as previously discussed, the test results showed no apparent correlation between EOS and stabilized flow rate. Therefore, the flow rate test results indicated no apparent justification for selecting a geotextile for field use based on EOS. Subsequent sections of this chapter will consider geotextile clogging characteristics based on EOS and thickness.

Effects of Geotextile Type

As mentioned previously, geotextiles can generally be subdivided into nonwoven and woven. The geotextile fiber may consist of polypropylene, polyester, polyvinylidene chloride, nylon or some other polymer. It is possible that the manufacturing method and/or the fiber polymer could have an effect on the system flow rate. The 20 geotextiles tested (not including the group C tests), included 9 woven and 11 nonwoven. The breakdown of fiber types was as follows:

Nonwoven:

Polypropylene - 6

Polyester - 5

Woven:

Polypropylene - 6

Polyester - 1

Polyvinylidene Chloride - 1

Unknown - 1

Total:

Polypropylene - 12

Polyester - 6

Polyvinylidene Chloride - 1

Unknown - 1

As shown above, twice as many geotextiles consisting of polypropylene fibers were tested as geotextiles consisting of polyester fibers. This seems to be fairly representative of geotextiles on the market in the United States today based on a review of the literature supplied by the manufacturers.

Table 4 summarizes the average initial and stabilized flow rates for nonwoven and woven geotextiles and for the various polymer types. The table indicates that the woven geotextiles exhibited a higher average initial flow rate but the nonwoven geotextiles exhibited a higher average stabilized flow rate. The average initial flow rate exhibited by the woven geotextiles was 9% higher than the nonwoven geotextiles and seems rather insignificant. However, the average stabilized flow rate exhibited by the nonwoven geotextiles was 52% higher than the woven geotextiles, a much more significant figure. In field consolidation applications the long term performance of the system is of greater significance due to the long term consolidation nature of clays. Therefore, the difference in average stabilized flow rate between the nonwoven and woven geotextiles is of greater significance than the average initial flow rate. Thus, the flow rate results seem to indicate that nonwoven geotextiles exhibited better long term performance characteristics than woven geotextiles in the laboratory.

Three different polymer fiber types were tested; polypropylene, polyester, and polyvinylidene chloride. Additionaly, one geotextile of unknown fiber type was tested. The testing included a total of 12 polypropylene geotextiles, 6 polyester geotextiles and 1 polyvinylidene chloride geotextile. However, the permeameter corresponding to the polyvinylidene chloride geotextile was broken during testing, before stabilization of the flow rate had occurred; therefore a stabilized flow rate was not obtained. Thus, the following discussion is limited to the polypropylene and polyester geotextiles.

A review of the results indicates that the polypropylene geotextiles exhibited an average initial flow rate of 28.4 cc/hr and the polyester geotextiles exhibited an average value of 31.0 cc/hr, a value 9% higher than for the polypropylene geotextiles. This number is the same as the difference between the average initial flow rates of nonwoven versus woven geotextiles and is considered relatively insignificant. The average stabilized flow rates exhibited by the polypropylene and polyester geotextiles were 8.4 and 6.6 cc/hr, respectively. Thus, the polypropylene geotextiles exhibited a 27% higher value for the average stabilized flow rate than did the polyester geotextiles, indicating that polypropylene geotextiles exhibited better long term filtration characteristics than did polyester geotextiles.

The previous discussion indicates that nonwoven and polypropylene geotextiles exhibited better long term filtration characteristics than did woven and polyester geotextiles. However, one must look at the performance of nonwoven polypropylene versus nonwoven polyester, woven polypropylene and woven polyester geotextiles before drawing any conclusions from these results. The results presented in Table 4 indicate that the woven and nonwoven polyester geotextiles exhibited higher average initial flow rates but that nonwoven polypropylene and nonwoven polyester geotextiles exhibited the highest average stabilized flow rates, with nonwoven polypropylene geotextiles exhibiting the higher values. Thus, the flow rate results indicate that nonwoven polypropylene geotextiles exhibit superior long term filtration characteristics over competitive types.

General Overview of Test Results

The previous discussion indicates that nonwoven polypropylene geotextiles with thicknesses in the range of 70-110 mils exhibited the best long term filtration characteristics in the lab. However, it would seem prudent to verify these results in the field, as different conditions exist in the field that are not encountered in the relatively controlled laboratory environment, such as handling and placement techniques, weather variations, ultraviolet light, among others. Each of these conditions, and any others that might be encountered, should be evaluated carefully before selecting a geotextile for large scale field use. The laboratory provides a means for evaluating various geotextiles under controlled conditions and for determining an initial conclusion as to long term performance characteristics.

A review of Table 4 reveals an interesting result. The initial flow rates of each group of geotextiles were generally fairly consistent as a group, exhibiting a relatively narrow range of values. Specifically, the initial flow rates of each group A geotextile were higher than the corresponding values for the group B geotextiles. The group B initial flow rates were lower as a group and individually than any other group or individual geotextile, with the exception of the test group C geotextiles, the results of which are considered inconsistent as discussed previously. This indicates that initially the soil seems to be controlling the permeability of the system. This seems logical since a review of Table 1 indicates that the permeability of each geotextile (as supplied by the manufacturer) was much greater than the permeability of the waste clay slurry. The least permeable layer within the system controls the permeability of the entire system. A review of the stabilized flow rates within each test group indicates a greater degree of fluctuation than for the initial flow rates which indicates that the geotextile may have some effect on the stabilized flow rates. This idea will be discussed in subsequent sections as the results of the scanning electron microphotographs are analyzed.

Manometer Data

An attempt was made to analyze geotextile clogging by measuring the variation in total heads at different points within the system, specifically, adjacent to the bottom of each geotextile and one inch below this level. The total head of each permeameter outflow level, and thus, the top of the geotextile remained constant for the duration of each test. Also, as discussed previously, the total applied head remained essentially constant for each test group. Thus, the head loss and hydraulic gradient across the geotextile and through the adjacent one inch of slurry could be determined. The ratio of the hydraulic gradient across the geotextile to the hydraulic gradient across the adjacent one inch of slurry was called the clogging indicator, and was similar to the gradient ratio and modified gradient ratio used by Calhoun, the U. S. Army Corps of Engineers, Colorado State University, and Haliburton & Associates. An increase in the clogging indicator indicates some degree of geotextile clogging. Clogging indicator results were obtained for the test group E and F geotextiles, which included a total of six geotextiles.

The clogging indicator results are presented in Figures B-1 through B-6 in Appendix B. A typical plot is shown in Figure 21. It should be noted that the approximate total head difference between the supply tank and the permeameter outflow levels was approximately 265 cm (equivalent to 3 psi applied air pressure and 21 inches elevation difference). The manometer test results are discussed in the following paragraphs.

The results for the geotextile designated as E2-FWPP-50-50/100 (a woven geotextile) shown in Figures 21 and B-l indicate erratic clogging indicator results for the initial approximate 50 hours of testing followed by relatively stable results thereafter. A review of the flow rate results indicates that the flow rates began to level off at an elapsed time of approximately 21 hours, but some inconsistencies were noted until an elapsed time of approximately 50 hours. Thus, there appears to be a correlation between the somewhat erratic nature of the flow rate results and the manometer results. A review the test data revealed that, when the air pressure was removed from the system after an elapsed time of 92 hours in order to add water to the supply tank, the water levels in the manometer tubes dropped significantly, indicating a decrease in pressure head. This indicated the need to modify the system such that the pressure heads were "locked" into the manometers when the air pressure was removed in order to decrease the time required for the manometer readings to reach stable values upon reapplication of the air pressure. It should also be noted that very little total head was lost to the point in the system located one inch below the bottom of the geotextile. This is an indication that significant slurry consolidation had occurred against the bottom of the geotextile since a greater head loss would be expected through a soil layer of higher solids content. This fact is verified by the solids content results as will be discussed later. The results also indicate a very gradual increase in clogging indicator with time, suggesting that the geotextile was undergoing some degree of clogging or plugging. However, as the flow rate results indicate, the long term filtration characteristics of the geotextile was not significantly affected.

The geotextile designated as E3-ANPP-45-70 (a nonwoven geotextile) exhibited clogging indicators that generally stabilized after a time period of approximately 10 hours, then decreased after a time period of approximately 120 hours. The values remained relatively steady until an elapsed time of approximately 359 hours, after which the results were somewhat erratic for the remainder of the test. These results are shown in Figure B-2 and are similar to the corresponding flow rate results, which generally leveled off after an elapsed time of approximatley 92 hours but fluctuated within a defined range of values thereafter. Water was added to the system after elapsed times of approximately 92 and 359 hours. It is felt that the leveling off of the clogging indicators after 10 hours indicates that the system had overcome initial instabilities. A possible explanation for the erratic behavior after 359 hours is that the addition of water may have disturbed the system in some way which affected the clogging indicator results. However, the results stabilized subsequent to adding water to the system after 92 hours, indicating that the addition of water affected the system differently each time. The stabilization of the clogging indicator results after 92 hours correspond to a general leveling off of the flow rate at the same time.

In contrast to the previously discussed geotextile, the clogging indicator for the geotextile corresponding to permeameter 3 showed no significant time lag before returning to steady conditions after the air pressure was removed from the system to add water to the supply tank. The results also indicate that very little total head was lost through the system to the point located one inch below the bottom of the geotextile as was indicated previously. A majority of the head loss occurred within the one-inch of slurry adjacent to the bottom of the geotextile, with very little head loss occurring across the geotextile, as indicated by the very small values obtained for the clogging indicator. Thus, this indicates that very little geotextile clogging occurred. However, a review of the scanning electron micrographs (SEM's) for this geotextile indicates that some degree of clogging had occurred. The SEM results will be discussed in detail in the following section of this report.

The test group F manometer results were inconsistent with the test group E results and, in some cases, theoretically impossible results were obtained. However, the results are presented in Figures B-3 through B-6 in Appendix B because the data was obtained as part of the research. All four of the tested geotextiles in test group F were nonwoven.

Geotextile F1-KNPE-75-60 (Figure B-3) showed inconsistent clogging indicator results until an elapsed time of approximately 74 hours, after which the values were relatively constant until an elapsed time of approximately 187 hours. The values then suddenly increased before stabilizing after an elapsed time of 290 hours. The values remained constant until an elapsed time of 362 hours, after which the data indicated no head loss across the geotextile for the remainder of the test. Geotextile F2-KNPE-90-70 (Figure B-4) showed somewhat erratic, results for the duration of the test although a general stabilization occurred after time periods of approximately 15 and 316 hours. The results indicated negative clogging indicator values for the duration of the test, the implications of which will be discussed in the following paragraph. Geotextile F3-INPE-102-170 (Figure B-5) showed erratic clogging indicator results with some negative values noted, until a general stabilization occurred after a time period of approximately 427 hours. Additionally, the data indicated no head loss occurred within the one-inch soil layer and adjacent to the bottom of the geotextile at an elapsed time of 41 hours. Geotextile F4-ENPP-14-70/100 (Figure B-6) exhibited initial erratic clogging indicator results which stabilized after a time period of approximately 15 hours. The values were relatively constant until an elapsed time of approximately 74 hours, after which the values increased gradually until relatively constant values again were obtained after a time period of 124 hours. The values then remained constant before steadily decreasing after a time period of approximately 448 hours and stabilizing for a final time after an elapsed time of approximately 620 hours. The values were negative for the duration of the test.

The manometer results for the group F tests were inconsistent with the group E test results. The group F test results indicate that a majority of the head loss occurred before the water flow reached the one-inch soil layer adjacent to the bottom of the geotextiles. Very little head loss occurred in this one-inch soi1 layer or across the geotextile. The group E test results indicated that virtually all of the head loss occurred within the one-inch soil layer adjacent to the geotextile and across the geotextile. Additionally, the negative clogging indicator values obtained for the group F geotextile indicate a gain in total head either within the one-inch soil layer adjacent to the bottom of the geotextile or across the geotextile, both conditions which are impossible under the applied test conditions. These results indicate that the manometers were not functioning properly. Thus, no conclusions will be developed from the manometer results, other than the fact that they were not functioning properly. However, that is not to say that conclusive results are not attainable. The major problem experienced with the manometer setup was that of inhibiting slurry flow through the manometer tubes. It is felt that good results can be obtained once this problem is overcome. The group E manometer results appear to be reasonable. The results indicate that the nonwoven geotextile experienced a lesser degree of clogging than did the woven geotextile as evidenced by stabilized clogging indicators on the order of 0.10 and 3.0, respectively. However, more results are needed before concrete conclusions can be developed.

SCANNING ELECTRON MICROPHOTOGRAPHS

SEM's were taken of seven different geotextiles before and after testing in order to investigate the phenomenon of geotextile clogging. It was hoped that the SEM's could be used to reinforce the manometer data and flow rate data in order to help in the selection of a geotextile for field use. However, because of the difficulties experienced with the manometer devices, the SEM's can only be compared with the manometer results as a first approximation and are best suited for use in conjunction with the flow rate data.

Table 6 lists the geotextiles that were photographed under the scanning electron microscope and the properties of and test results obtained. The SEM's were performed on five nonwoven and two woven geotextiles. The microphotographs are shown in Figures C-1 through C-7 Figures C-1, C-2, C-4, C-6 and C-7 show the wide range of pore sizes exhibited by nonwoven geotextiles. The nonwoven needlepunched geotextiles shown in Figures C-1, C-6 and C-7 show a more random fiber orientation than the spunbounded geotextiles of Figures C-2 and C-4,

TABLE 6. LIST OF GEOTEXTILES AND THEIR PROPERTIES OF WHICH SEMs WERE OBTAINED

GEOTEXTILE	EOS (in x 10^{-3})	THICKNESS (inches)	STABILIZED FLOW RATE (cc/hr)	FINAL CLOGGING INDICATOR
A4-JNPP-90-80/100	5.9-7.0	.090	6.4	-
B1-ENPP-18-140/170	3.5-4.1	.018	6.8	-
B3-AWPP-18-70/100	5.9-8.3	.018	7.6	-
B4-HNPE-10-70/100	5.9-8.3	.010	2.6	-
D1-CWPV-16-100	5.9	.106	-	-
D3-KNPE-190-100	5.9	.190	3.3	-
E3-ANPP-45-70	8.3	.045	27.9	0.08

which show a much more parallel orientation to the fibers. The SEM's also show that the woven geotextiles (Figures C-3 and C-5) possess more distinct pore openings than the nonwoven, resulting in a less tortuous flow path to water and solid particles.

The SEM's indicate that for the two woven geotextiles shown in Figures C-3 and C-5, geotextile B3-AWPP-18-70/100 appears to have undergone a greater degree of clogging during testing than geotextile D1-CWPV-15-100. Additionally, the microphotographs indicate a large amount of slurry buildup on the polymer fibers in both cases. However, it should be noted that the permeameter corresponding to geotextile D1-CWPV-16-100 was broken during testing and that a stabilized flow rate was not attained. The flow rate at the end of testing was 6.0 cc/hr for geotextile D1-CWPV-16-100 and the stabilized flow rate for geotextile B3-AWPP-18-70/100 was 7.6 cc/hr. It would be expected that the geotextile with the greater degree of clogging would show the lowest flow rate, which was not the case. However, it should be noted that the magnification that resulted in the microphotographs enabled only one opening to be photographed for the woven geotextile, and, thus, may not be representative of the entire geotextile area. Perhaps a lesser magnification would have been more appropriate. Therefore, the microphotographs obtained for the woven geotextile indicate that some clogging and slurry buildup on the fibers did occur during testing; however, they are inconclusive in relating stabilized flow rates to clogging.

The microphotographs obtained for the nonwoven geotextiles are more conclusive. Figure C-2 shows that virtually no clogging occurred in geotextile B1-ENPP-18-140/170. Figure C-7 indicates a small amount of clogging occurred in geotextile E3-ANPP-45-70. Figures C1 and C-6 indicate that a moderate amount of clogging occurred in geotextiles A4-JNPP-90-60/100 and D3-KNPE-190-100, respectively, and Figure C-4 indicates a large amount of clogging occurred in geotextile B4-HNPE-10-70/100. These results seem to show a reasonable correlation with the stabilized flow rate results presented in Table 6, as the higher stabilized flow rates correspond to the geotextiles which the SEM's indicate to have undergone the least amount of clogging and the lower stabilized flow rates correspond to the geotextiles which appear to have undergone the greatest degree of clogging. Thus, the microphotographs indicate that some degree of clogging occurred in all of the geotextiles and that for the nonwoven geotextiles, the stabilized flow rate was controlled to a large degree by clogging or plugging of the pores by solid clay particles. The microphotographs obtained for the woven geotextile are inconclusive.

As mentioned above, the microphotograph indicated that virtually no clogging occurred in geotextile B1-ENPP-18-140/170. As noted in Table 6, this was a relatively thin geotextile, exhibiting a thickness of 18 mils. A possible explanation for this phenomenon is that, because of the thin nature of the geotextile, a less tortuous flow path results, and any solid particles that penetrate the geotextile have a greater chance of being"washed" completely through rather than becoming lodged within the pores. However, this was not noted in all of the thin geotextiles, indicating that other factors, such as the consolidation of the slurry against the bottom of the geotextile, must be involved in this phenomenon. Thus, it appears that the stabilized flow rates were a result of a combination of geotextile clogging and slurry consolidation. It should be emphasized that the laboratory testing was performed with an initial slurry solids content ranging from approximately 17 to 19 percent. Some passage of solid particles occurred during the course of testing, as noted by a thin film of clay on top of most of the geotextiles at the conclusion of testing. No procedure was developed for quantifying the amount of solids that passed through each geotextile, as only general observations were made. With the exception of the test group E geotextiles, which experienced a significant amount of solids piping at the onset of testing, the amount of piping was not significant to the performance of the geotextile and appeared to have no effect on the stabilized flow rates. The piping appears to be a natural phenomenon that occurs in the formation of a "bridge" of solids against the bottom of the geotextile and did not appear to correlate to the EOS or percent open area. However, a general observation was that the nonwoven geotextiles appeared to allow less piping than the woven. It is not known why the test group E geotextiles experienced significant piping before the formation of the above mentioned "bridge," as test procedures were consistent with the remainder of the test.

Table 5 shows that at the completion of testing, the solids contents within the permeameters were greatest adjacent to the geotextiles and generally decreased with distance from the geotextile. This indicates that, after a period of time, water may become trapped beneath this "crust" of material and the consolidation process may not continue within the waste clays. *Thus, the use of a geotextile for* *capping phosphate waste clays may not provide the desired consolidation results.*

General Discussion

It should be kept in mind that the previous discussion of results were developed from the laboratory test results which were obtained under laboratory conditions. Although every attempt was made to duplicate field conditions where possible, rarely do laboratory conditions adequately duplicate the field environment. Some of the important field conditions which it is felt were reasonably duplicated in the lab were the initial solids content of the slurry and consolidation of the slurry against the bottom of the geotextile and the upward ("squeezing" out of water as opposed to the downward flow of water in the standard permeability test.Some field conditions that must be considered which were not encountered by the laboratory specimens include exposure to ultraviolet light, microorganisms, and fluctuating weather conditions (i.e., temperature, rainfall, humidity); shipping, storage, and handling considerations; and construction considerations such as geotextile and surcharge placement techniques and anchorage around the geotextile edges.The reader may be able to add to the above list, all of which must be taken into consideration before a geotextile is selected for utilization in field application.

