t No. FHWA/RD-80/021
PB 81-156150

ALUATION OF TEST METHODS AND USE CRITERIA FOR GEOTECHNICAL FABRICS IN HIGHWAY APPLICATIONS

June 1980

Interim Report

Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Structures & Applied Mechanics Division
Washington, D.C. 20590

FOREWORD

This report introduces the potential beneficial uses of filter fabrics in highway applications; specifically, and primarily, how these uses may provide improvement in the reinforcement, stabilization, drainage, and/or erosion control of the soil structure. It also identifies and provides a definition of the required properties of the fabric material, how these properties are affected by type of polymer and manufacture, gives an appraisal of corresponding performance and cost effectiveness, and recommends new and modified test methods and procedures for the evaluation of these properties. The technical information presented in this report is considered to have significant implementable value to State and local highway and road agencies interested in potential improvements in soil structures for highways and roads.

Publication and distribution of this report is being disseminated and promoted jointly by the Pavement Systems Group, Structures and Applied Mechanics Division, Office of Research, and by the Construction, Materials and Methods Group, Implementation Division, Office of Development, which is currently planning and scheduling a series of several information workshops on the contents of this report. State and local highway and road agencies are invited and encouraged to review and consider potential utilization and implementation of the technical information presented in this report.

This report is being distributed under FHWA bulletin with sufficient copies of the report to provide a minimum of five copies to each regional office, five copies to each division, and ten copies to each State highway department. Direct distribution is being made to the division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

Technical Report Documentation Page

1. Report No. FHWA/RD-80/021	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EVALUATION OF TEST METHODS AND USE CRITERIA FOR GEOTECHNICAL FABRICS IN HIGHWAY APPLICATIONS		5. Report Date June 1980
		6. Performing Organization Code
7. Author(s) J.R. Bell, R.G. Hicks, et. al.		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering Oregon State University Corvallis, Oregon 97331		10. Work Unit No. (TRAIS) 35D3-142
		11. Contract or Grant No. DOT-FH-11-9353
12. Sponsoring Agency Name and Address Federal Highway Administration U.S. Department of Transportation Washington, D.C. 20590		13. Type of Report and Period Covered Interim (78-79)
		14. Sponsoring Agency Code
15. Supplementary Notes FHWA Contract Manager - George W. Ring (HRS-14)		

16. Abstract

This report presents results achieved during the first year's effort to develop test methods and use criteria for fabrics in drainage, erosion control and soil reinforcement applications. The report does not treat fabrics for use in asphalt pavement reinforcement.

An extensive literature search and field survey was conducted resulting in the development of interim criteria and fabric properties needed for a wide range of fabric applications. Test methods to evaluate these properties are identified and new test methods suggested where existing ones are considered inadequate. Specific results obtained include a discussion of important fabric properties and how they are affected by type of polymer and manufacture, an identification of fabric uses together with what fabric properties are important for each use, and an appraisal of the current knowledge regarding soil-fabric interaction, fabric performance and cost effectiveness. Recommendations are made for new test methods, or modifications of existing ones which need to be developed, to evaluate important fabric properties. A wealth of basic data has been accumulated for the development of improved tests and criteria to be used in the next phase of the project.

17. Key Words Fabrics, drainage, reinforcement, subgrade stabilization, erosion control.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 202	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

GLOSSARY OF TERMS

The following definitions are as used in this report.

ABRASION RESISTANCE

The ability of a surface to resist wear by friction.

ABSORPTION

The process of a gas or liquid being incorporated into a fabric.

ACTINIC RESISTANCE

Ability to resist deterioration on exposure to sunlight.

ADHESION

Shearing resistance between fabric and soil other than that due to friction.

ALKALI OR ACID RESISTANCE

Ability to resist deterioration or exposure to alkali or acid environments.

ARMOR

A protective covering.

BIAS

A direction diagonal to the warp and fill.

BINDER FIBERS

Fibers having a relatively low softening point compared to other fibers in the web, which upon the application of heat and pressure, act as an adhesive.

BIOLOGICAL RESISTANCE

Ability to resist degradation due to microorganisms.

BLINDING

Plugging of a fabric by partial penetration of particles into surface pores. The formation of a surface crust or cake.

BONDING

A process of binding fabric fibers by means of adhesives, plastics or melting.

BURST STRENGTH

The resistance of a fabric to rupture due to pressure applied at right angles to the plane of the fabric under specified conditions, usually expressed as the pressure causing failure. Burst is due to tensile failure of the fabric.

CALENDER

A machine used in finishing to impart a variety of surface effects to fabrics. It essentially consists of two or more heavy rollers, sometimes heated, between which the fabric passes under pressure.

CHEMICAL RESISTANCE

Ability to resist chemicals, such as acids, bases, solvents, oils and oxidation agents; and chemical reactions, including those catalyzed by light.

CLOGGING

The plugging of a fabric by deposition of particles within the fabric pores other than blinding.

CLOGGING RATIO

The ratio of the average hydraulic gradient across the fabric and the one inch of soil immediately next to the fabric to the average hydraulic gradient across the two inches of soil between one and three inches above the fabric.

COAXIAL HETEROFILAMENT

A filament having a core of one polymer and a sheath of another polymer.

COMPRESSIBILITY

Property of a fabric describing the ease with which it can be compressed normal to the plane of the fabric.

CONSTRUCTABILITY

Ease with which a fabric can be controlled, worked, handled, and fabricated.

CONSTRUCTION, FABRIC

The way the fibers, filament, and/or yarns are oriented and bonded to produce a fabric.

CONTINUOUS FILAMENT

A filament that is extruded and drawn in one continuous fiber.

CREEP, CYCLIC

Unrecoverable strain accumulated with repeated loading.

CREEP, STATIC

Increasing strain at constant stress.

CRITERION

A rule or test by which a judgement can be made.

CROSS DIRECTION (CROSS MACHINE DIRECTION)

The axis within the plane of a nonwoven fabric perpendicular to the direction of motion in the final forming step.

CUTTING RESISTANCE

The resistance of the fabric or fiber to cutting when struck between two hard objects.

DEGRADATION

Loss of desired physical properties of a fabric.

DENIER

A weight-per-unit-length measure of any linear material numerically equal to the weight in grams of 9,000 meters of the material.

DETERIORATION

See Degradation.

DRAPE

A term to describe the way a fabric falls while it hangs.

DUCTILITY

Permanent deformation before fracture, measured as elongation or reduction in area.

DURABILITY

A relative term for the resistance of a material to loss of physical properties or appearance as a result of wear or dynamic operation.

EQUIVALENT OPENING SIZE - E.O.S.

Number of U.S. standard sieve having openings closest in size to the diameter of uniform particles which will have 95% by weight retained by the fabric when shaken in a prescribed manner.

FABRIC - BONDED

A textile structure wherein the fibers are bonded together with an adhesive or by welding with heat and pressure.

FABRIC - COATED

A textile to which a substance such as lacquer, plastic, resin, rubber or varnish has been applied in firmly adhering layers to provide certain properties such as water impermeability.