Another factor which must be considered, and certainly a major factor, is the cost/benefit of the procedure. Certainly the results presented in this report indicate that the procedure is effective in the lab and, thus, may be effective in the field. If proven effective in field tests, then the benefit would certainly be attractive. However, in analyzing the cost of such a procedure, all of the above factors, and any others that the reader may be able to add to the list, should be considered.

In summary, the laboratory results indicate that the addition of a geotextile as a phosphatic waste clay capping material will result in a decrease in flow rate with time until a stabilized flow rate is attained, with this decrease likely due to a combination of consolidation of the slurry and partial clogging/plugging of solid particles within the geotextile. A correlation appeared to exist between clogging/plugging and stabilized flow rates for nonwoven geotextiles.

The test results indicate that nonwoven polypropylene geotextiles with a thickness in the range of 70 to 110 mils exhibited the best long-term filtration characteristics under the applied laboratory procedures as previously discussed. Thus, it is recommended that these guidelines be utilized in selecting a geotextile for field testing such that long-term filtration characteristics may be observed under actual field conditions. If the selected geotextile performs satisfactorily in field tests and if the method appears to be cost effective, it is suggested that the method be utilized for large scale field use to enhance the consolidation process of phosphatic waste clays.

CHAPTER V: CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

CONCLUSIONS

The following conclusions in line with the objectives presented in the Introduction were developed based on the laboratory results as presented in this report:

1. Nonwoven polypropylene geotextiles with a thickness in the range of 70 to 110 mils exhibited the best long-term permeability/filtration characteristics and should be selected for field testing.
2. Geotextiles manufactured of polypropylene yarns and filaments exhibited better long term flow rate/filtration characteristics than geotextiles manufactured of polyester yarns and filaments.
3. No correlations existed between geotextile EOS and stabilized flow rate or long term filtration performance under the applied laboratory conditions.
4. Some piping of clay particles across the geotextiles occurs with the slurry at an initial solids content of 17-19% until the slurry attains a solids content such that the solid particles will "bridge" the geotextile. However, this piping does not adversely affect the long term performance characteristics for the desired applications.
5. The geotextiles generally prevent significant piping of solid clay particles with the slurry at an initial solids content of 17-19%.

6. With the exception of some thin nonwoven geotextiles, all geotextiles undergo partial clogging/ plugging from solid clay particles under the application of approximately 8.7 feet of water head.
7. Economics, construction procedures, and exposure to field conditions should be taken into consideration before a geotextile is utilized in the field to enhance the consolidation of phosphatic waste clay slurries.
8. It appears that the use of geotextiles for capping phosphate waste clay ponds will cause the development of a solids content profile within the clays that will be greatest adjacent to the geotextile and will decrease with depth, which may, after a period of time, prevent water from escaping and, thus, prevent the clays from consolidating further.

The following conclusions were developed concerning the laboratory test procedures:

1. The test can be considered as a constant head test and may be evaluated and analyzed as such.
2. The test could have been performed for a shorter period of time such as 200 hours, in order to obtain stabilized flow rates for the slurry/geotextile systems.
3. The decrease in flow rate with time, is the result of a both slurry consolidation and partial geotextile clogging/plugging.
4. The initial flow rate across the geotextile is likely controlled by the slurry.

5. If the system is disturbed after a stabilized flow rate is attained, the stabilized flow rate will eventually return to the same approximate value.
6. The stabilized flow rate across a nonwoven geotextile is related to clogging/plugging of solid particles within the geotextile.
7. Scanning electron microphotographs provide an effective means of analyzing clogging/plugging within geotextiles.

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APPENDIX A

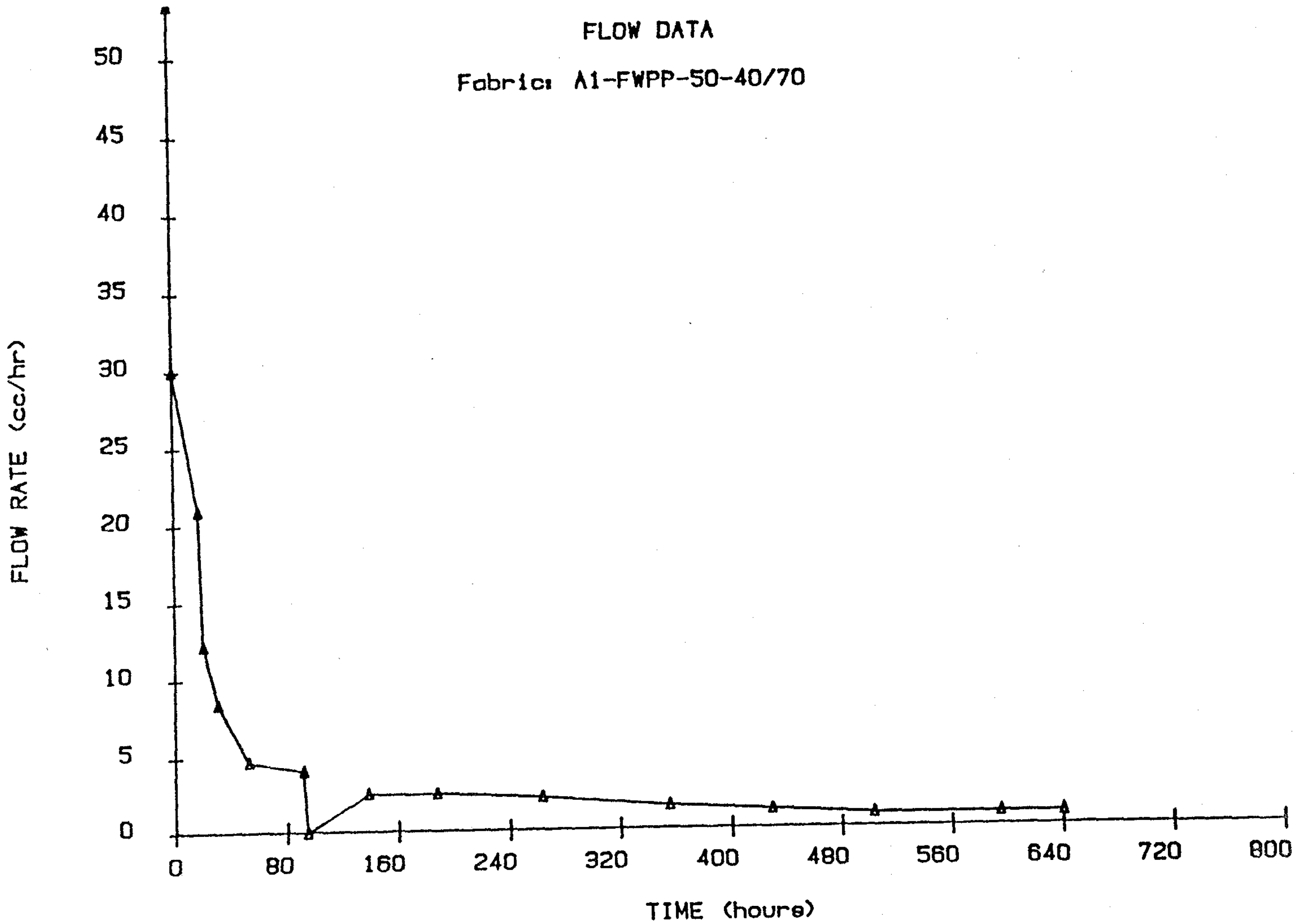


Figure A1: Flow Rate Versus Time for Geotextile A1-FWPP-50-40/70

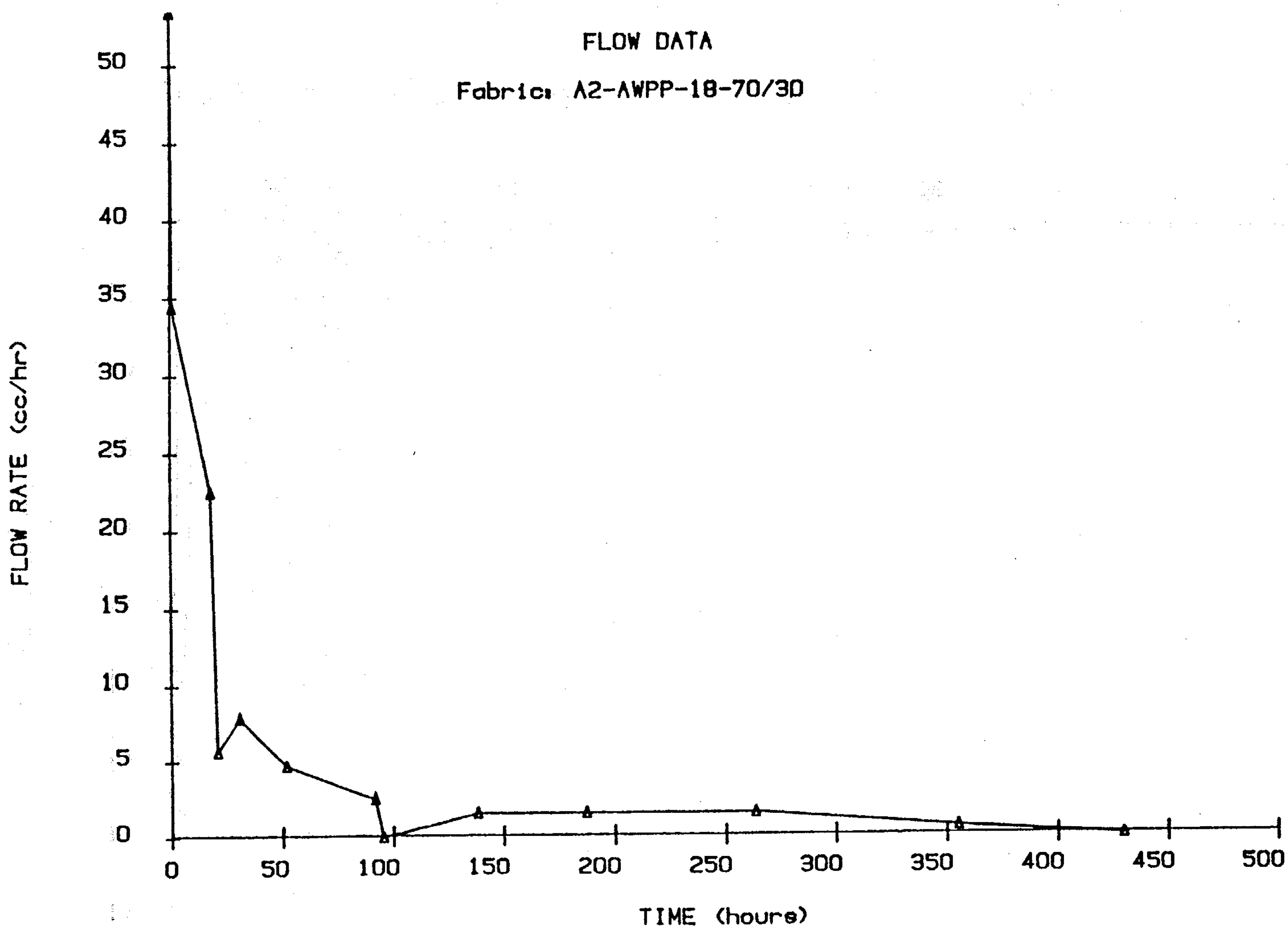


Figure A2: Flow Rate Versus Time for Geotextile A2-AWPP-18-70/30

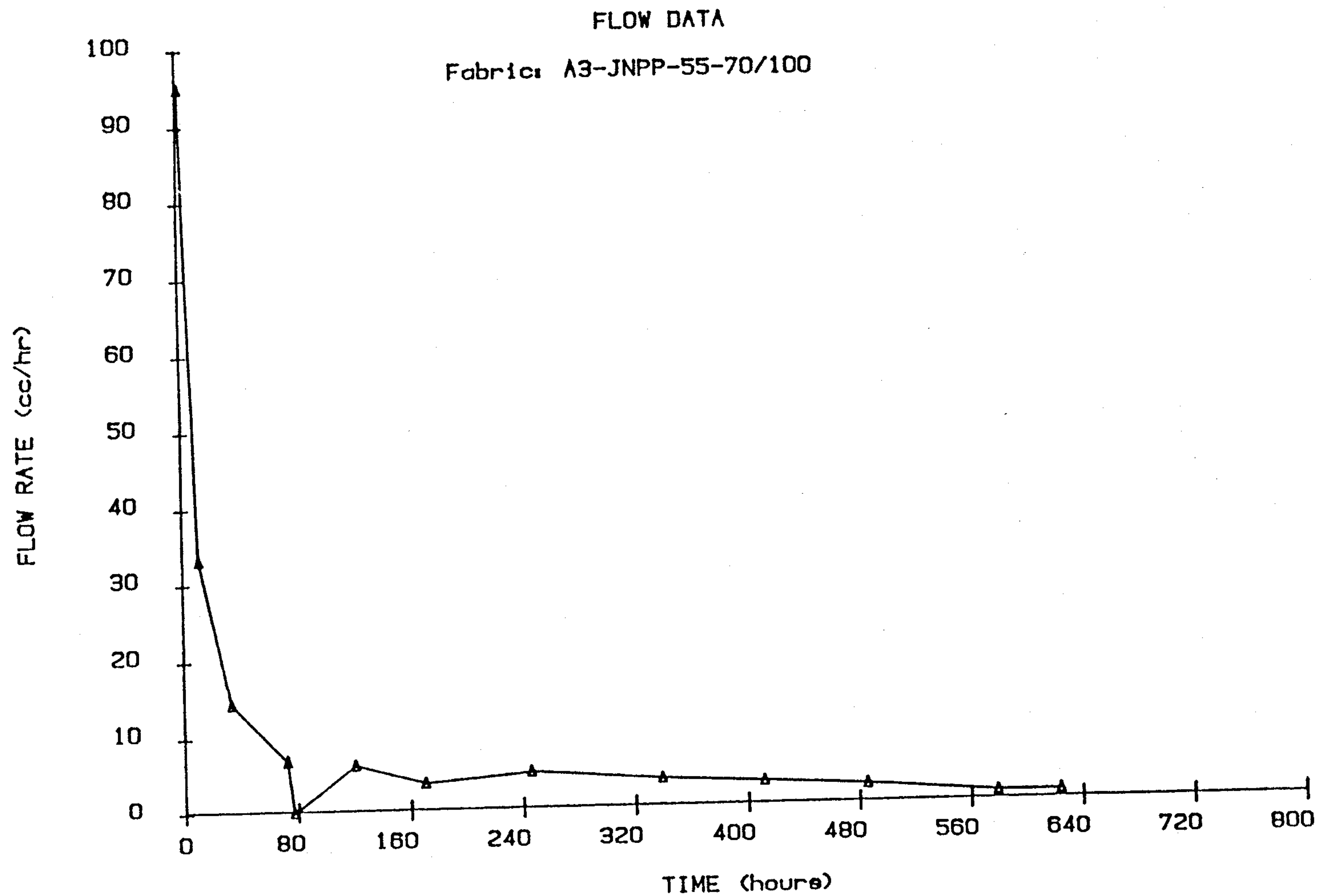


Figure A3: Flow Rate Versus Time for Geotextile A3-JNPP-55-70/100

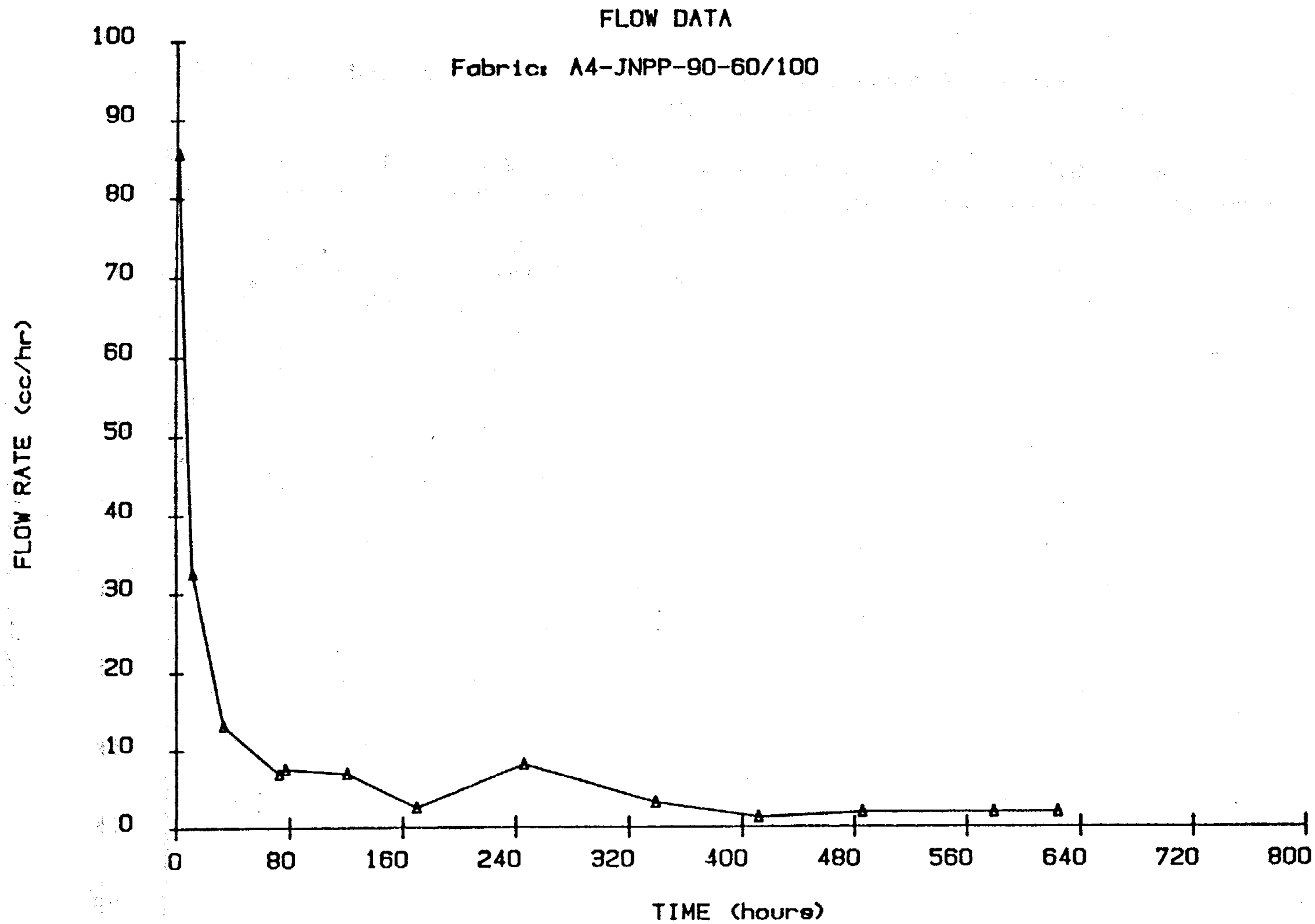


Figure A4: Flow Rate Versus Time for Geotextile A4-JNPP-90-60/100

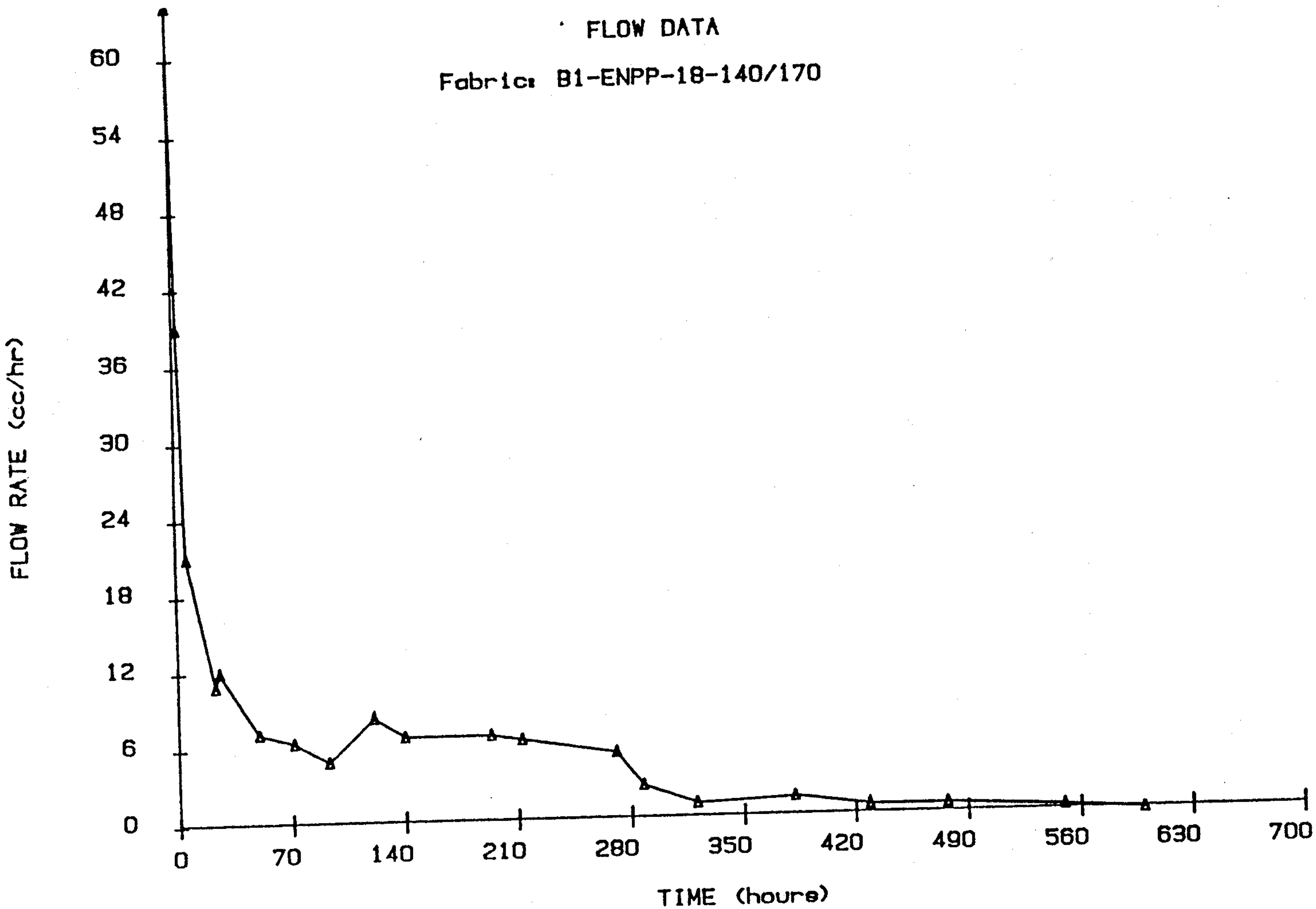


Figure A5: Flow Rate Versus Time for Geotextile B1-ENPP-18-140/170

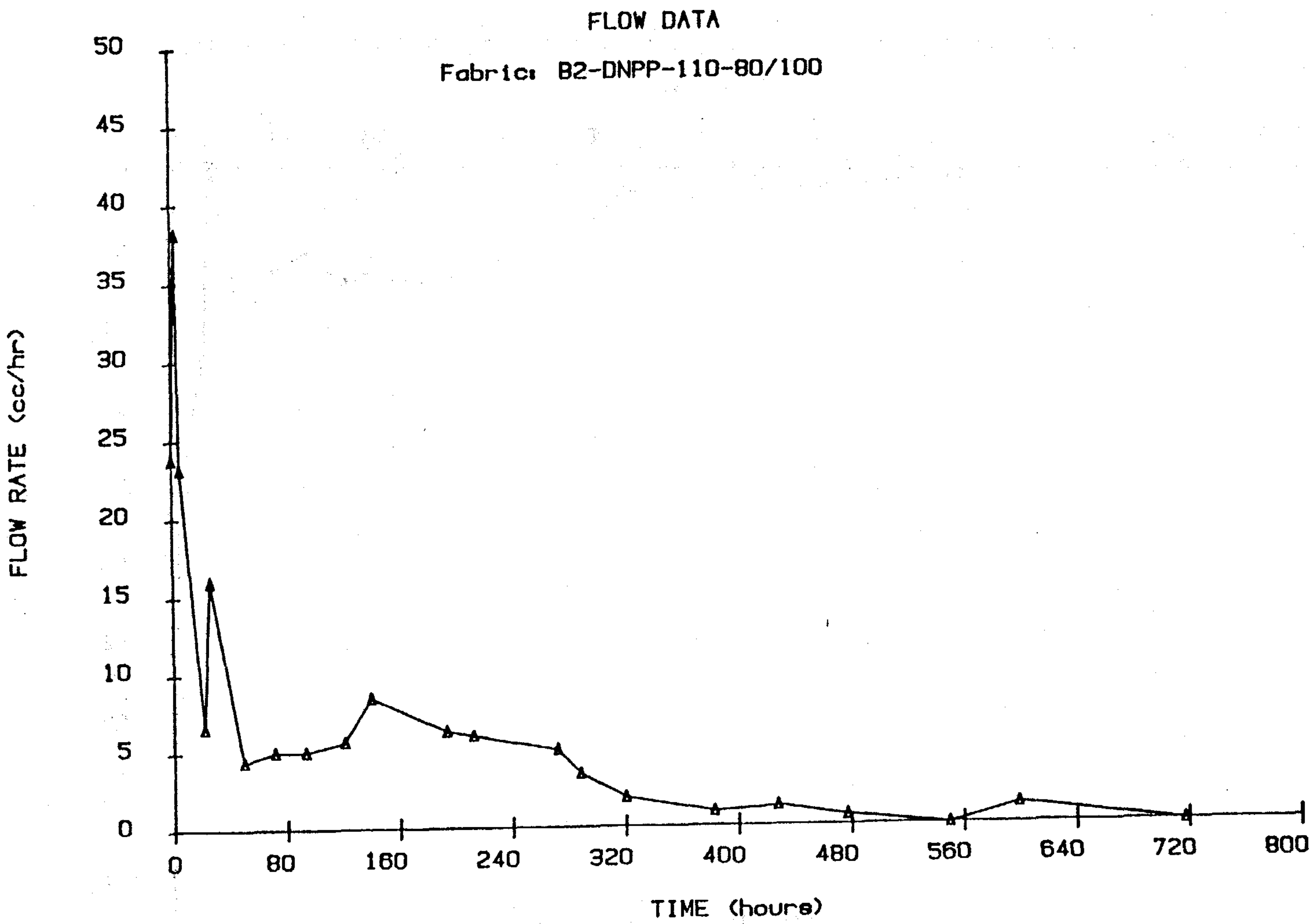