FABRIC - KNITTED

Textile made up of loops of fibers connected by straight segments.

FABRIC - NONWOVEN

A textile structure produced by bonding or interlocking of fibers, or both, accomplished by mechanical, chemical or solvent means and combinations thereof excluding woven and knitted fabrics.

FABRIC - WOVEN

A textile structure comprising two or more sets of filaments of yarns interlaced in such a way that the elements pass each other essentially at right angles and one set of elements is parallel to the fabric axis.

FELT

A sheet of matted fibers made by a combination of mechanical and chemical action, pressure, moisture and heat.

FIBER

Basic element of fabrics and other textile structures, characterized by having a length at least 100 times its diameter or width which can be spun into a yarn or otherwise made into a fabric.

FILAMENT

A fiber of extreme length.

FILL

Fibers or yarns placed at right angles to the warp.

FILTER CAKE

A thin layer of fine soil particles accumulated in the soil adjacent to the fabric as a result of smaller soil particles being washed through the soil pores.

FILTRATION

The process of allowing water to easily escape from soil while retaining soil in place.

FLAMMABILITY

The ease with which a fabric may be ignited.

FLEXIBILITY

The ability to bend around a small radius with the application of only a small flexural stress. Low stiffness.

FREEZE-THAW RESISTANCE

Ability to resist degradation caused by freeze-thaw cycles.

FIBRILLATION

A process of forming fibers from sheet plastic film.

FRICTION ANGLE

An angle, the tangent of which is equal to the ratio of the friction force per unit area to the normal stress between two materials.

GRAB STRENGTH

A modified tensile strength of a fabric. The strength of a specific width of fabric together with the additional strength contributed by adjacent areas. Typically, grab strength is determined on a four-inch wide strip of fabric, with the tensile load applied at the midpoint of the fabric width through one-inch wide jaw faces.

GRADIENT RATIO

See Clogging Ratio.

HEAT BONDED

The fabric web is subjected to a relatively high temperature. The filaments are welded together at the contact points.

HETEROFILAMENT

A filament composed of more than one polymer

ISOTROPY

Exhibiting uniform physical properties in all directions within the plane of the fabric.

MACHINE DIRECTION

The axis parallel to the motion of a nonwoven fabric in the final forming step and within the plane of the fabric.

MELT BONDED

See Heat Bonded.

MODULUS

A measure of the resistance to elongation under stress. The ratio of the change in tensile stress to the corresponding change in strain. The reciprocal of compliance.

MONOFILAMENT

A single filament of a man-made fiber, usually of a denier higher than 15.

MULTIFILAMENT

A yarn consisting of many continuous filaments or strands.

NAP

A hairy or downy surface on a fabric.

NEEDLE PUNCHING

Subjecting a web of fibers to repeated entry of barbed needles that compact and entangle individual fibers to form a fabric.

NYLON FIBER

A manufactured fiber in which the fiber-forming substance is any long chain synthetic polyamide having recurring amide groups (-NH-CO-) as an integral part of the polymer chian.

PENETRATION RESISTANCE

The fabric property determined by the force required to penetrate a fabric with a sharp pointed object. Initial penetration is by separating the fibers. Further penetration is essentially a tearing process.

PERCENT OPENING AREA

The visible net area of a fabric that is available for water to pass through the fabric, normally determinable only for woven and non-woven fabrics having distinct visible and measurable openings that continue directly through the fabric.

PERMEABILITY - LONGITUDINAL or IN PLANE

The fabric property which permits water to be transmitted in the plane of the fabric.

PERMEABILITY - TRANSVERSE

The fabric property which allows water to pass through perpendicular to the plane of the fabric.

PERMEABILITY COEFFICIENT

A measure of the permeability to water. For uniform laminar flow, it is equal to the ratio of the outflow velocity to the average hydraulic gradient.

PIPING

The process by which soil particles are washed in or through pore spaces in drains and filters.

PLANE STRAIN

A loading condition where strains in the plane of the fabric occur in only one direction.

PLUGGING

The partial or total closure of fabric pores as a result of particle or chemical deposition or biological growth within or on a fabric.

POLYESTER FIBER

A manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of at least 85% by weight of an ester of dihyric alcohol and terephthalic acid (FTC).

POLYETHYLENE FIBER

A manufactured fiber in which the fiber-forming substance is an olefin made from polymers or copolymers of ethylene.

POLYMER

A high molecular chain-like structure from which man-made fibers are derived; produced by linking together molecular units called monomers - consisting predominantly of nonmetallic elements or compounds.

POLYPROPYLENE FIBER

A manufactured fiber in which the fiber-forming substance is an olefin made from polymers or copolymers of propylene.

POLYVINYLIDENE CHLORIDE FIBER

A manufactured fiber fiber in which the fiber-forming substance is a thermoplastic derived by copolymerization of two or more vinyl monomers.

PUNCTURE RESISTANCE

Resistance to failure of a fabric due to a blunt object applying a load over a relatively small area. Failure is due to tensile failure of the fibers.

REINFORCEMENT

Strengthening of a soil-reinforcement system with a tension member coupled to the soil by friction/adhesion.

RESIN BONDING

The fabric web is impregnated with a resin which serves to coat and cement the fibers together.

RUPTURE ENERGY

The energy required to elongate and totally rupture a fabric, causing ultimate failure.

SCRIM

A woven fabric to which nonwoven fibers are bonded or needlepunched to form a composite fabric.

SEPARATION

Function of fabric as a partition between two adjacent materials to prevent mixing of the two materials.

SLIT FILM TAPE

Tape filament produced by fibrillation.

SPLIT FILM TAPE

See Slit Film Tape.

SPUN-BONDED

Fabrics formed by continuous filaments which have been extruded and drawn.

STABILITY

A term used to describe the tendency of a fiber or fabric to retain its original characteristics after being subjected to an external influence.

STANDARD

A numerical value set for a criterion.

STAPLE FILAMENTS

Filaments that are cut to a desired length before using in the fabric.

STIFFNESS

The ability of a fabric to resist bending when flexural stress is applied.

STRENGTH

Load at failure. Depending on the usage, load may be expressed in stress, force per unit width, or force.

TAPE FILAMENT

A filament with a width many times its thickness.

TEAR STRENGTH

The force required to begin or continue a tear in a fabric under specified conditions.

TENACITY

The breaking tensile stress for a fiber in terms of the size of the unstrained fiber expressed as grams-force per denier.

TENSILE STRENGTH

The strength shown by a fabric subjected to tension as distinct from torsion, compression or shear.

THERMAL STABILITY

The ability of fibers and yarns to resist degradation at extreme temperatures.

THICKNESS

The dimension of a sheet or lamina measured perpendicular to the plane of the sheet under a specific pressure.

TOUGHNESS

The property of a fabric by which it can absorb work energy. It is proportional to the area under the load-elongation curve from origin to breaking point.

TRANSMISSIVITY

The coefficient of longitudinal permeability times the fabric thickness.