Figure A6: Flow Rate Versus Time for Geotextile B2-DNPP-110-80/100

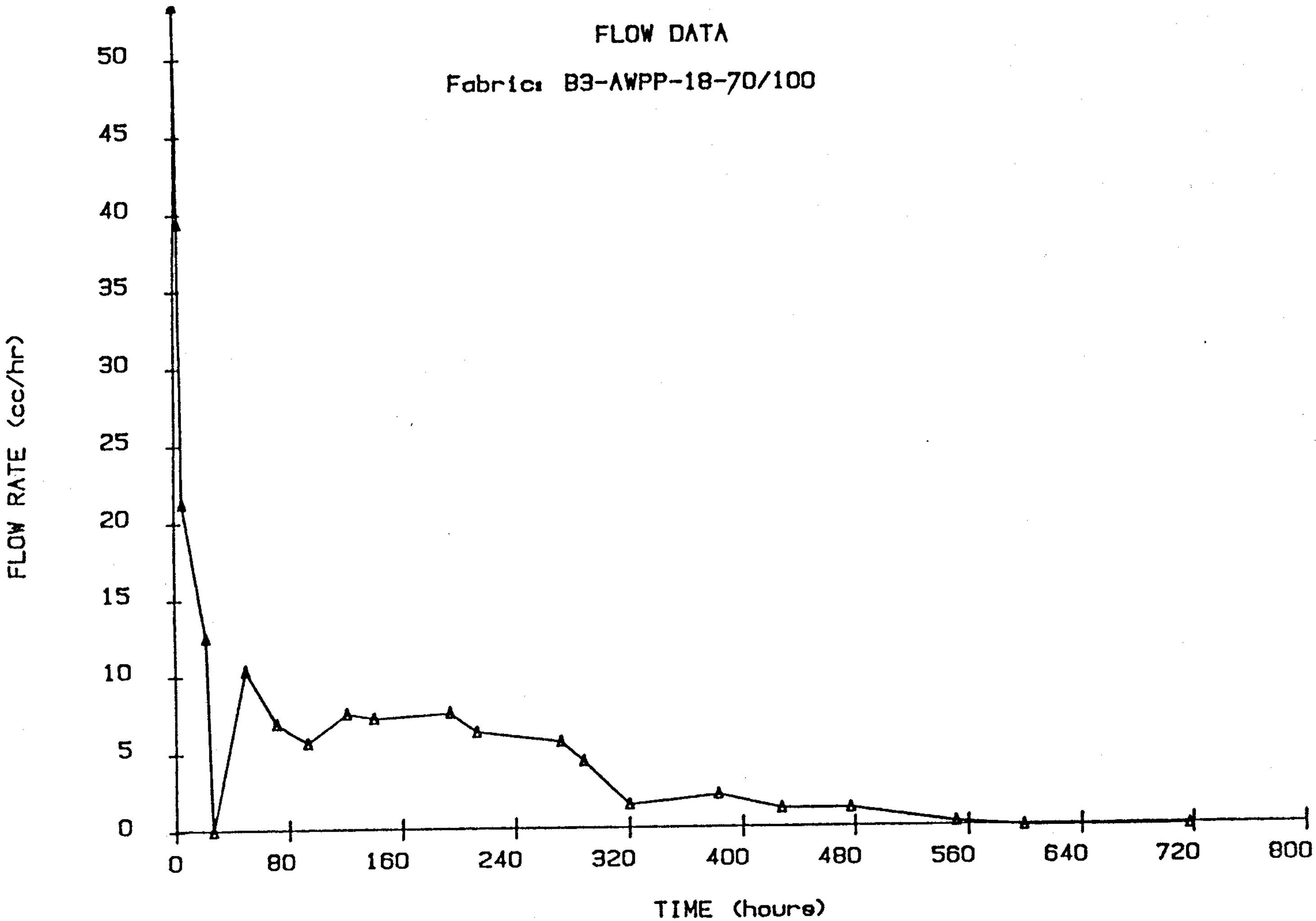


Figure A7: Flow Rate Versus Time for Geotextile B3-AWPP-18-70/100

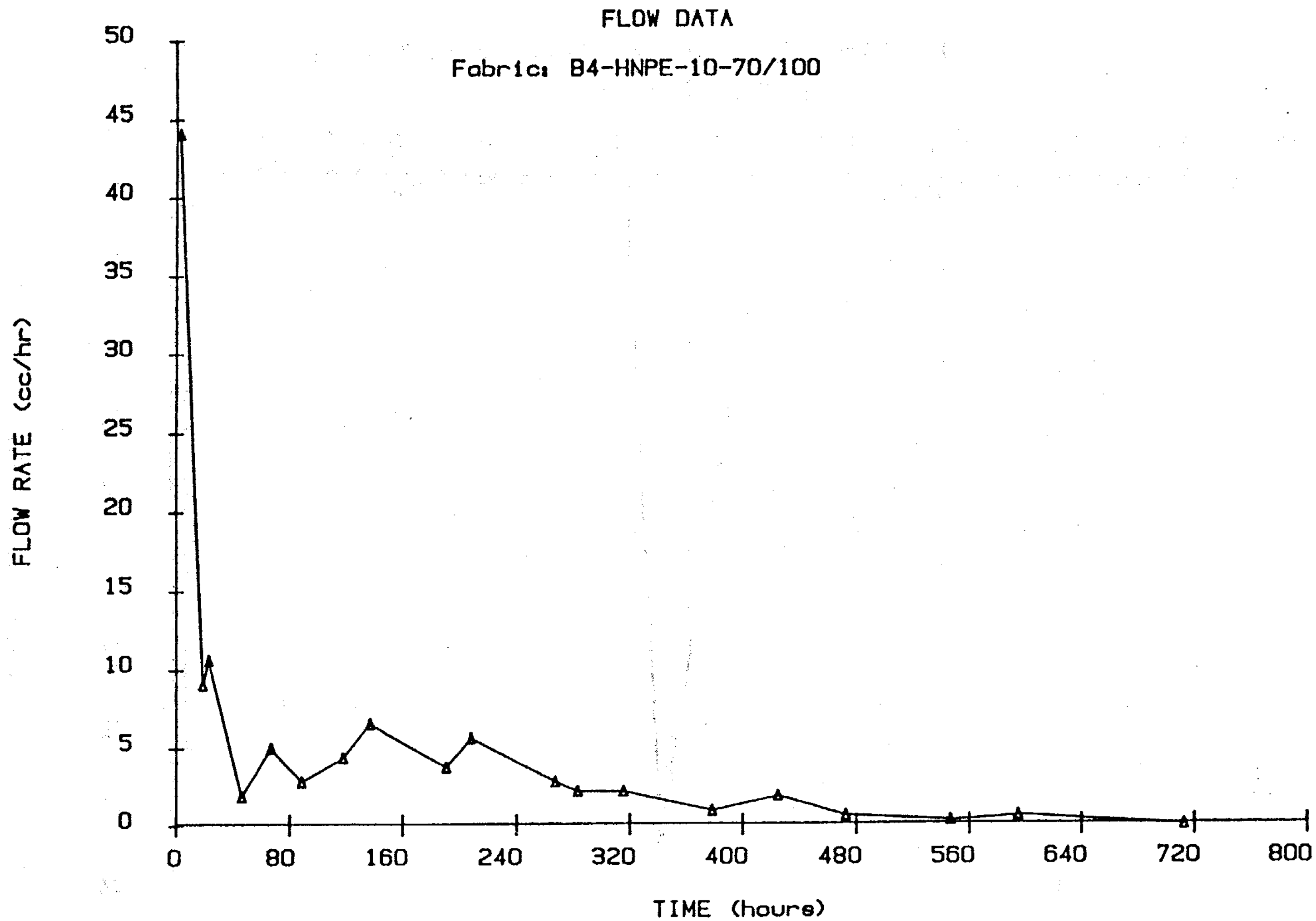


Figure A8: Flow Rate Versus Time for Geotextile B4-HNPE-10-70/100

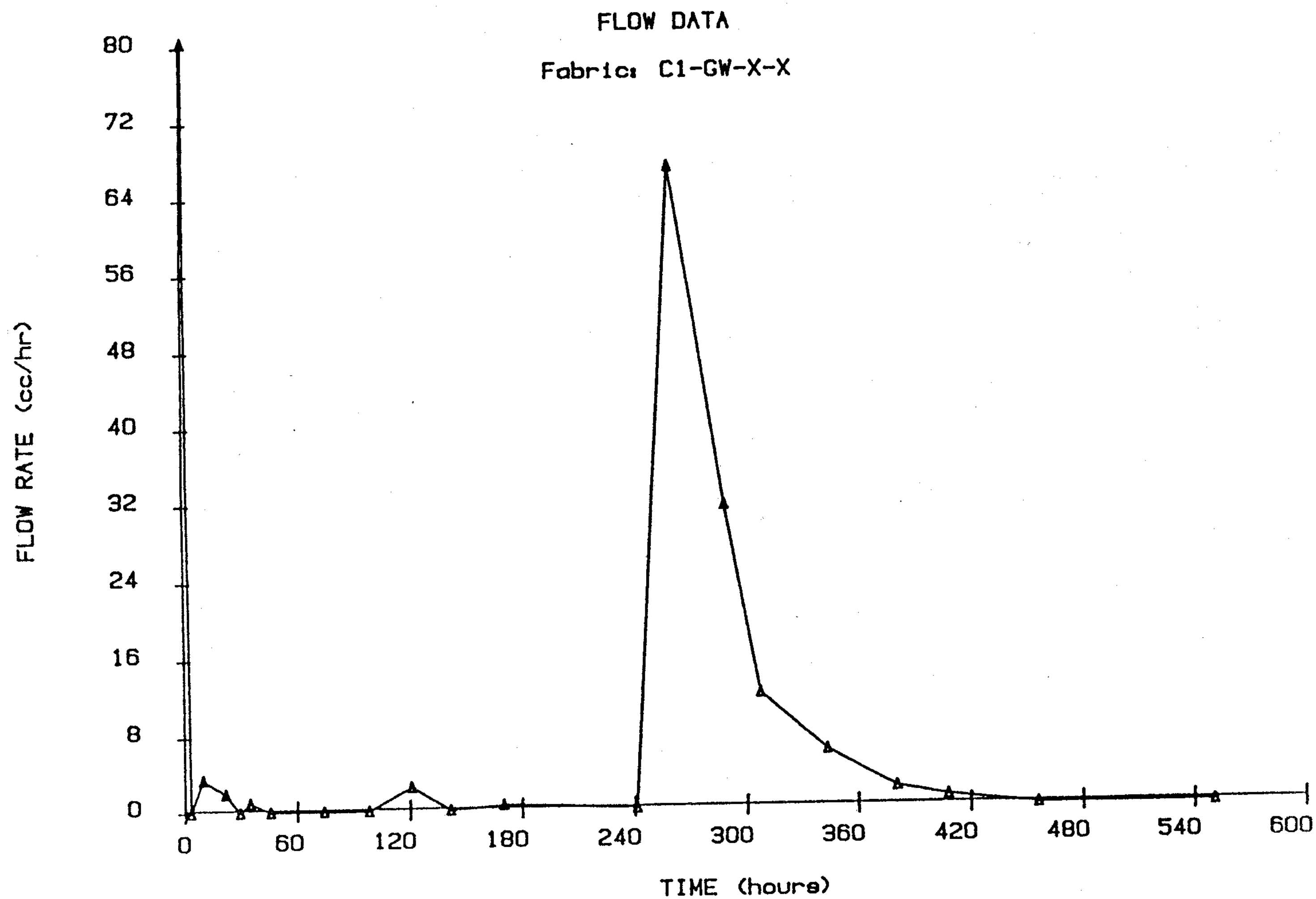


Figure A9: Flow Rate Versus Time for Geotextile C1-GW-X-X

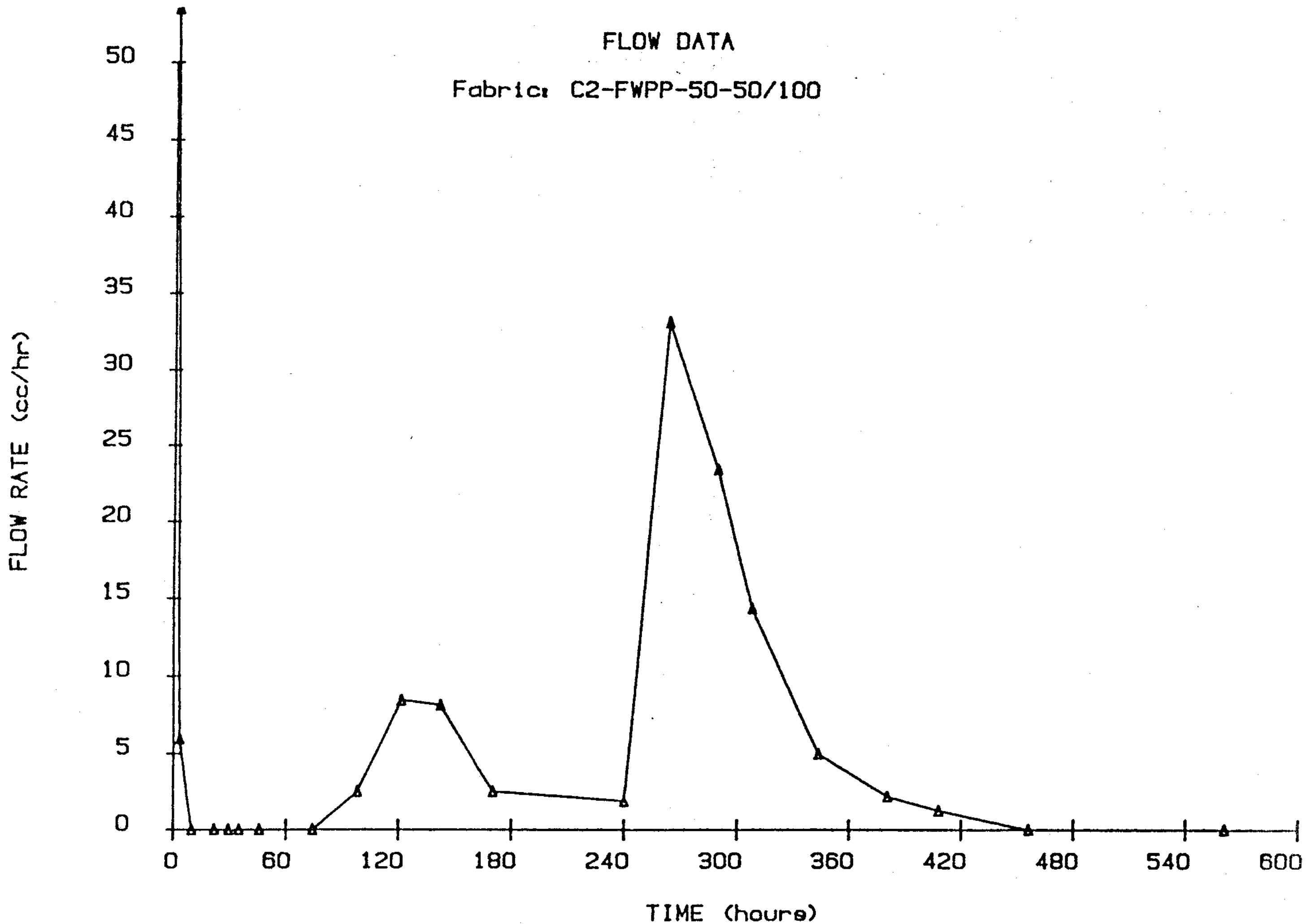


Figure A10: Flow Rate Versus Time for Geotextile C2-FWPP-50-50/100

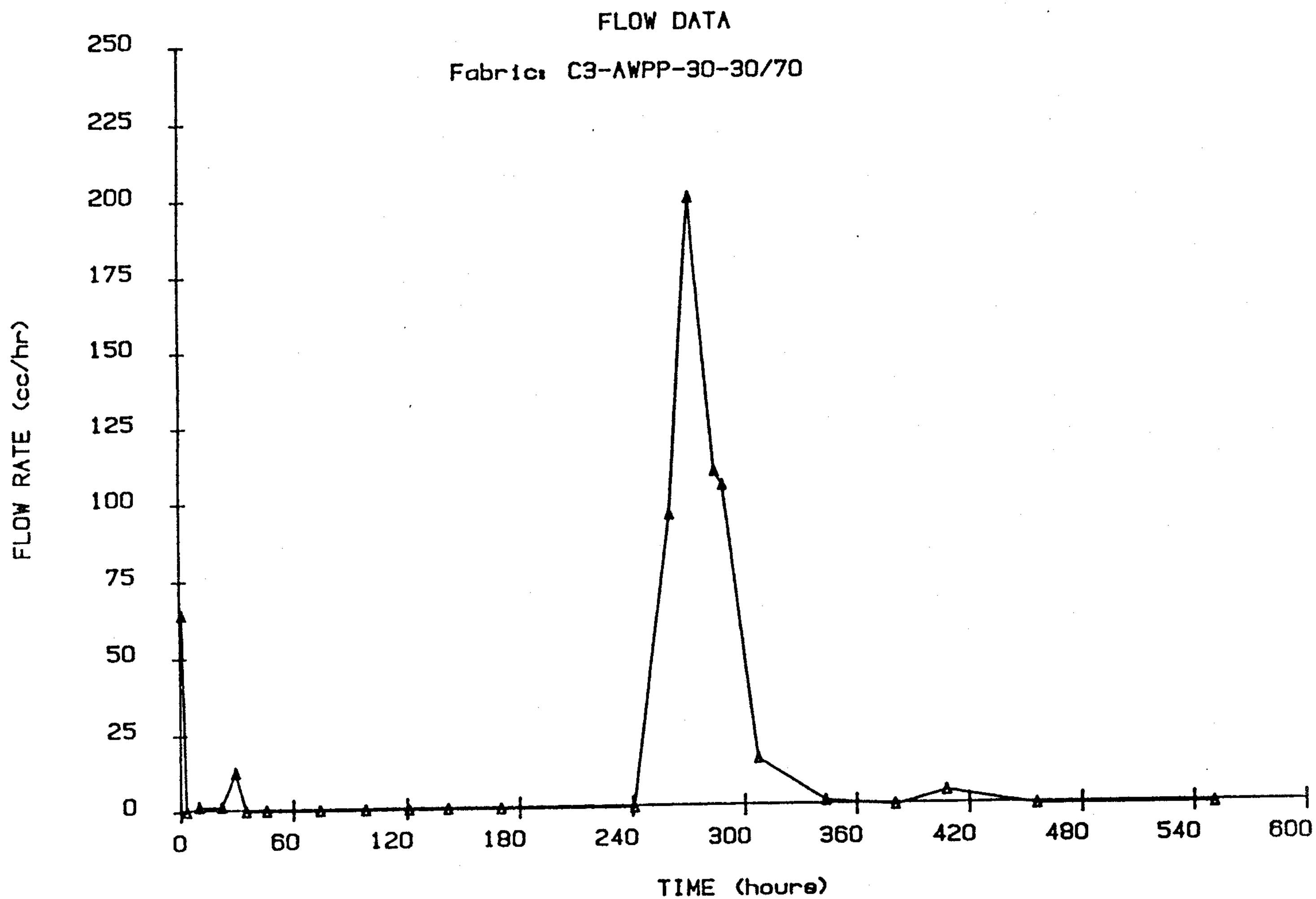


Figure A11: Flow Rate Versus Time for Geotextile C3-AWPP-30-30/70

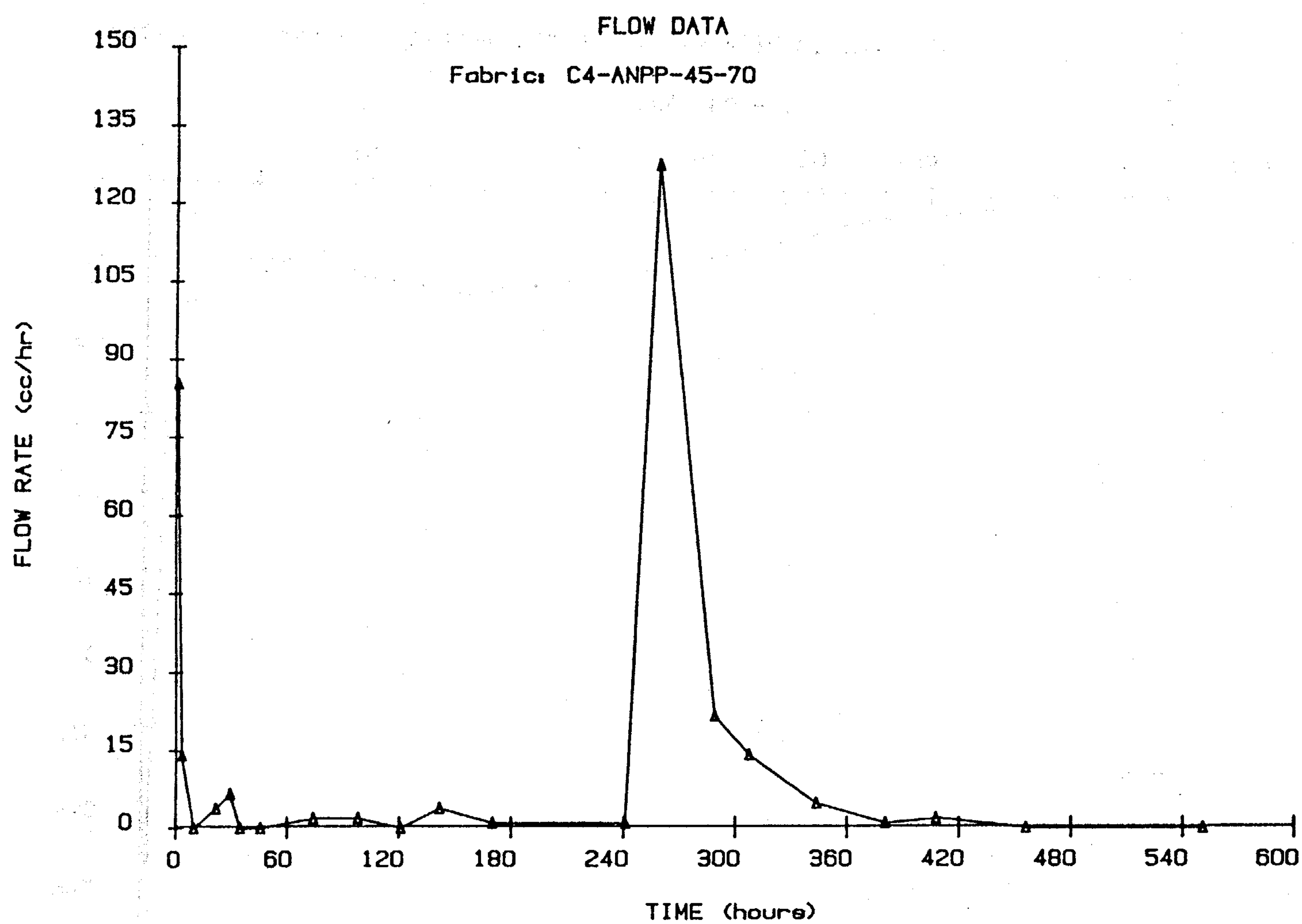


Figure A12: Flow Rate Versus Time for Geotextile C4-ANPP-45-70

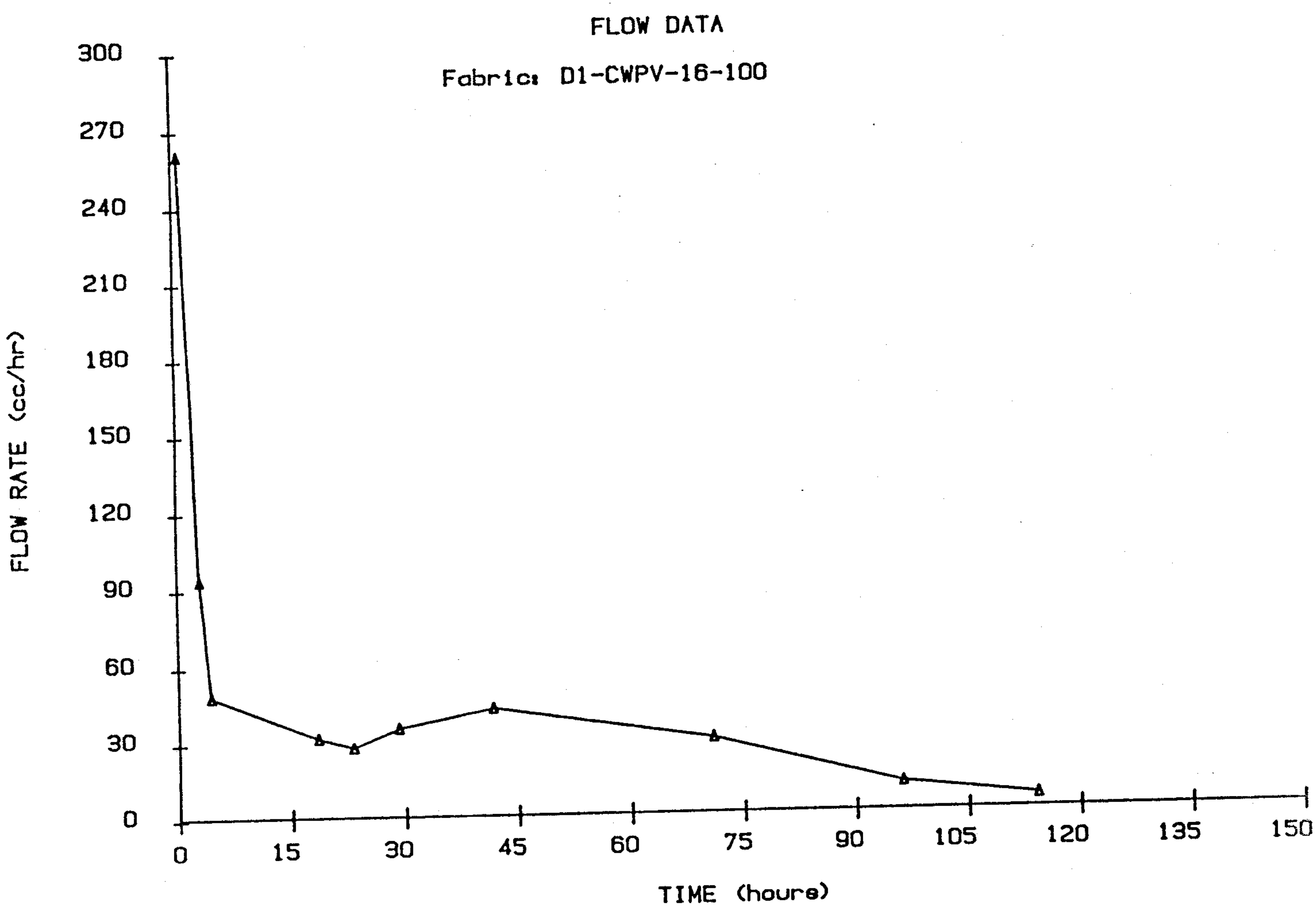


Figure A13: Flow Rate Versus Time for Geotextile D1-CWPV-16-100

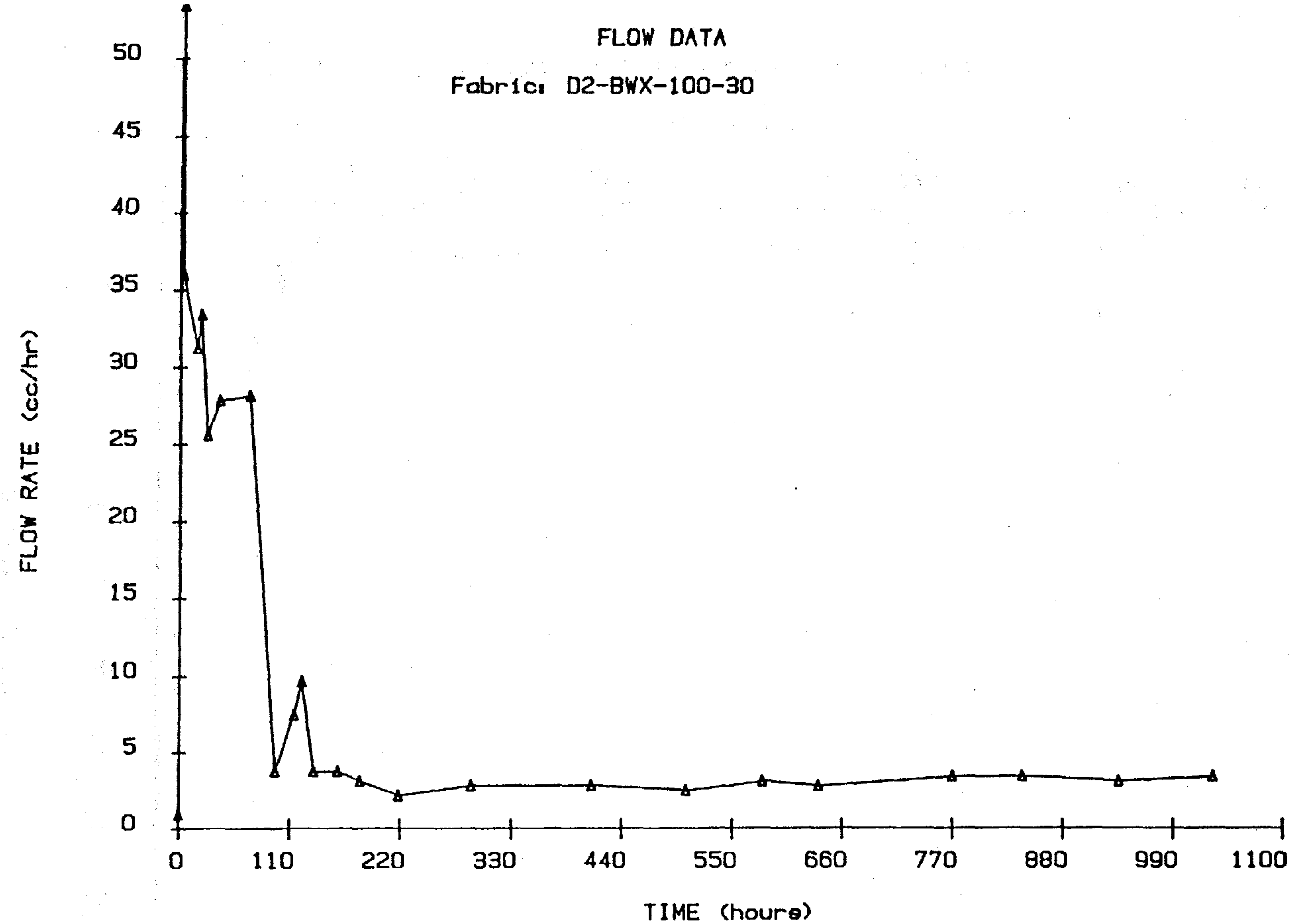


Figure A14:Flow Rate Versus Time for Geotextile D2-BWX-100-30

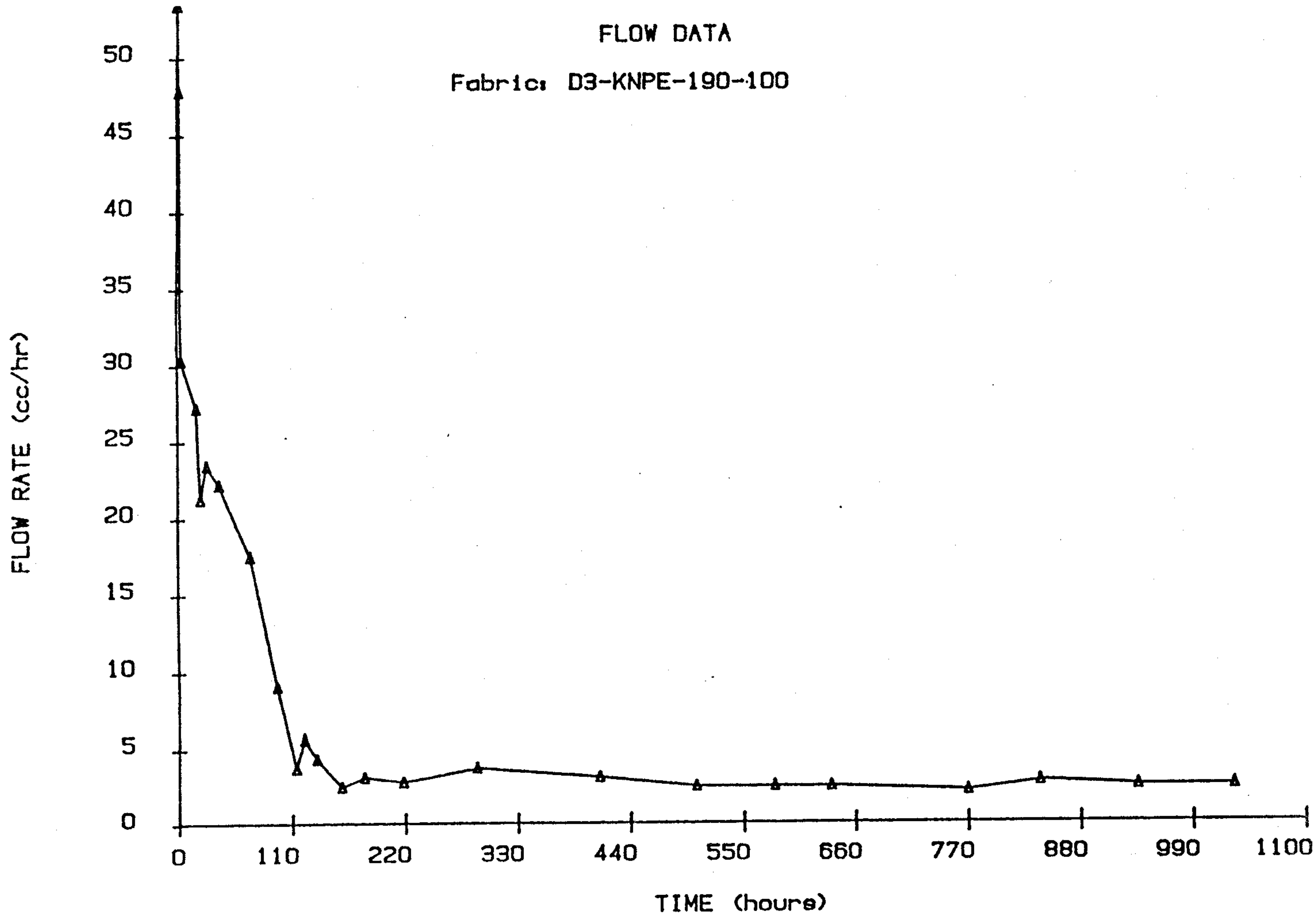


Figure A15: Flow Rate Versus Time for Geotextile D3-KNPE-190-100

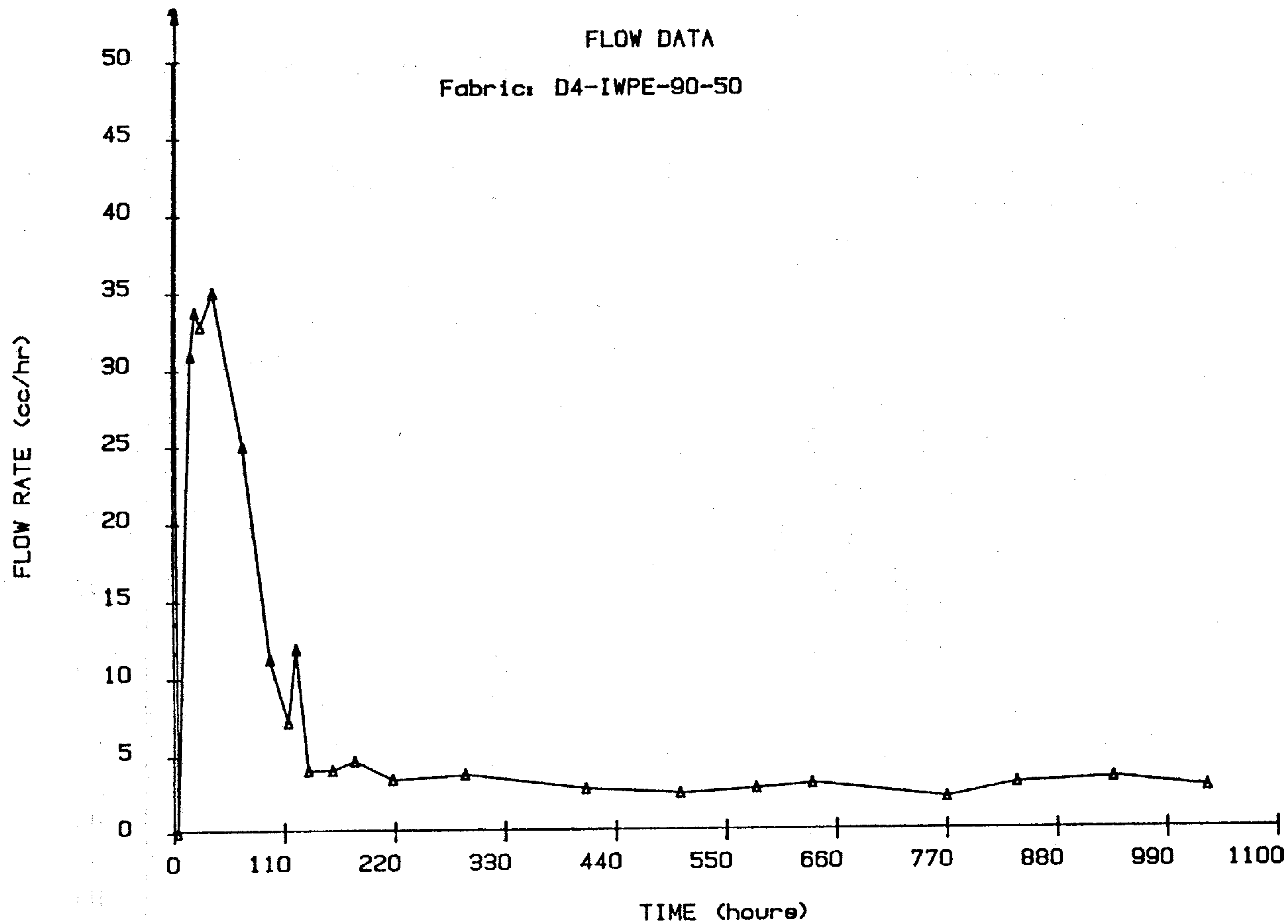


Figure A16: Flow Rate Versus Time for Geotextile D4-IWPE-90-50

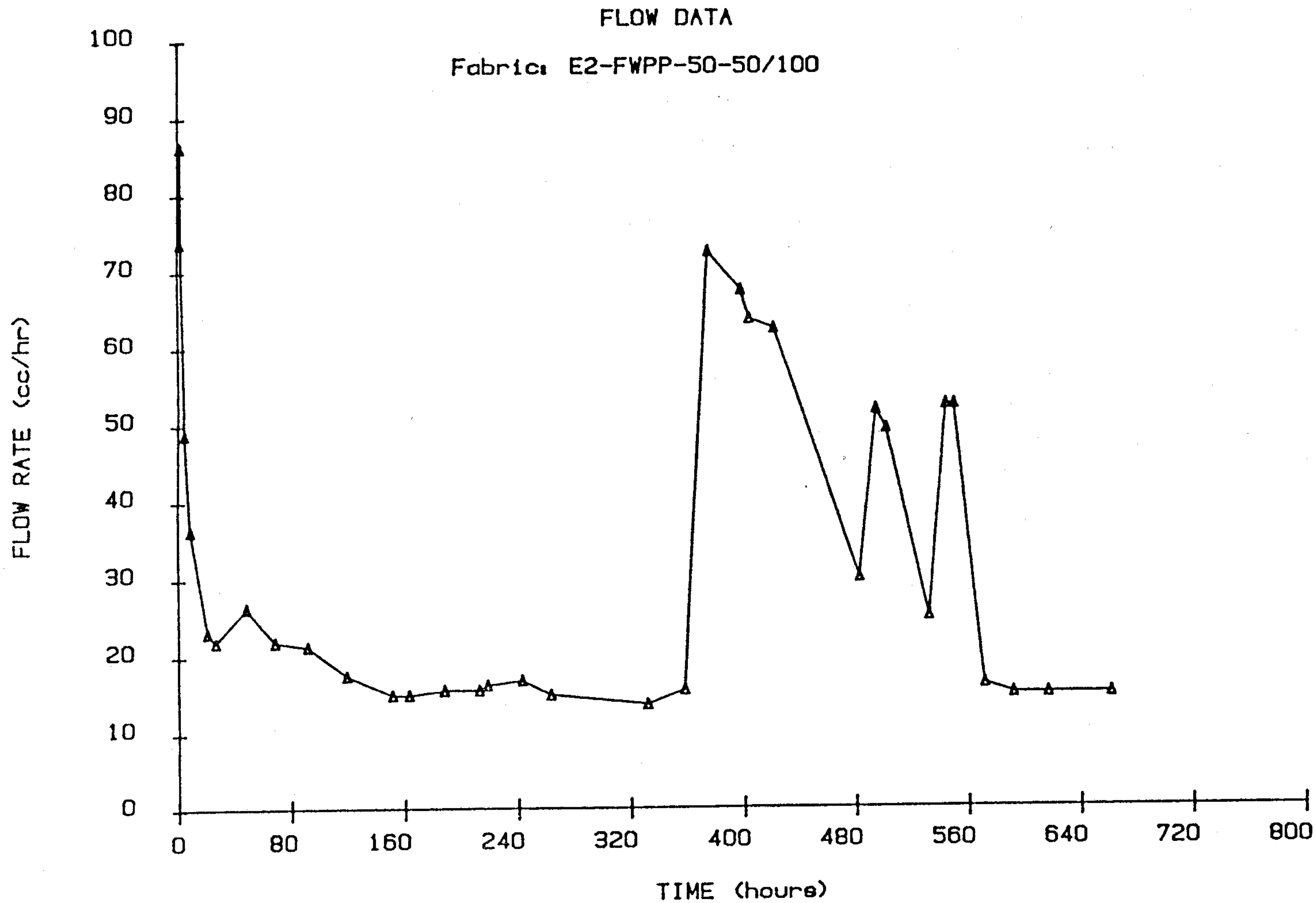


Figure A17: Flow Rate Versus Time for Geotextile E2-FWPP-50-50/100

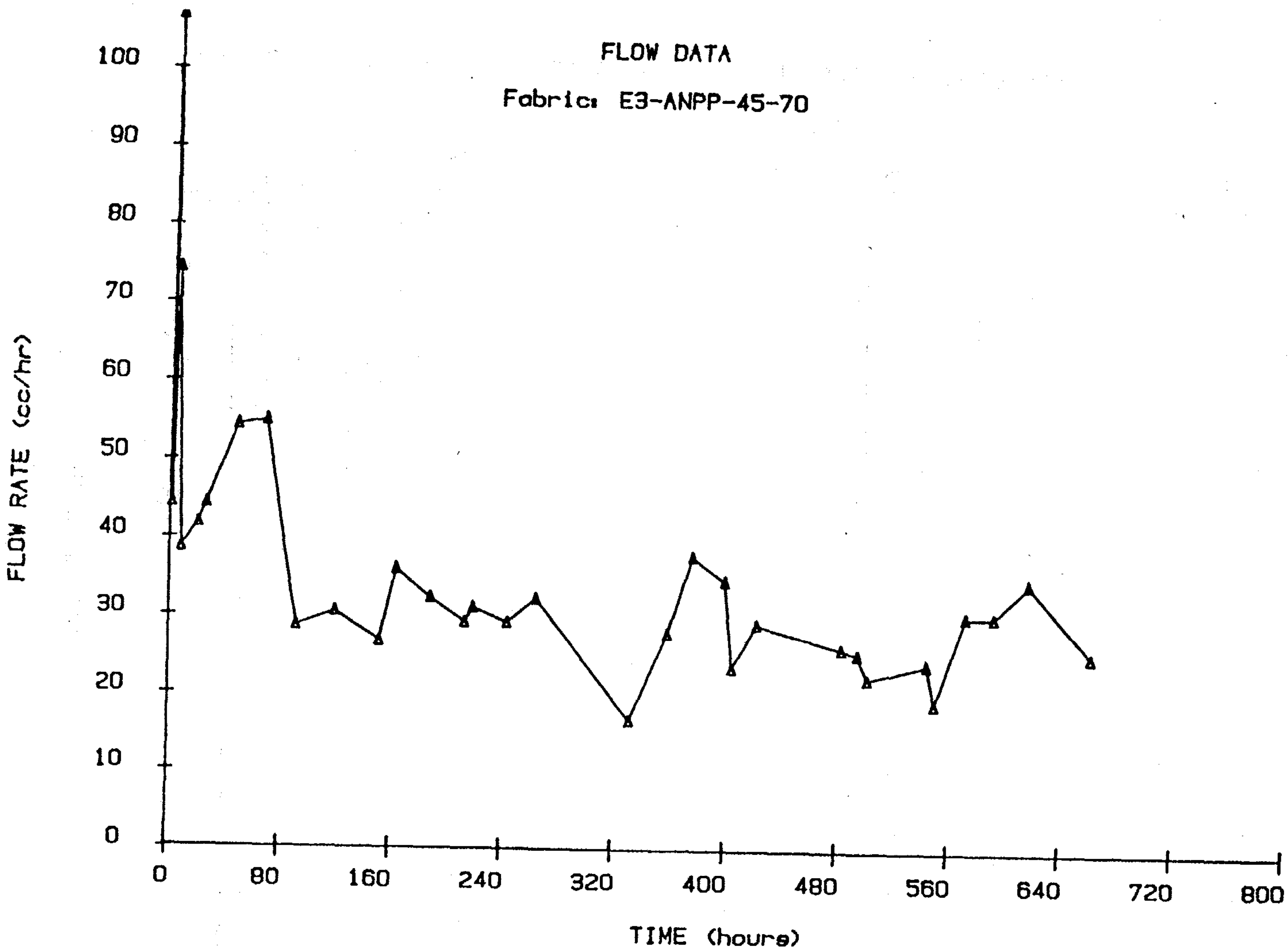


Figure A18:Flow Rate Versus Time for Geotextile E3-ANPP-45-70