ULTRAVIOLET STABILITY

See Actinic Resistance.

UNIDIRECTIONAL

Performing best in one direction.

WARP

Fibers or yarns lengthwise in the fabric.

WEB

The sheet or mat of fibers or filaments before bonding or needlepunching to form a nonwoven fabric.

WEIGHT, FABRIC

The mass of a fabric expressed in weight per unit area.

WICKING

The process whereby a fabric raises water above a free water surface by capillary action.

YARN

A generic term for a continuous strand of textile fibers, filaments or materials in a form suitable for weaving or otherwise intertwining to form a textile fabric.

1.0 INTRODUCTION

Development of the use of fabrics in the transportation field has been very rapid. As recently as a decade ago, the only applications of fabrics in highway applications were a few experimental applications. Today, several agencies use fabrics routinely. An estimate of 15,000,000 square yards (12,500,000 m^2) of fabric used in the United States in 1977 would be conservative. Marketing reports indicate that this quantity could increase rapidly each year for the next several years. In Europe, use of fabrics exceeds that of the United States. Estimates of quantity used in Europe range from 30 to 40 million square yards (25 to 33 million square meters) per year.

Along with this growth in the use of fabrics, there has been a large number of companies entering into the market with a proliferation of new fabrics. In the United States alone, there are fabrics available from over two dozen sources, where several of the fabrics are available with a variety of characteristics. New fabrics are being added to the list constantly. Because of the newness of the use of fabrics in highway applications, there has been little in the way of in-depth state-of-the-art reports on design of fabric installations. This has resulted in users having to rely many times on little or no information to select fabrics for different applications.

The fact that fabrics have generally been developed by the textile industry, rather than one of the more conventional construction material industries, has added additional confusion in that much of the terminology and tests used to characterize the fabrics are not familiar to most engineers.

1.1 PURPOSE

This report presents the results obtained during the first year's effort on the project entitled, "Evaluation of Test Methods and Use Criteria for Geotechnical Fabrics in Highway Applications," where the major objectives of the project were to:

(1) Identify criteria for the highway uses of fabrics, particularly in subdrainage, erosion control and soil reinforcement applications, and

(2) Evaluate existing test methods and modify them as needed or to develop new test methods (as needed) for evaluating the important properties of fabrics.

The report includes the following:

(1) Descriptions of fabric types, including the relationships of manufacturing method and polymer type to properties,

(2) Description of fabric uses, including criteria, properties, and test methods important for each use. Where possible, standards for good performance are suggested, and

(3) Appraisal of the current state of the knowledge as well as needs for additional information.

This information hopefully will serve as an interim basis for use of fabrics in drainage, erosion control and soil reinforcement applications until additional information is developed. Phase II of this study will consist of the development and evaluation of test methods.

1.2 RESEARCH APPROACH

The research approach shown in Figure 1-1 was used to develop basic data and information from which test methods and use criteria could be developed. It relies heavily upon information gained from prior research, field visits and analytical evaluations.

Over two hundred references were collected and analyzed for information relating to:

(1) Test methods used to characterize fabrics,

(2) Properties and factors affecting properties of fabrics,

(3) Soil-fabric interaction theories,

(4) Performance and cost information related to fabric installations,

(5) Standards or criteria used by agencies to select fabrics for various uses, and

(6) Information on construction methods and problems associated with fabric installations.

Limited analytical studies were made to assist in the understanding of soil-fabric interaction theories and in the evaluation of design criteria.

Field visits were made to selected state highway and transportation departments and other agencies to collect first-hand information on use and evaluation of fabrics. Interviews were held with engineers responsible for design, construction and evaluation of fabric installations. Where possible, visits to field installations were made and information on performance of fabrics was collected.

This study is limited only to the use of fabrics in drainage, erosion control, soil reinforcement and separation applications for highways. The use of fabrics to minimize or prevent reflection cracking is outside the scope of the project. Also, applications for uses other than highway uses are outside the scope of the project.

1.3 SCOPE

The results of this study are presented in the following sequence:

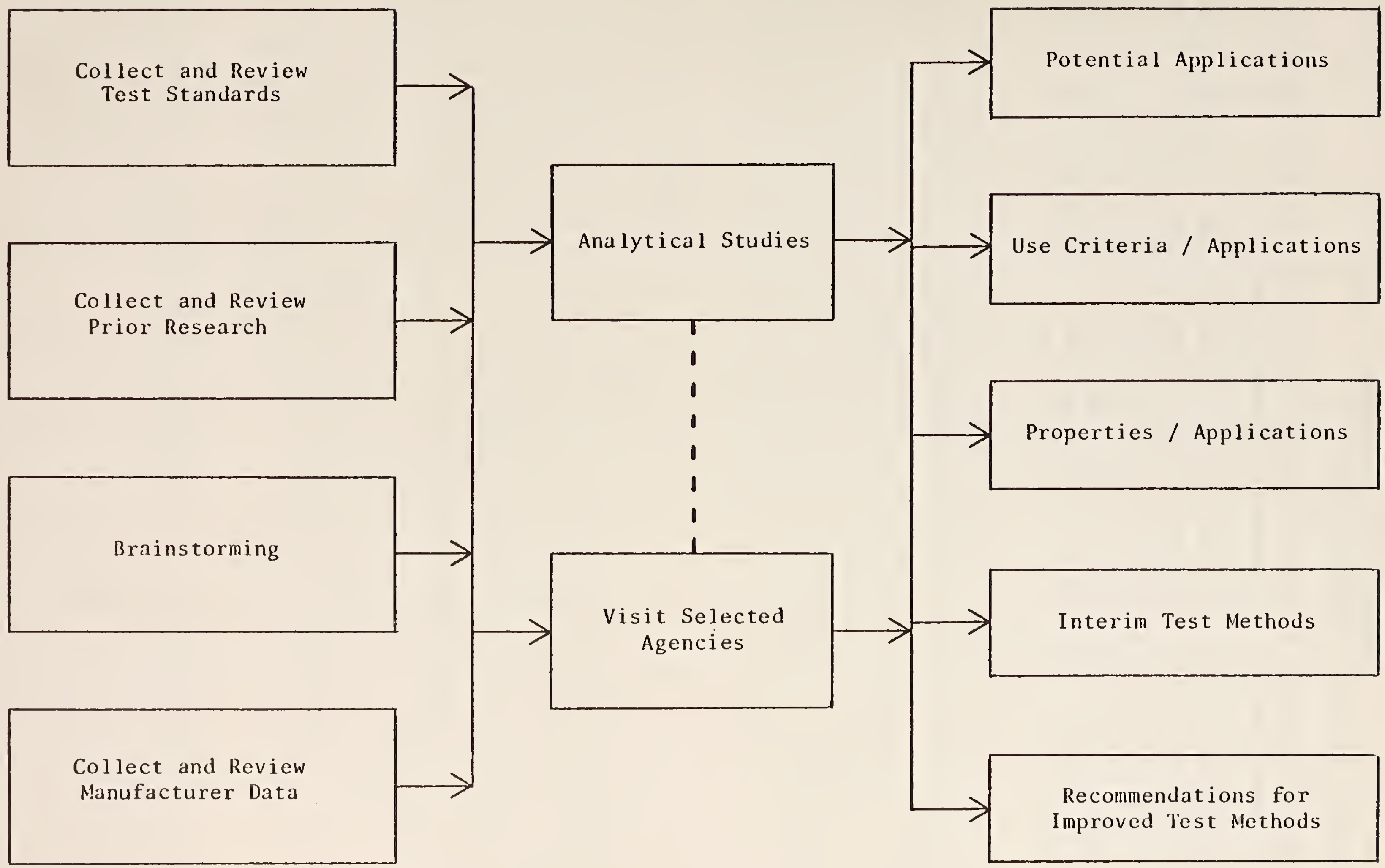


FIGURE 1-1. Approach Used in Developing Test Methods and Use Criteria for Filter Fabrics