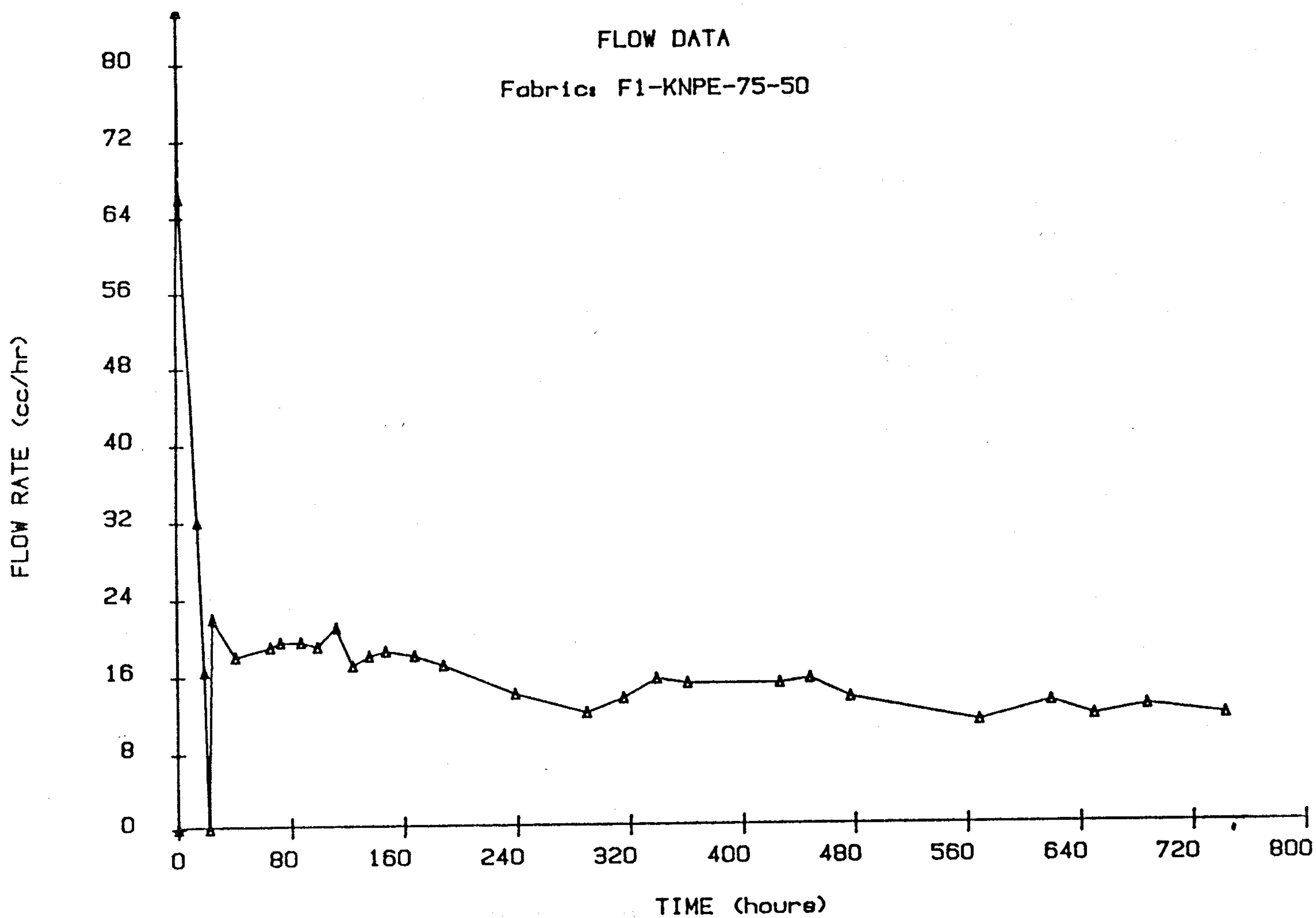


Figure A19:Flow Rate Versus Time for Geotextile F1-KNPE-75-50

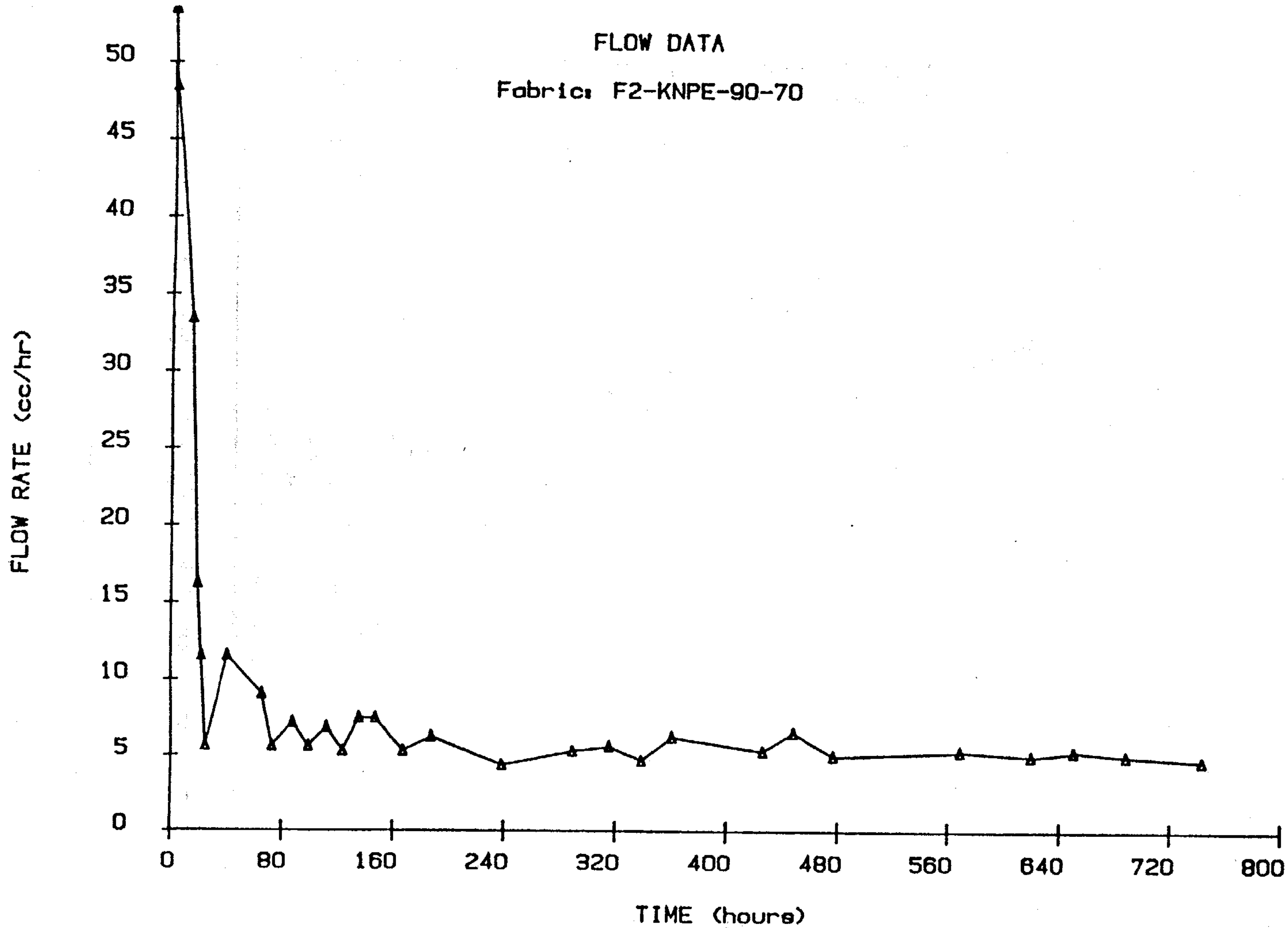


Figure A20:Flow Rate Versus Time for Geotextile F2-KNPE-90-70

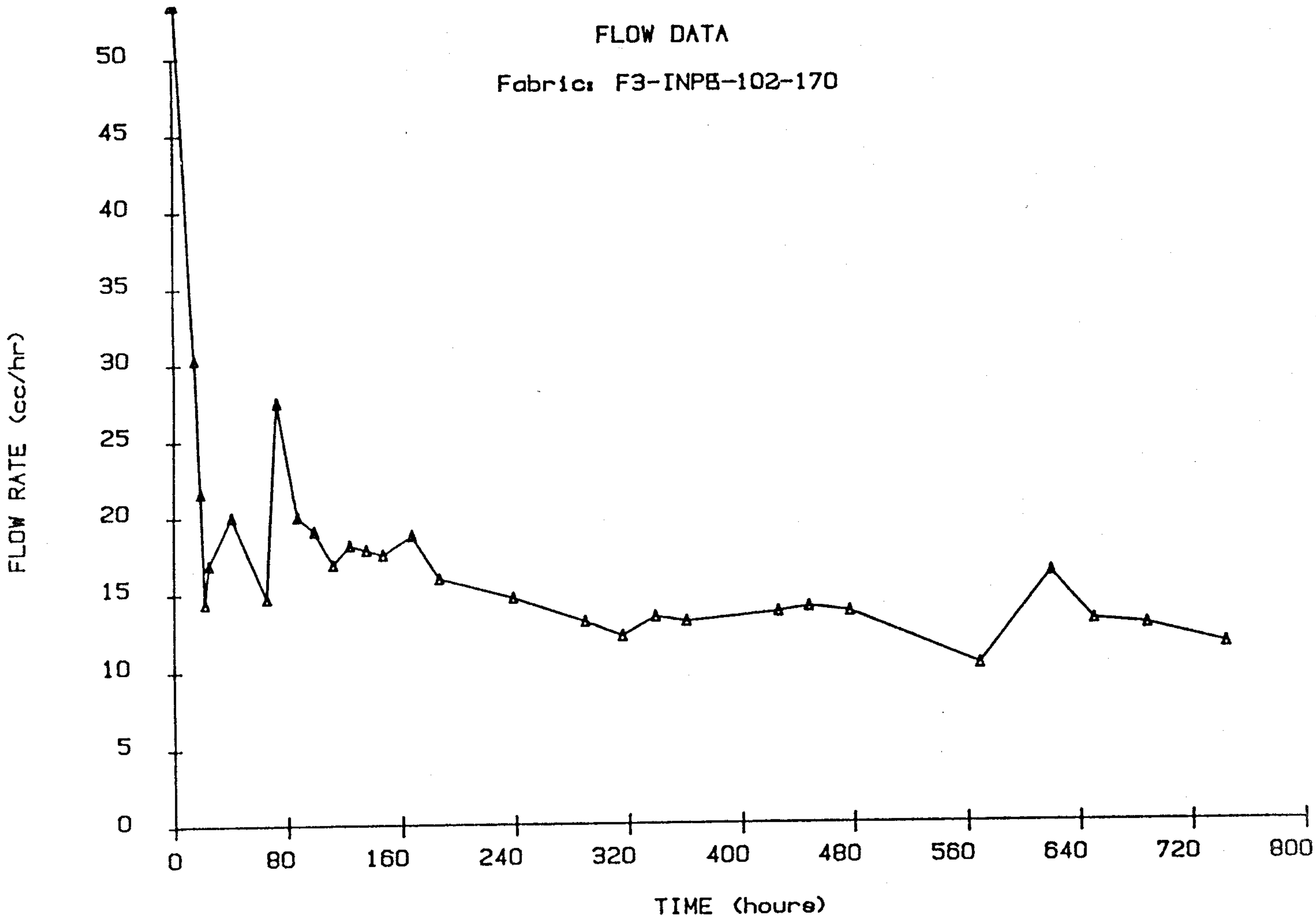


Figure A21:Flow Rate Versus Time for Geotextile F3-INPE-102-170

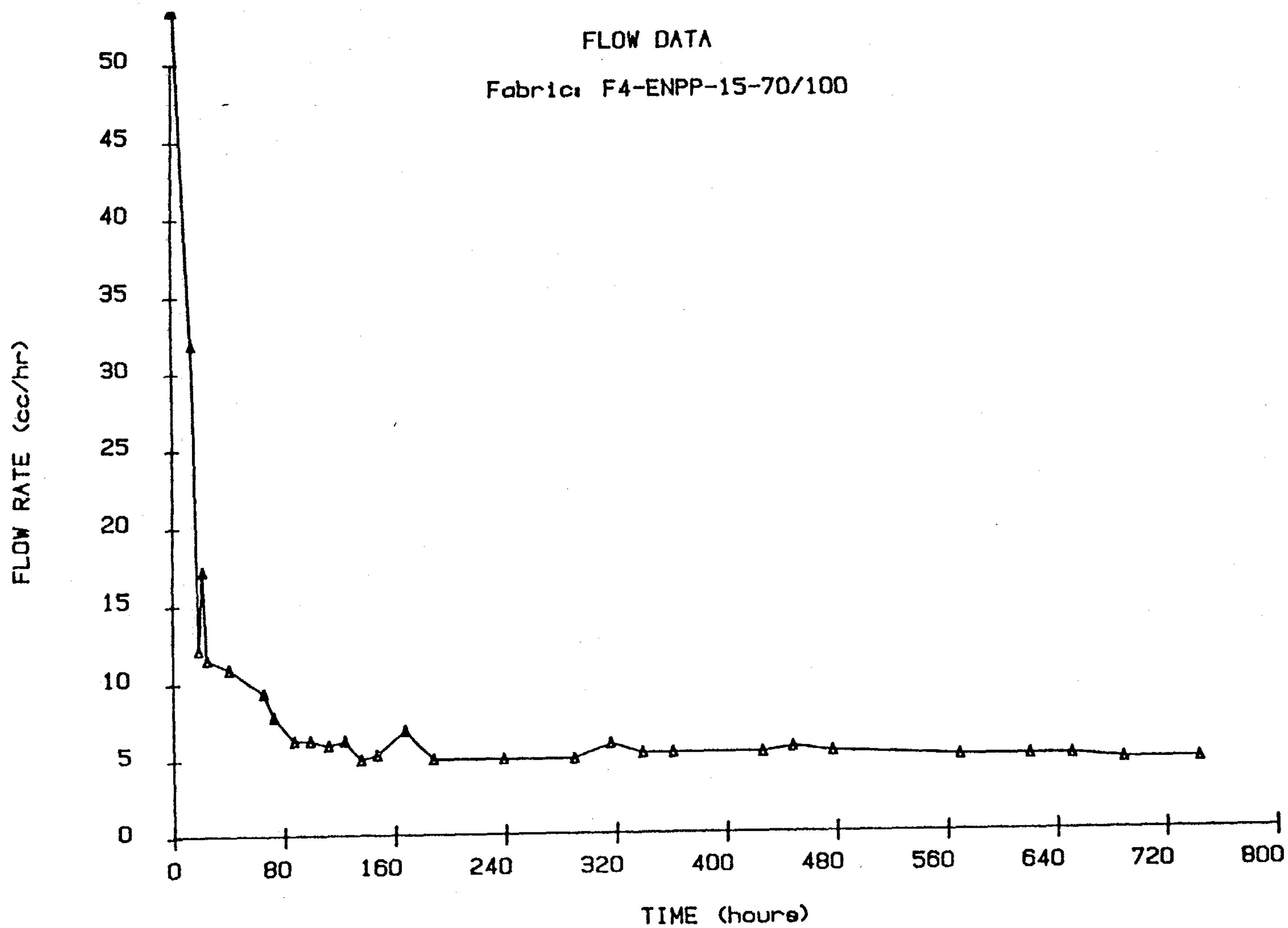


Figure A22: Flow Rate Versus Time for Geotextile F4-ENPP-15-70/100

APPENDIX B

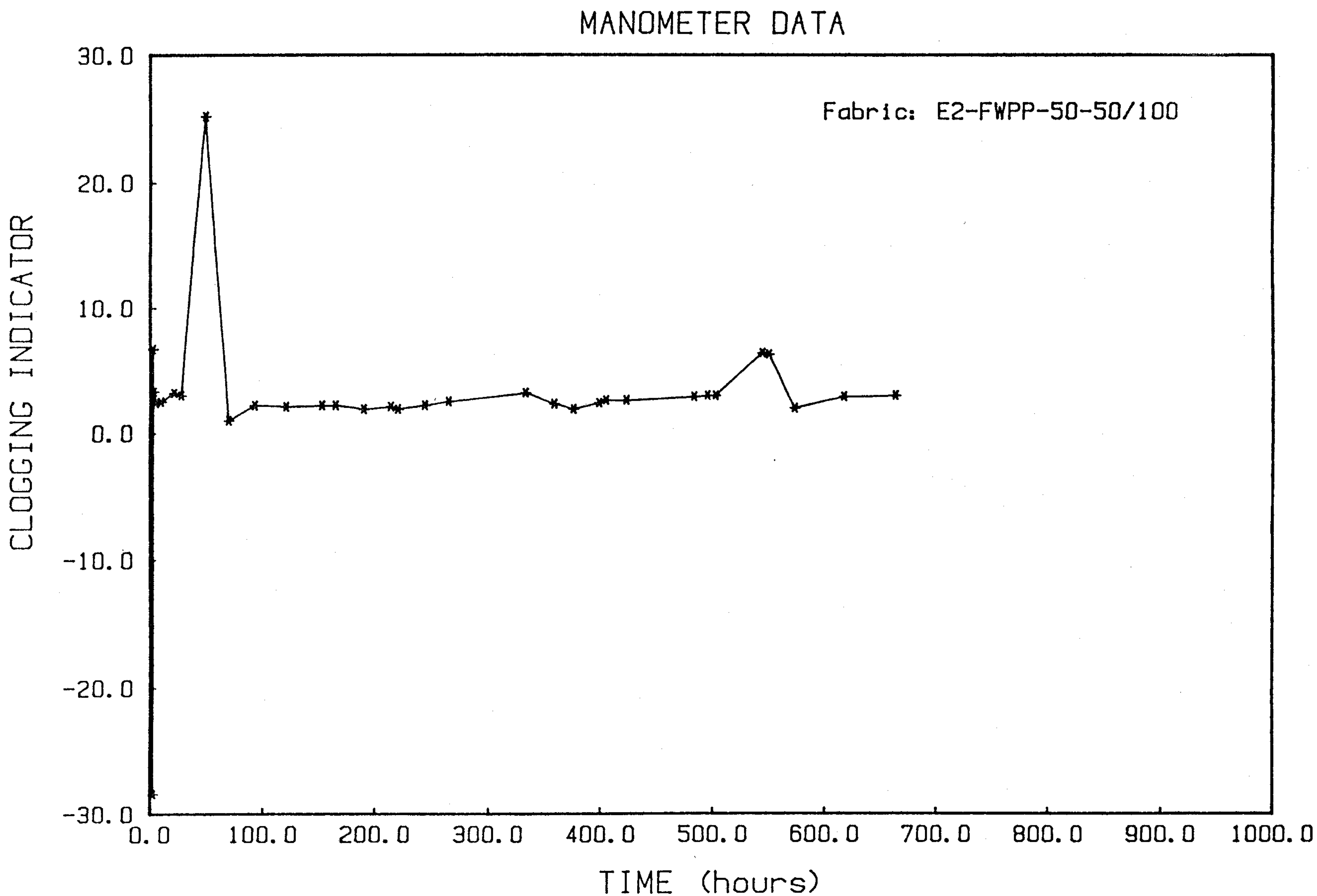


Figure B1: Clogging Indicator Versus Time for Geotextile E2-FWPP-50-50/100

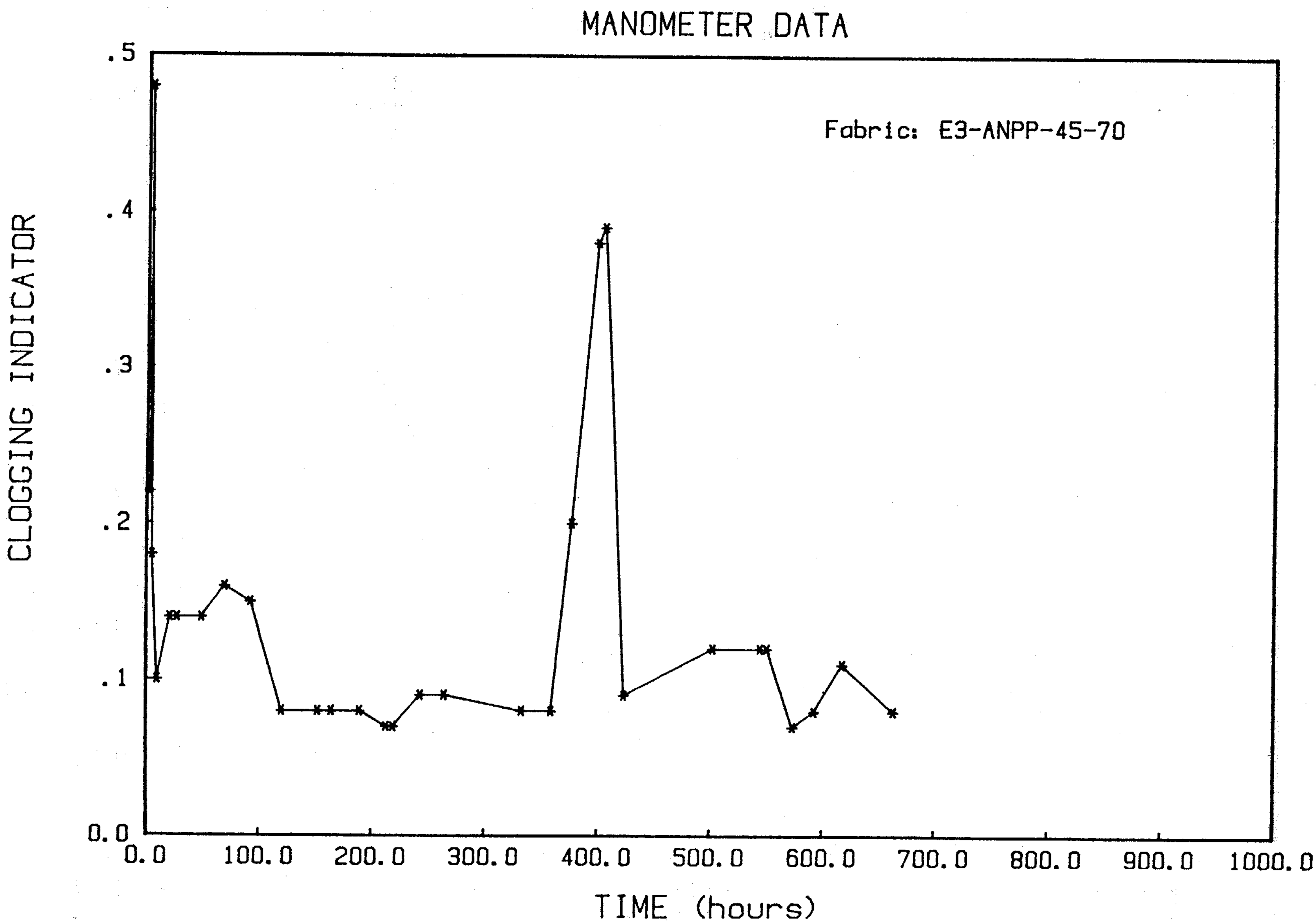


Figure B2: Clogging Indicator Versus Time for Geotextile E3-ANPP-45-70