CHAPTER 2 describes the types of fabrics available and how method of manufacture and polymer type affect fabric properties.

CHAPTER 3 identifies for each use the important criteria and fabric properties and suggests interim methods of evaluating these properties.

CHAPTER 4 appraises the current state of the knowledge as to soil-fabric interaction theories, use criteria and performance of fabric installations, as well as making suggestions for classification systems for fabric usage.

CHAPTER 5 summarizes the results of Phase I and makes recommendations for Phase II.

2.0 FABRICS CLASSIFICATION

In the past few years, many fabrics have been introduced to the market. Additional fabrics are being added continually. It is important to note that these fabrics vary greatly in their characteristics. Further, it is highly unlikely that any one fabric is the best for all possible applications. It is necessary for the engineer to select from the wide variety of available fabrics the fabric which is most likely to be satisfactory and least expensive for his particular application and specific job. The primary fabric types considered in this publication are enumerated in Table 2-1. To make an intelligent selection of fabrics, it is necessary that the engineer have an understanding of the factors which control the engineering behavior of fabric materials.

The properties of fabrics are principally controlled by the fabric construction, the nature of the filament, and the weight of the material per unit area in the fabric. It is important to realize that in most instances the fabric construction is more important than polymer type. This chapter discusses the more common polymers which are used to manufacture the filaments for current fabrics and their general characteristics. Secondly, it discusses the methods of fabric construction and the general effects these construction methods have on the properties of the fabric. Finally, the more important fabric properties are discussed relative to the combined effects of filament polymer and fabric construction.

2.1 FABRIC POLYMERS

Currently, geotechnical fabrics in the United States are manufactured from polypropylene, polyester, nylon, polyethylene and polyvinylidene chloride. Of these, polypropylene and polyester are by far the most common. The polyvinylidene chloride is only known to be used in one fabric. Polyethylene is currently only being used in two or three fabrics. Most fabrics incorporate only one polymer; however, several fabrics use fibers made from more than one material. One popular fabric uses a heterofilament which is a coaxial fiber consisting of a polypropylene core and nylon or polyethylene sheath.

While there are significant differences between the different polymers, it is important to note that there may be significant differences between fibers produced by different processes from the same polymer. The properties may be altered by additives and most significantly by method of forming the polymer into a filament [3].

The more important polymer characteristics influencing the properties of the fabric are specific gravity, strength, strain at failure, modulus of elasticity, creep, reaction to cyclic loading and stability or durability with respect to temperature, water immersion, ultraviolet light, chemical activity, and biological attack. Cost will, of course, be important in determining the suitability of a fabric for a specific engineering application. These factors are discussed below. In these discussions, polyvinylidene chloride is not considered because of its very limited application in geotechnical fabric applications. Also, nylon is given limited consideration because of its small use. Polyethylene is used very little in the United States but is discussed

TABLE 2-1. Numbers* of Known Fabrics Available and Distributions by Polymer and Types

CATEGORY	FABRIC TYPE AND POLYMER	NUMBER
Woven	MONOFILAMENT	
	Polypropylene	6
	Polyvinylidene Chloride	1
	MULTIFILAMENT	
	Polyester	2
	Polypropylene	1
	RIBBON FILAMENT	
	Polypropylene	2
Non-woven	FILAMENT	
	Staple	7
	Continuous	7
	POLYMER	
	Polypropylene	6
	Polyester	5
	Nylon	1
	Combination	2
	CONSTRUCTION	
	Needlepunched	4
	Heat bonded	4
	Resin bonded	2
	Combination bonding	4
Combination Woven and Non-woven		5

*1977

some because it is used in foreign applications to a considerable degree and will probably become more common in the United States. The Japanese use an expanded polyethylene net to a significant extent [14,15] and one of the largest producers of fabrics is producing a fabric composed of coaxial hetero-filaments, having a polyethylene sheath over a polypropylene core [5]. The emphasis in this chapter is on polyester and polypropylene because of their extensive use.

The common polymers have certain similarities. They have specific gravities fairly close to unity. Also, they are relatively low-cost materials, are strong for their cost and weight, and have relatively low resistance to ultraviolet light. With respect to chemical and biological stability, their durabilities are very high. There are, of course, significant differences between polymers and these are discussed below.

As produced for fibers in most geotechnical fabrics, polyester tends to have a higher modulus and lower failure strain than polypropylene. Polyester also has superior creep resistance characteristics compared to polypropylene [1]. Polypropylene fibers have a higher resistance to cutting due to impact than polyester [16]. Polypropylene also has a higher toughness for low rates of loading but for very rapid loading the two may be about equal [25]. Nylon fibers are more resistant to abrasion relative than the others [1].

Polyethylene has a different stress-strain curve than do the other materials. It increases to a peak stress at a yield strain beyond which the strain increases at a decreased stress and straining continues to very high values before breaking. The other materials all tend to show an increase in stress to the failure strain, or if there is a decrease in stress at high strains, it is modest [1].

It is clear that, as currently used for geotechnical fabric fibers, polyester generally has mechanical properties superior to those of polypropylene. The polyester polymer also is somewhat more expensive on a weight basis. If a given application requires very good mechanical properties the more expensive polyester may prove to be the more economical. On the other hand, if superior mechanical properties are not necessary the less costly polypropylene will probably be more economical, other factors being equal.

Polyester and nylon have specific gravities greater than one while both polypropylene and polyethylene have specific gravities less than unity. In the case of underwater installations, this may be significant because these latter two fibers will float while the others may sink.

All of the common polymers deteriorate when exposed to ultraviolet (UV) light. The polyester and nylon are significantly more resistant than the polypropylene and polyethylene; however, for permanent installations exposed to the sunlight, none of the untreated materials are likely to be satisfactory [4]. The materials can be stabilized by chemical additives. This operation increases the cost and it is doubtful that it would render the materials truly permanent for some applications. Filaments may be stabilized at low cost by the addition of carbon black. This has been used successfully with polyethylene for many years.