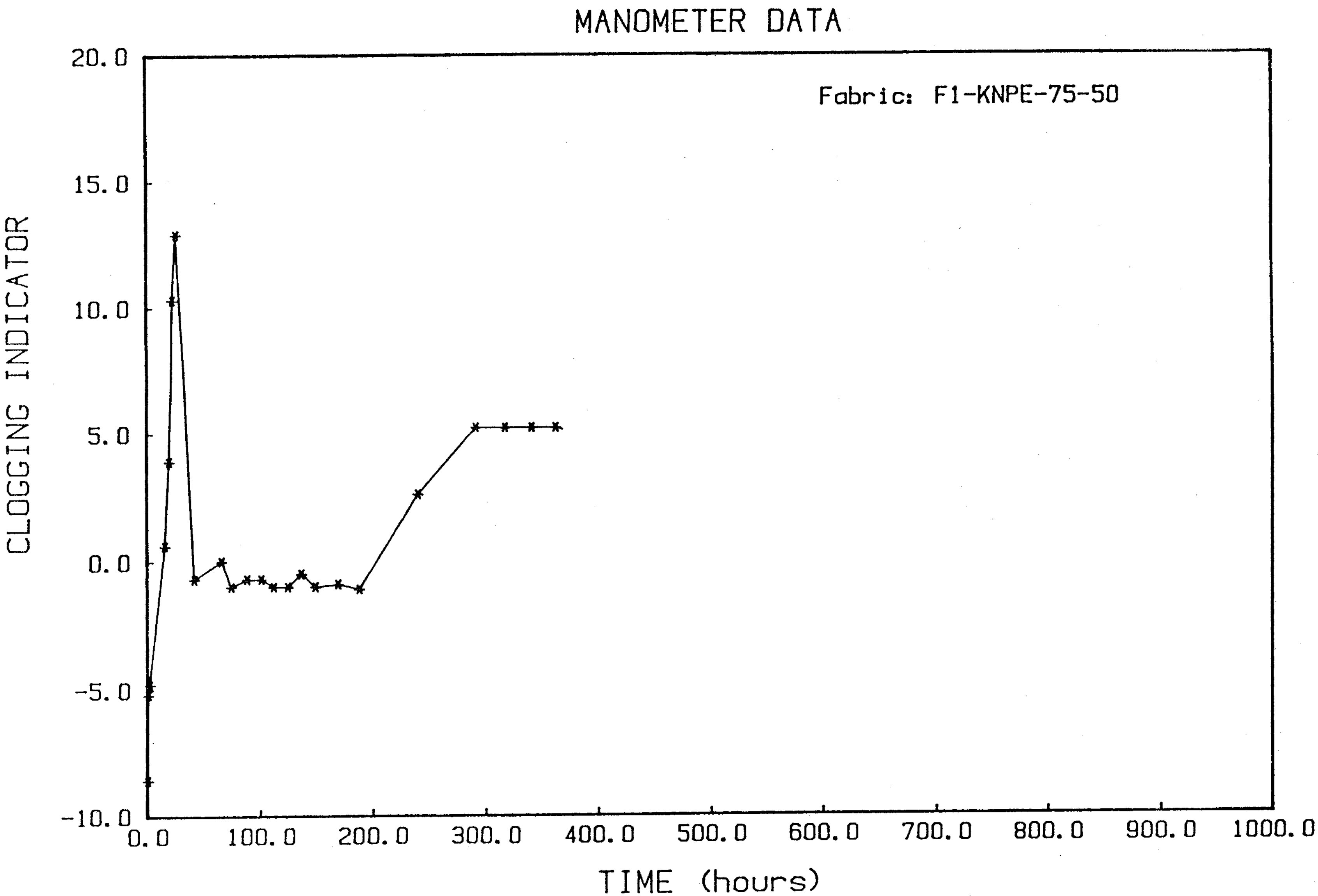


Figure B3: Clogging Indicator Versus Time for Geotextile F1-KNPE-75-50

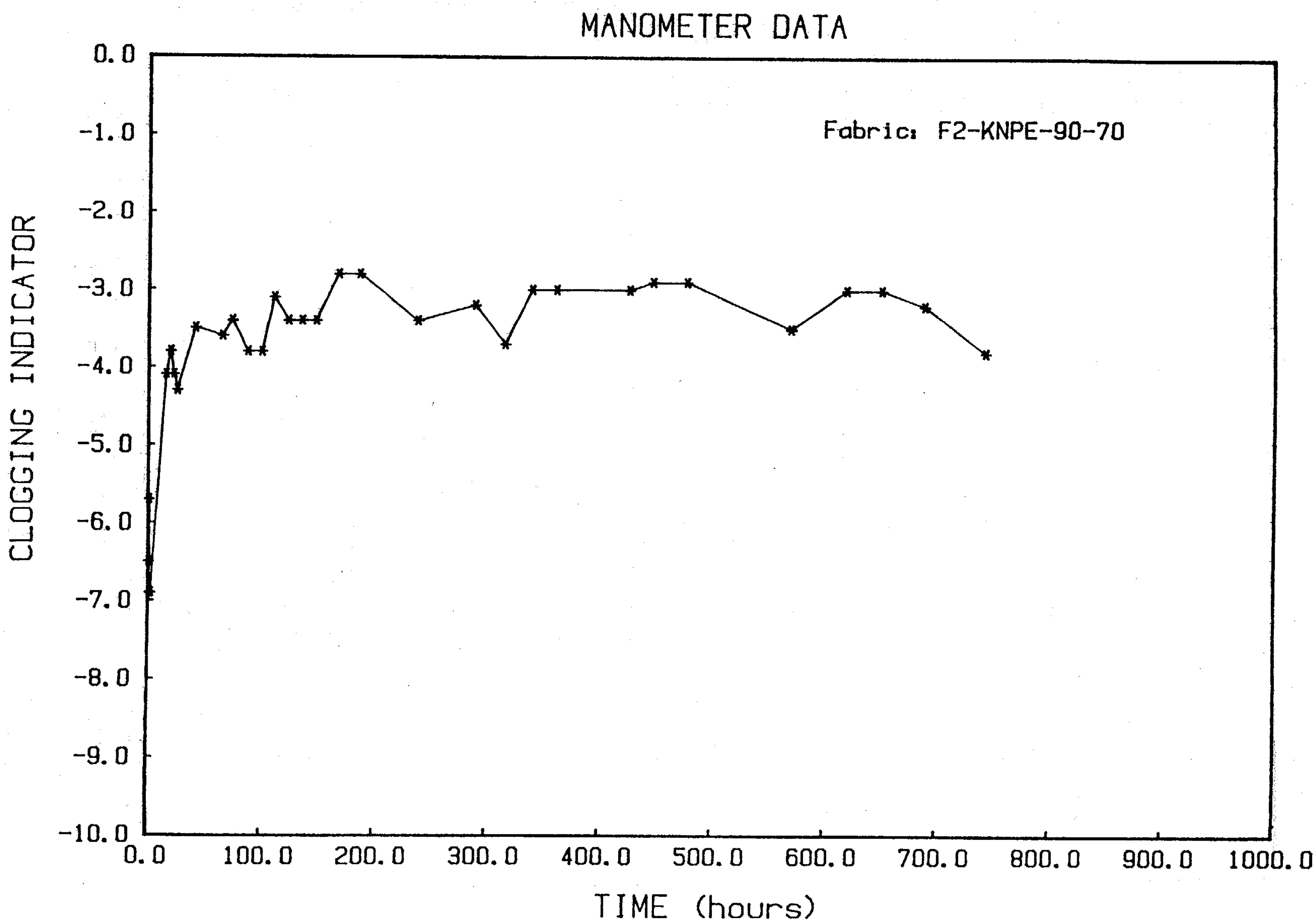


Figure B4: Clogging Indicator Versus Time for Geotextile F2-KNPE-90-70

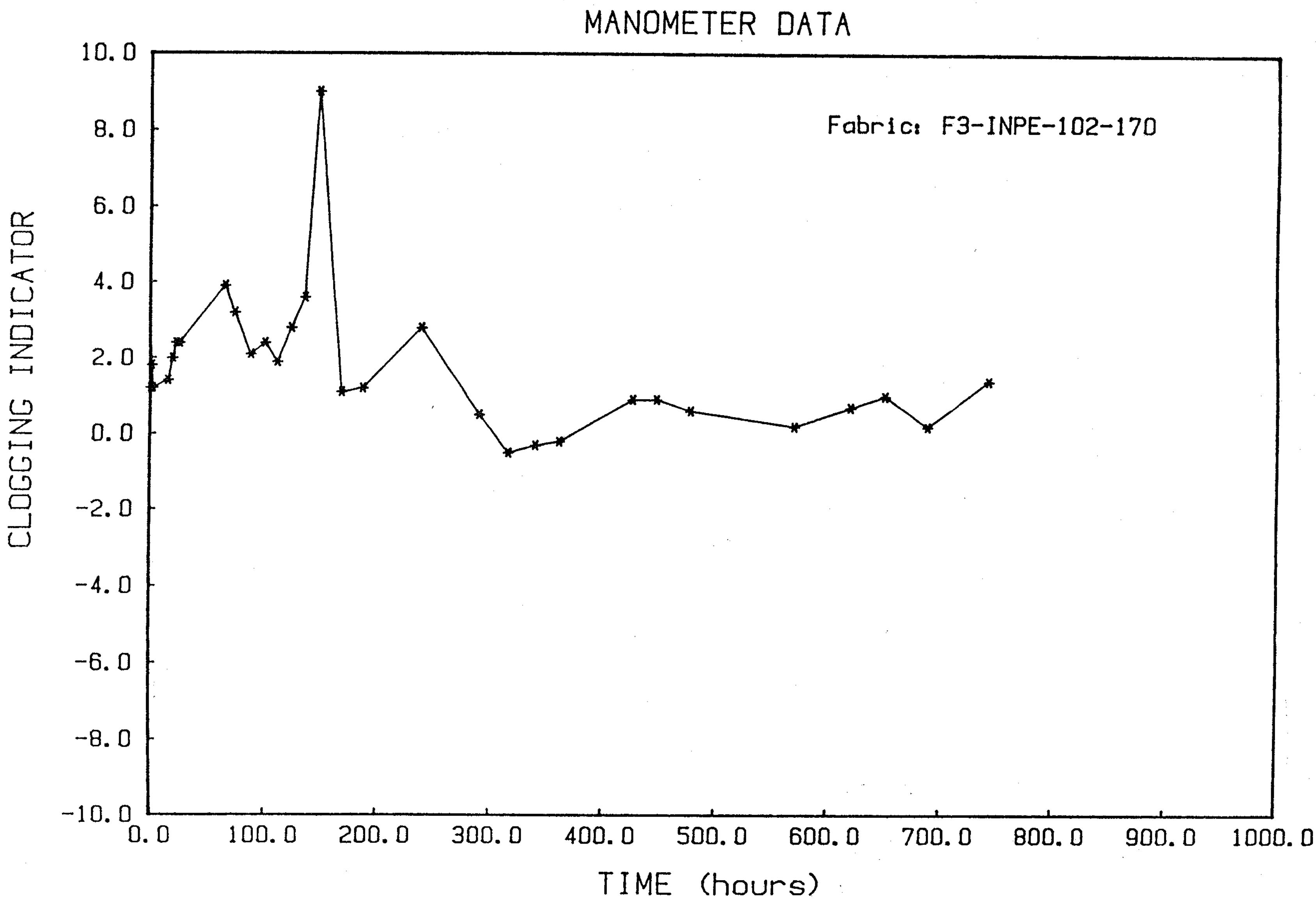


Figure B5: Clogging Indicator Versus Time for Geotextile F3-INPE-102-170

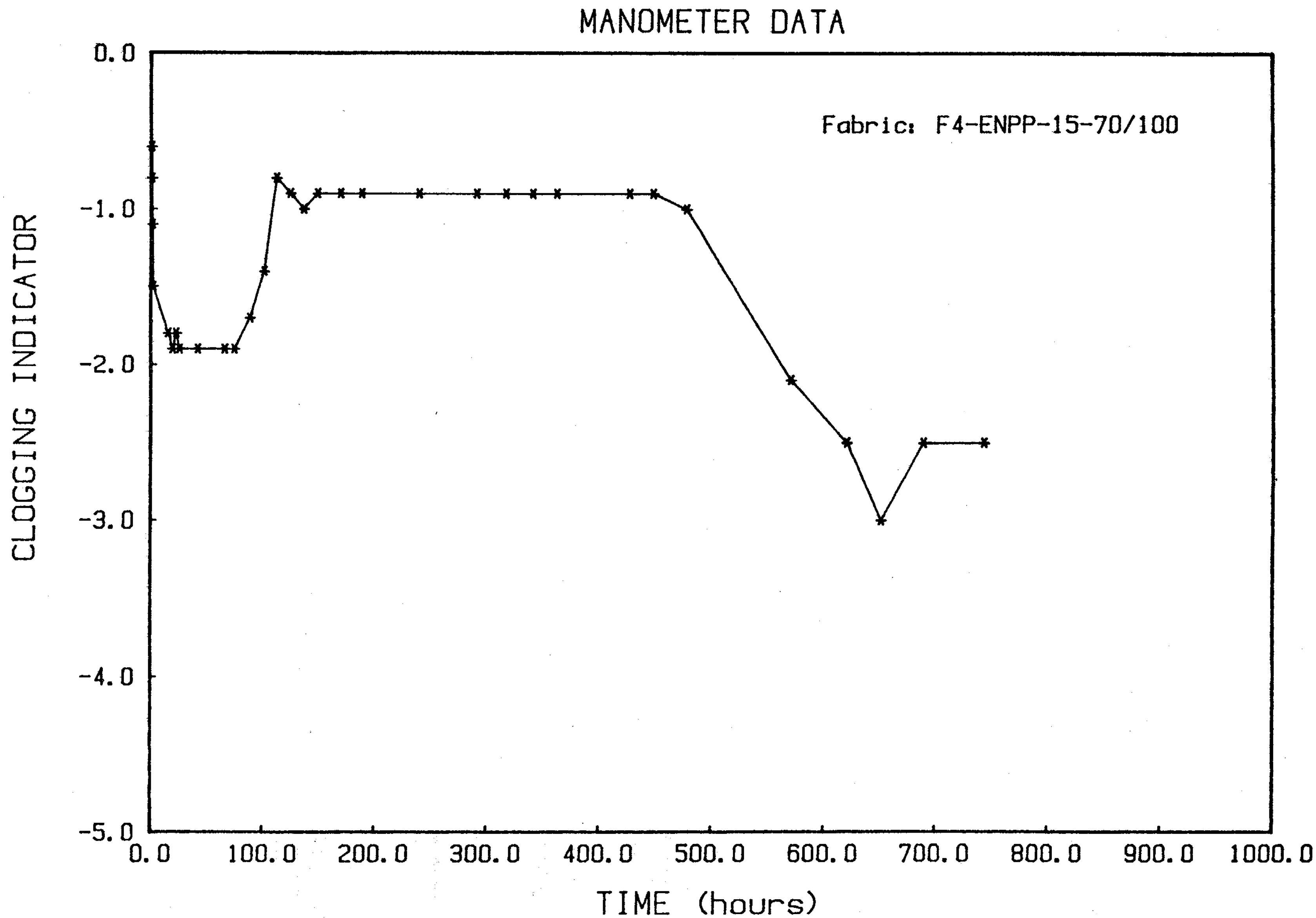


Figure B6: Clogging Indicator Versus Time for Geotextile F4-ENPP-15-70/100

APPENDIX C

Before Testing

After Testing

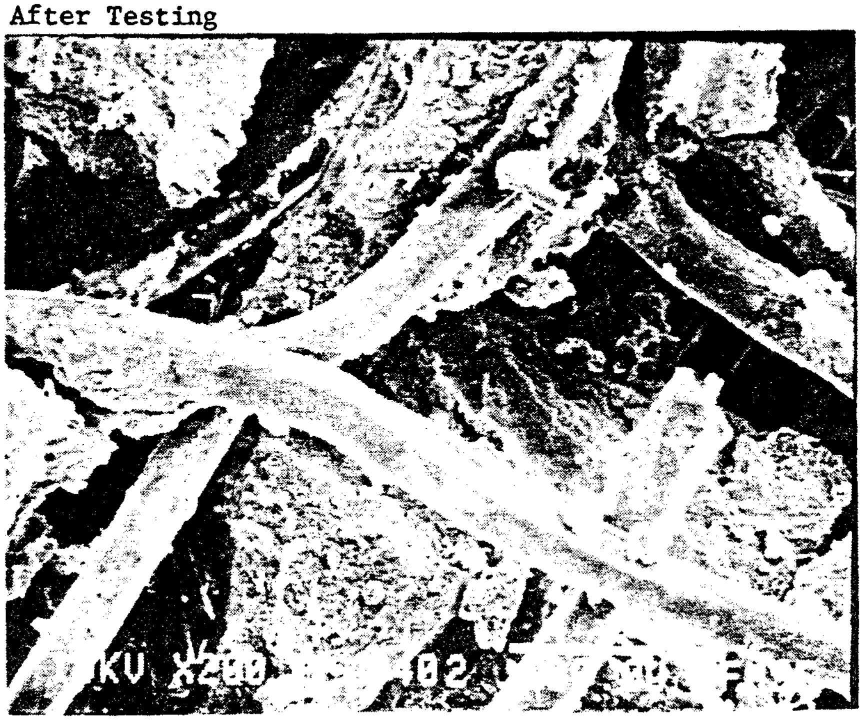
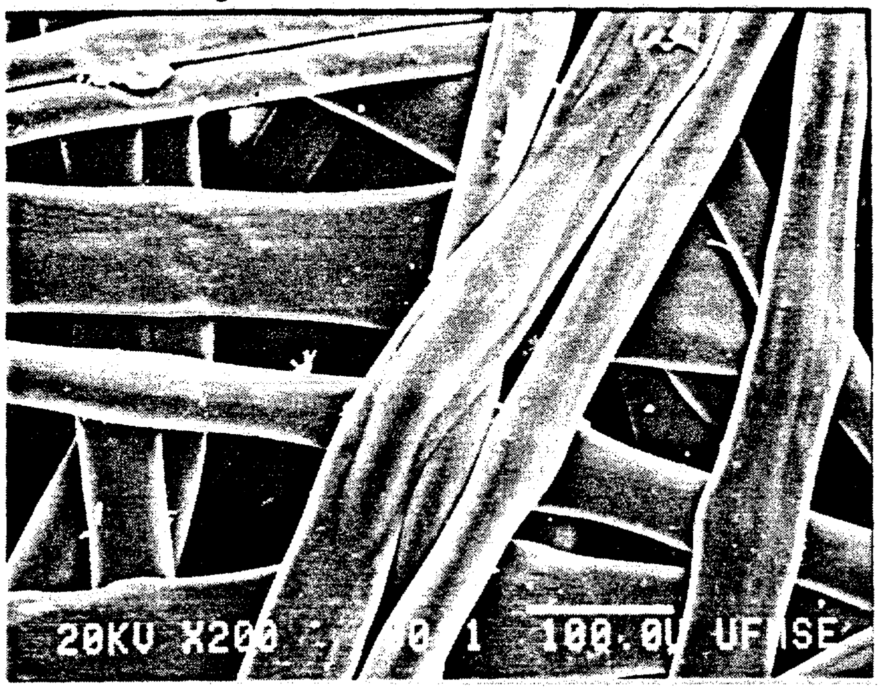


Figure C1: Scanning Electron Microphotographs, Before and After Testing, for Geotextile A4-JNPP-90-60/100.