Polyester has sufficient UV resistance that given reasonable protection during storage and a minimum consideration in construction planning it should not be damaged by exposure during normal construction operations. Untreated polypropylene, however, may lose significant strength if exposed to bright sunlight for only a few days. This requires more care during construction and may be a problem in some instances. Polypropylene fabrics currently available are not ordinarily stabilized against UV; however, it would be possible to treat them at very little cost so that their UV resistance would be great enough to eliminate virtually any construction problem.

When buried, all of the polymers being considered have very high resistance to most forms of chemical attack [4]. They are highly resistant to both acids and alkalies. Chemical deterioration of these materials protected from ultraviolet light should be very slight at pH levels likely to be encountered in the soil. There does not appear to be any very significant difference between polymers for these conditions. Polypropylene, however, is significantly affected by liquid hydrocarbons such as diesel fuel.

It is also unlikely that biological destruction of these polymers will occur. Microorganisms are highly specialized in their activities, and these materials have not been common in the environment long enough to expect that a set of bacteria which would attack these materials would have evolved [6].

The fibers all have low moisture absorption and swelling. Moisture absorption, where it occurs, may result in slight losses in strength of the fibers on wetting. Of the materials under discussion, nylon absorbs the greatest amount of water. This material may show a 20-30% reduction in ultimate strength with soaking in water [1]. This absorbed moisture may also result in a reduction in strength upon freezing; however, the actual effects of moisture on different fabrics is still unclear.

The polymers used for fabric materials all have relatively low melting points. Nylon and polyester are comparatively higher with melting temperatures of approximately 260°C (500°F), while polypropylene and polyethylene have lower melting temperatures of about 175°C and 135°C (347°F and 275°F), respectively. Even at temperatures below the actual melting point, the molecular orientation of some of the fibers may be altered, and hence their mechanical properties changed.

Polyester, polypropylene and nylon all develop crystalline orientation during the manufacture of the fabric fibers. In manufacture, the polymer is first melted and extruded. The fibers are then drawn. This drawing increases the length of the fiber and reduces its diameter and increases the crystalline orientation of the polymer. Within limits, the more the fiber is drawn the greater the orientation resulting in increased strength and modulus for a given polymer. Heat tends to destroy this orientation, and thereby reduces the modulus and strength and increases failure elongation. Therefore, fibers which have been subjected to temperatures approaching their melting temperature may have their mechanical properties significantly altered, even without any obvious visual damage to the fabric. In most instances, low temperatures do not cause a significant change in ultimate strength, but low temperatures do strongly influence the elongation at failure and increase the modulus of the materials, making it more brittle [8,11]. The formulation and structure of fibers produced from the same type of polymer may vary so much that it is not possible to give "typical" values for their mechanical properties However, some typical values for some physical properties are given for the common polymers in Table 2-2.

It is apparent from the above discussion that all of the common polymers used in filter fabrics have relative advantages and disadvantages. It is unlikely that any polymer will prove to be the best for all applications. Therefore, one should select the polymer or combination of polymers which will meet the needs of a specific application in the best and most economical manner. The relative properties of the most common polymers are indicated in Table 2-3. Note the scale used to rate the polymers in this table is not linear and is very subjective. A 3 is only slightly lower than a 4, but a 2 is considerably lower. From a practical point of view, there may be little significant difference between a 3 and a 4 rating, but there is a significant difference between a 3 and a 2. In giving the ratings, the effort is to indicate the significance rather than the numerical magnitude of the actual numerical difference. It is also important to note that a 4 is not necessarily desirable. It only denotes the highest value. For some properties and uses a low value might be the most desirable. Creep is such a property.

While the fiber polymer is important, most fabric properties are more strongly influenced by the fabric construction than the polymer. Fabric construction is discussed in the next section.

2.2 FABRIC CONSTRUCTION

There is a wide variety of fabric constructions in use today and new ones are continually being developed. By fabric construction is meant the methods whereby the polymers are formed into filaments and the filaments are assembled and bonded together to produce a coherent fabric. Each of the various fabric constructions has its own relative advantages and disadvantages and it is unlikely that any single method will emerge as the most suitable for all possible uses. It is also important to note that almost every feature that is an advantage for one application will be a disadvantage for some other use of the fabric. This section discusses the various construction methods with respect to the process and the general nature of the resulting fabric. The combined effects of fabric polymer and fabric construction properties are discussed in the next section.

This section does not discuss all existing methods of construction or all possible methods, but is limited to those methods which are significant with respect to the geotechnical fabrics being produced in the world today. These methods can be divided into five categories. These categories and important subdivisions are:

(1) Woven

- (a) Monofilament
- (b) Multifilament
- (c) Ribbon Filament

TABLE 2-2. Typical Values for Some Physical Properties of Common Polymers [1,2,3,4]

PROPERTY	POLYMER			
	POLYPROPYLENE	POLYESTER	NYLON	POLYETHYLENE
Specific Gravity	0.9	1.3	1.1	0.9
Melting Temperature (°C)	175	260	260	135
Water Absorption (%)	Nil	0.6	2.0	Nil

TABLE 2-3. Comparison of Polypropylene and Polyester Fibers as Commonly Produced for Geotechnical Fabrics

PROPERTY	VALUE*	
	POLYPROPYLENE	POLYESTER
Specific Gravity	2	4
Tensile Strength	4-2	3
Modulus	2	4
Elongation at Break	4	2
Melting Temperature	2	4
Abrasion Resistance	?	?
Resistance to Impact Cutting	4	2
Absorption	3	4
Percent Strength Loss on Wetting	3	4
Tendency to Creep	4	1
UV Resistance	2	4
Chemical Resistance	4-2	4-2
Biological Resistance	4	4
Cost on a Weight Basis	2	4

Property Value Scale*

4 - Highest
3 - Slightly Lower
2 - Considerably Lower
1 - Greatly Lower
0 - Insignificant or Negligible
? - Unknown

*This scale does not indicate desirability. In some instances a high value is best in others a low value is best.

(2) Knitted,

(3) Nonwoven

 (a) Needle punched
 (b) Heat bonded
 (c) Resin bonded,

(4) Combinations, and

(5) Special.

Photos of a fabric from each category are given in Figure 2-1.

Some of the terminology in this section may be unfamiliar; therefore, the most-used terms have been defined in the Glossary. The terminology used is consistent with that currently used in geotechnical fabric literature and does not necessarily strictly adhere to textile industry definitions. Also, these discussions consider only major or broad classifications of fabric construction and those methods which are currently more common in geotechnical fabric construction. In reality, there are many subtle and different methods of construction not alluded to in this report. For example, one reference lists forty-eight different classes of nonwoven fabrics alone [7].

2.2.1 Woven Fabrics

Woven fabrics consist of filaments or yarns of polymer oriented in two mutually perpendicular directions, overlapped one over the other. Fabrics may be woven in many patterns, but for the geotechnical applications, they are usually woven in a simple uniform rectangular pattern. Compared to the other methods of construction, weaving is the more expensive. It has the advantage of producing a product with a simple structure. The pore size distribution is relatively uniform, simple and easily determined.

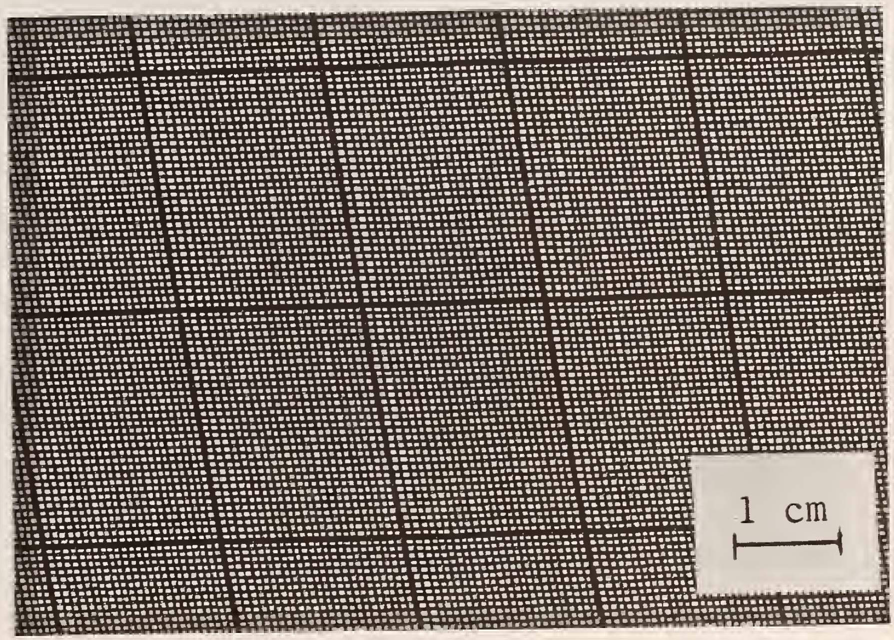
Fabrics may be woven so they are isotropic or anisotropic. That is, they may have the same mechanical properties in both the warp and fill directions, or different in the two directions. They may be woven with more and stronger fibers in the warp direction than the fill direction, or possibly with different polymers in the two directions. Isotropic fabrics would have the same stress-strain characteristics in the warp and fill directions.

It is important to note that stress-strain characteristics of woven fabrics are almost always presented in terms of the warp or fill directions. When woven fabrics are stressed in a bias (diagonal) direction their properties are greatly different. Their modulus is greatly reduced.

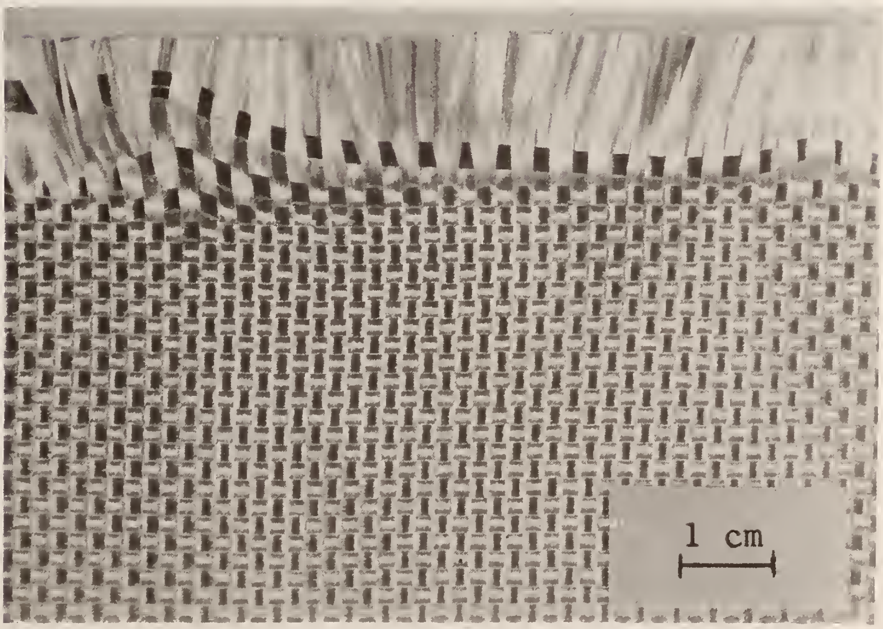
Also when a woven fabric is loaded in either the warp or fill direction, the stress-strain curve will show a high initial modulus; however, as the stress increases slightly, the modulus will decrease. As the load is increased further, the modulus will again increase. The first high initial modulus is evidently due to a frictional interaction between the fibers. The lower intermediate modulus is a result of the straightening of the fibers. In the unstressed fabric, the individual fibers are straight in the warp di-