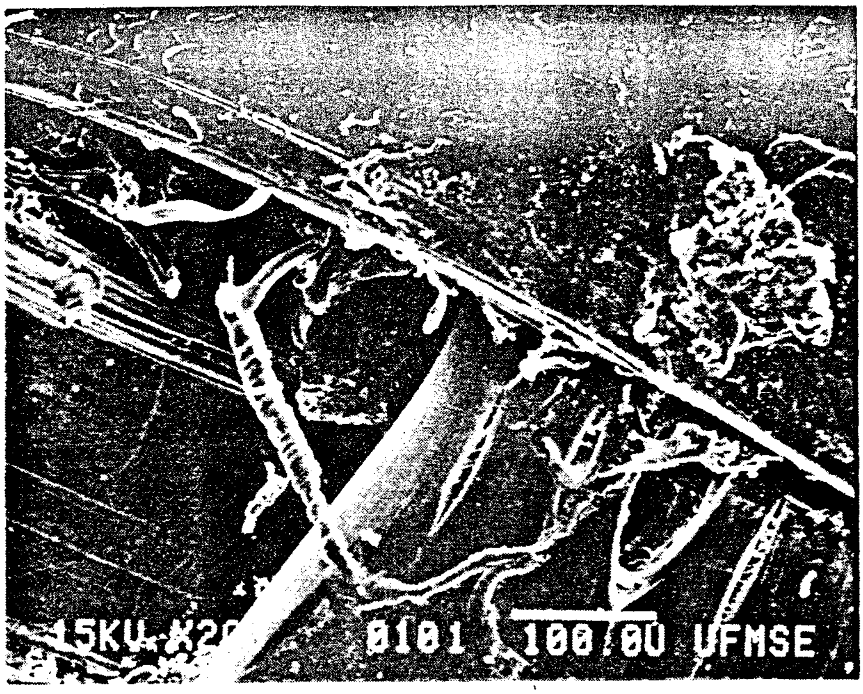
Before Testing



After Testing

Figure C2: Scanning Electron Microphotographs, Before and After Testing, for Geotextile B1-ENPP-18-140/170.

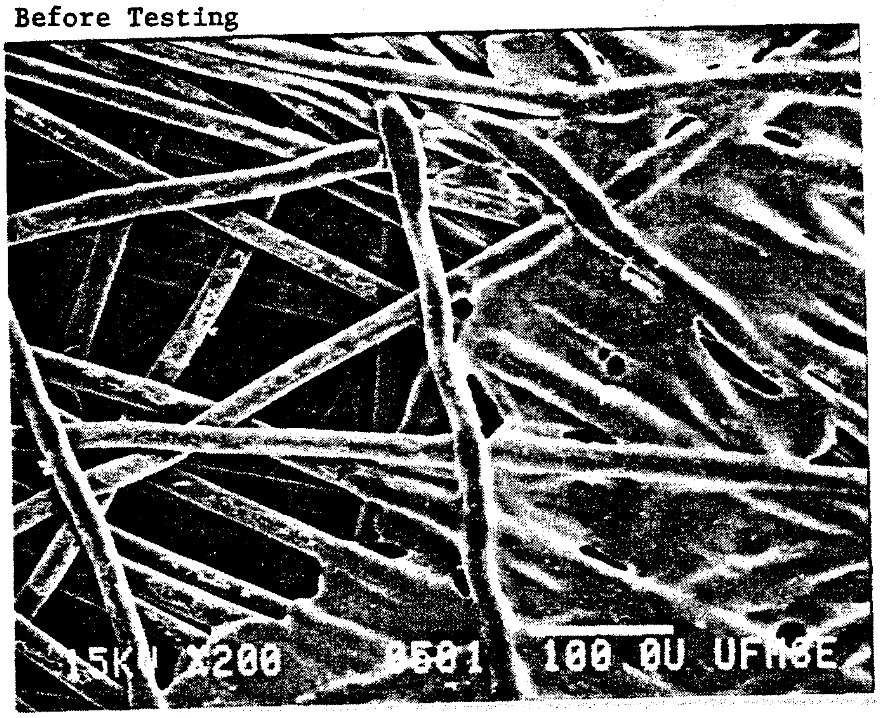
Before Testing



After Testing

Figure C3: Scanning Electron Microphotographs, Before and After Testing, for Geotextile B3-AWPP-18-70/100.

Before Testing



After Testing

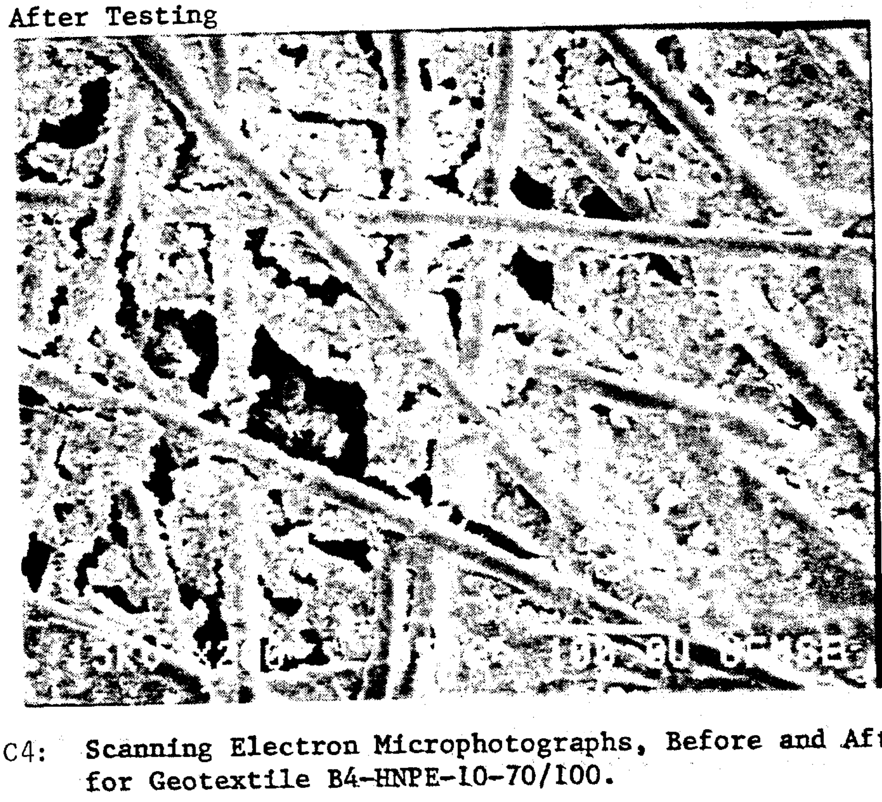
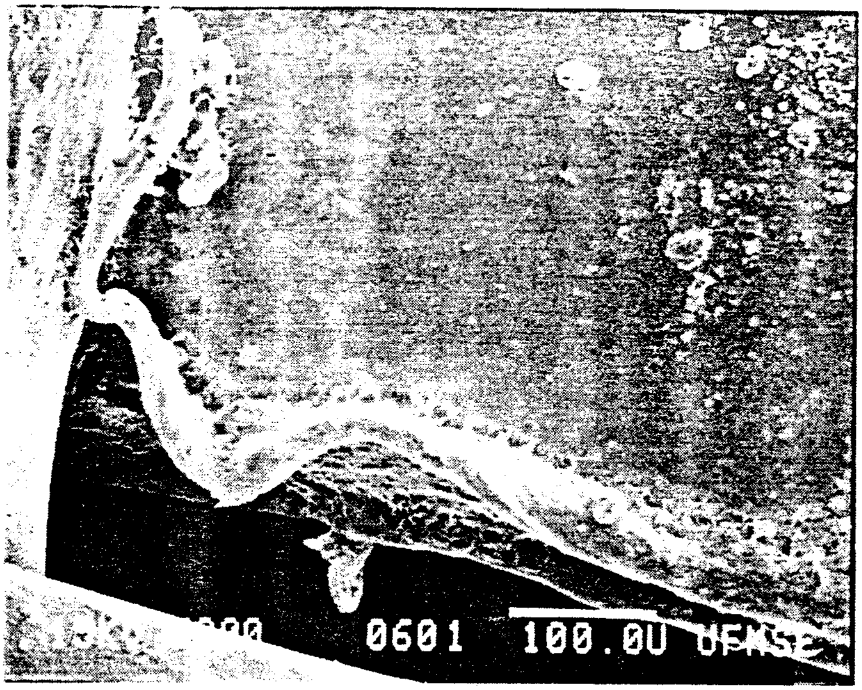


Figure C4: Scanning Electron Microphotographs, Before and After Testing, for Geotextile B4-HNPE-10-70/100.

Before Testing



After Testing

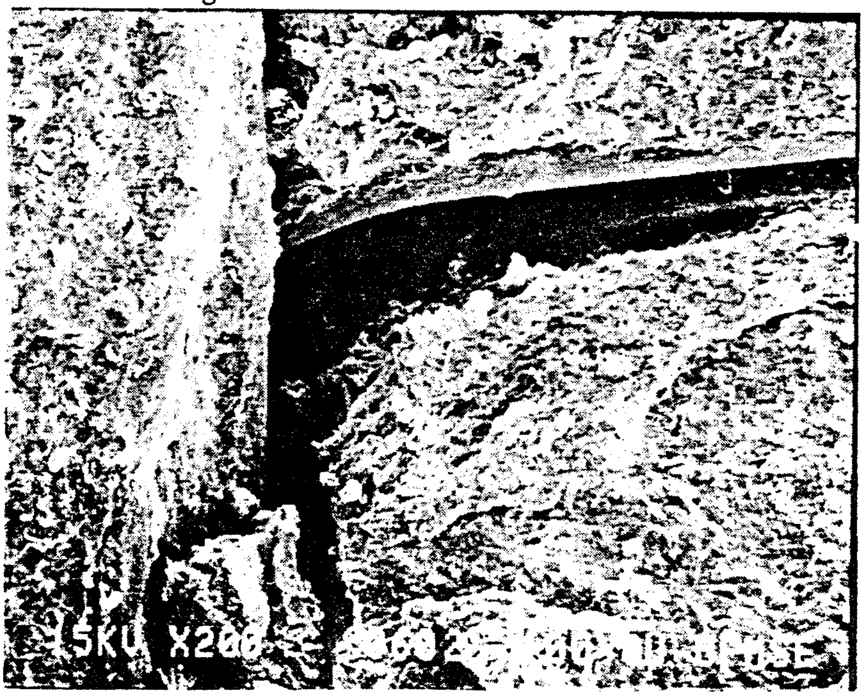
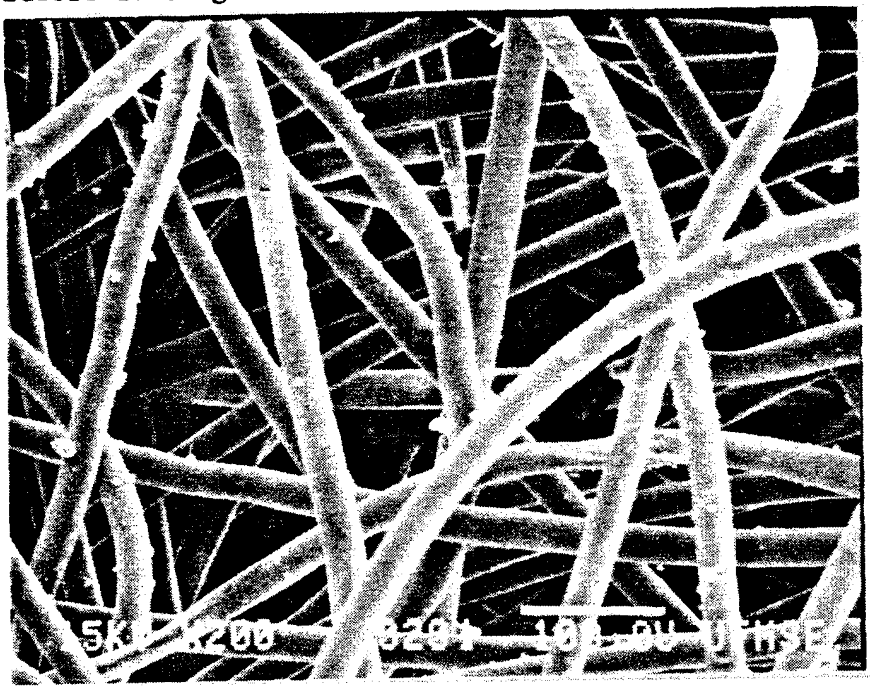


Figure C5: Scanning Electron Microphotographs, Before and After Testing, for Geotextile DI-CWPV-16-100.

Before Testing



After Testing

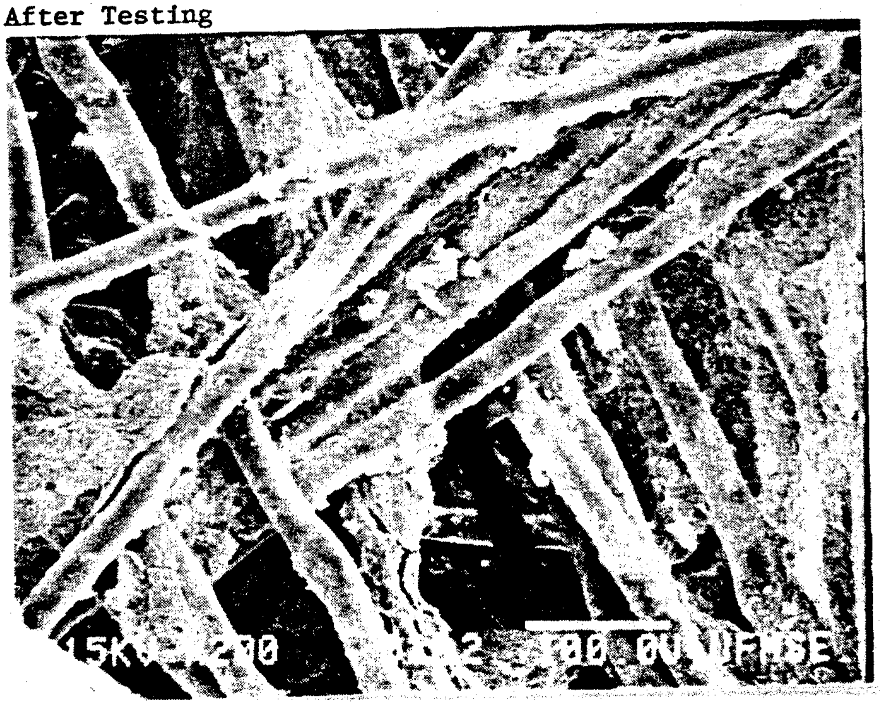
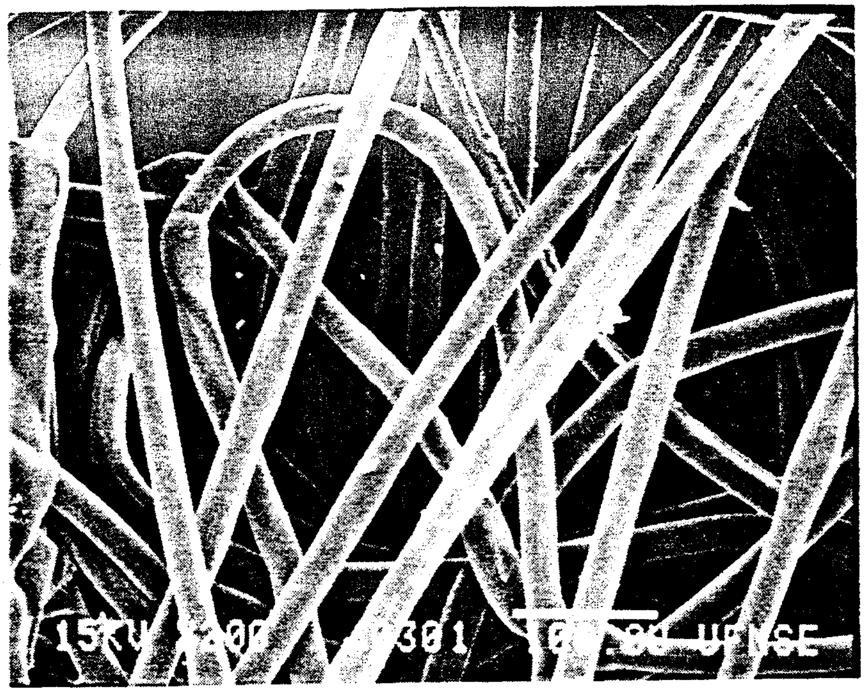


Figure C6: Scanning Electron Microphotographs, Before and After Testing, for Geotextile D3-KNPE-190-100.

Before Testing



After Testing

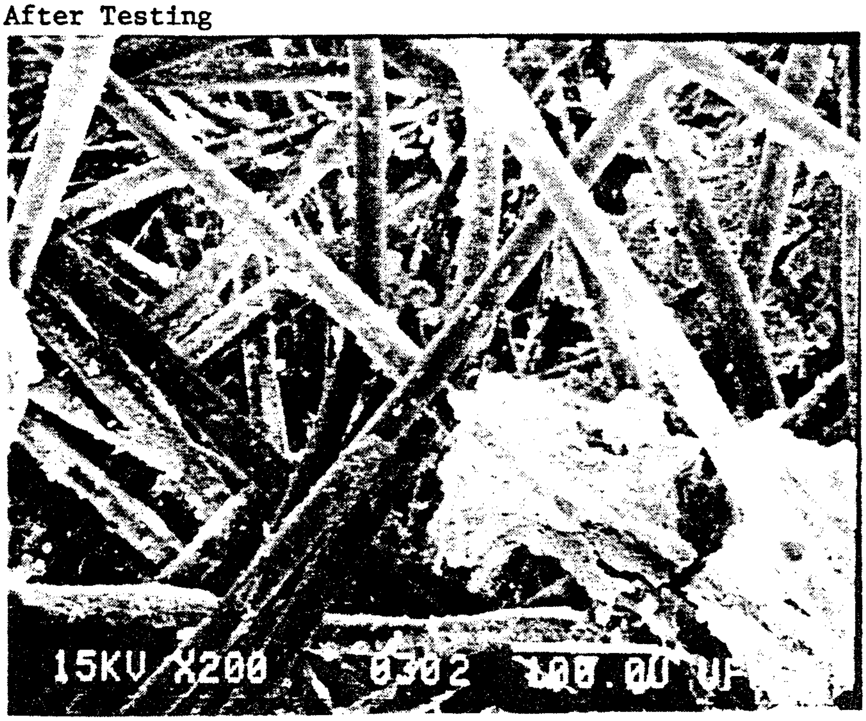


Figure C7: Scanning Electron Microphotographs, Before and After Testing, for Geotextile E3-ANPP-45-70.