Figure 2-1. FABRIC CATAGORIES

(1) Woven Fabrics

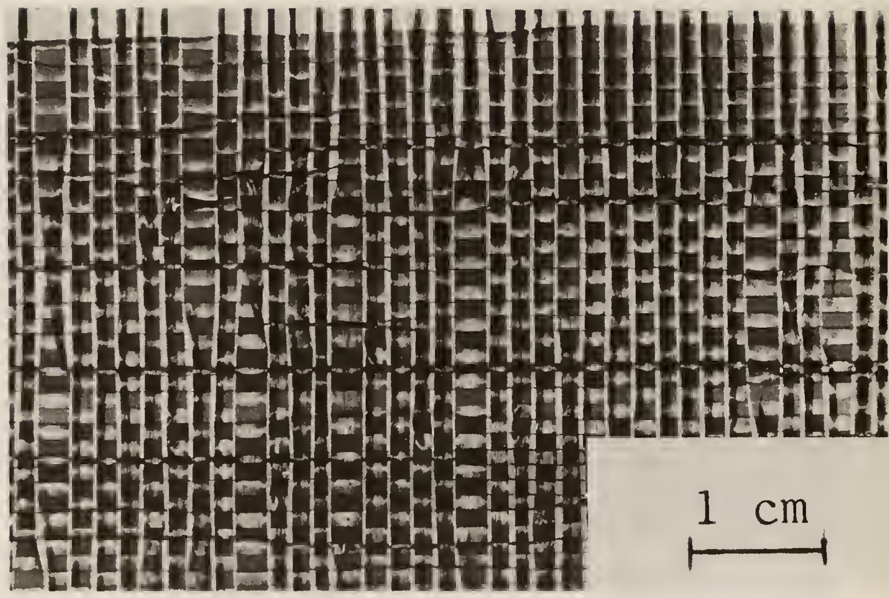


a) Monofilament

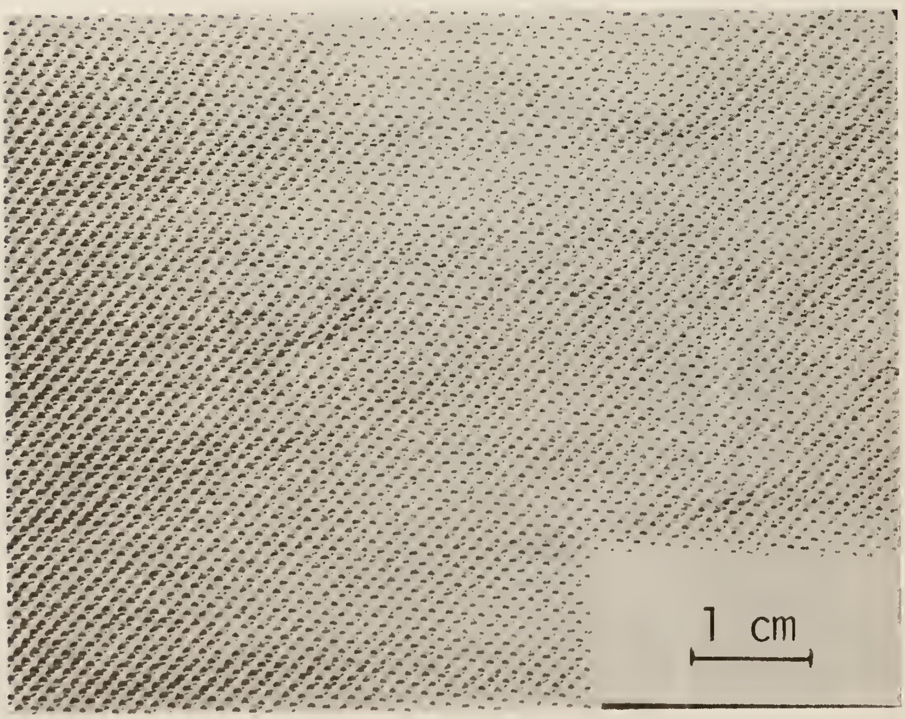


b) Multifilament

Figure 2-1. Continued.



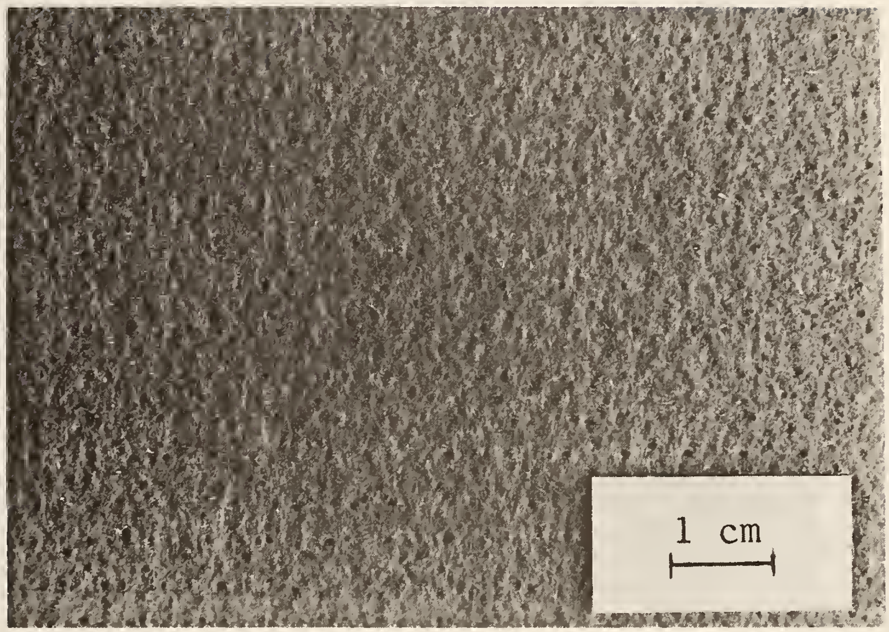
c) Slit Film Ribbon Filament



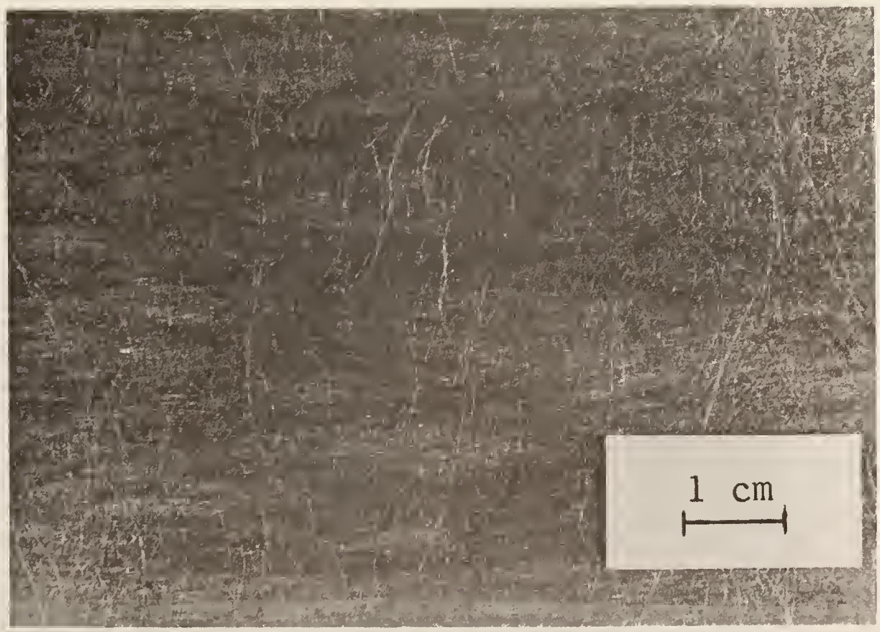
(2) Knitted Fabric

Figure 2-1. Continued

(3) Nonwoven Fabrics

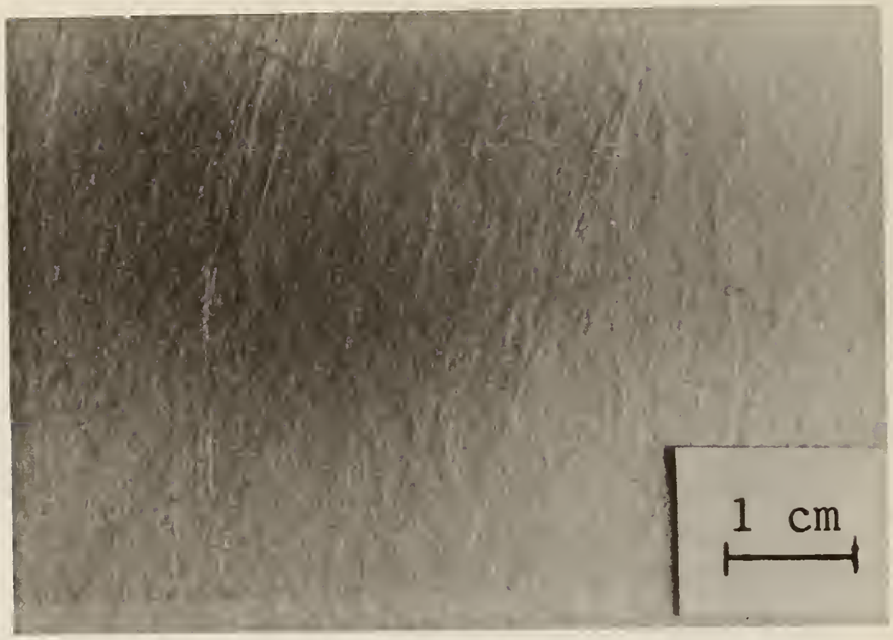


a) Needle Punched



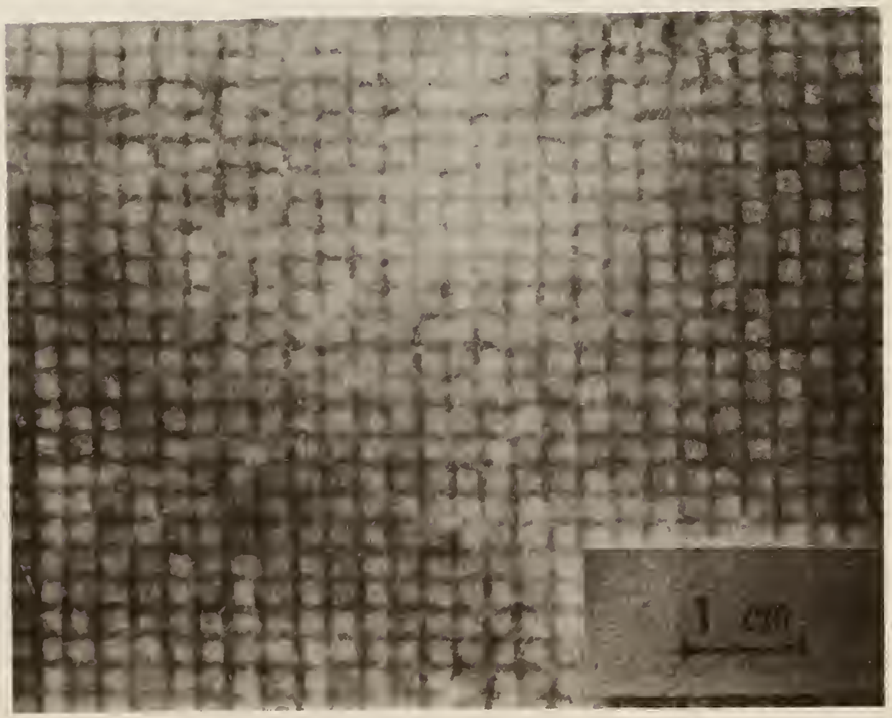
b) Heat Bonded

Figure 2-1. Continued.



c) Resin Bonded

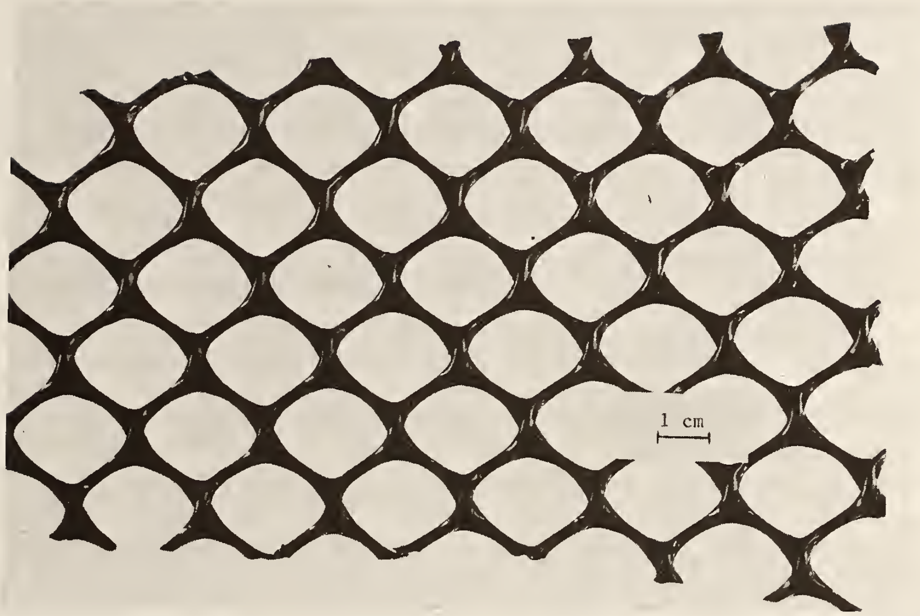
(4) Combination Fabric



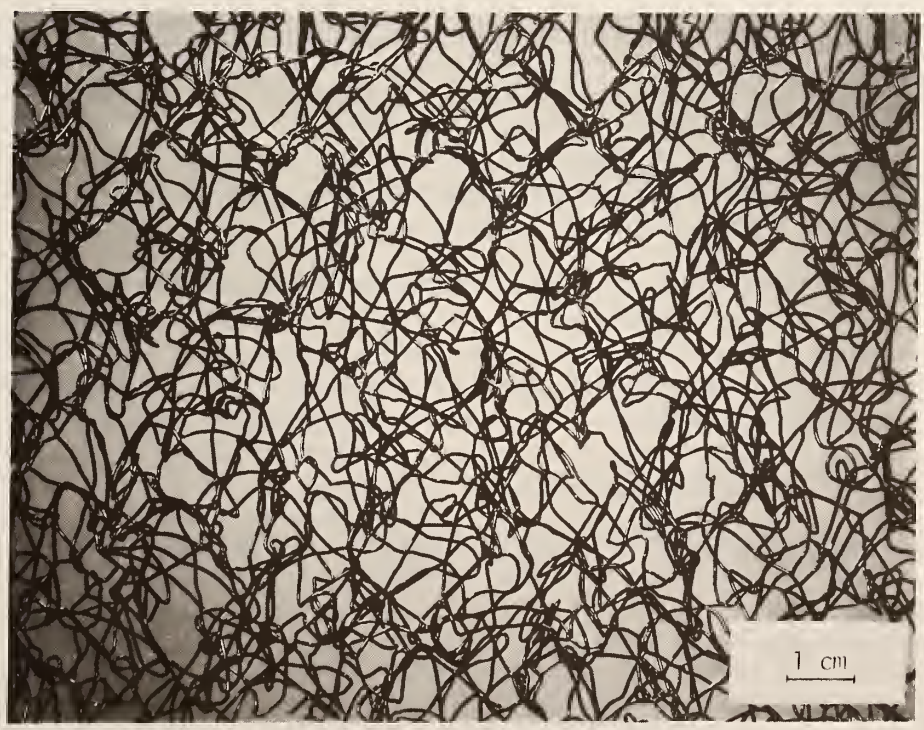
a) Woven scrim with needle punched nap

Figure 2-1. Continued

(5) Special Fabrics



a) Extruded Plastic Mesh



b) Entangled melt bonded monofilaments

rection, but in the plane of the fabric, they are curved vertically as they are woven over and under the fill fibers. As one set of fibers is stressed, it displaces the unstressed cross-fibers and becomes straight in the plane of the fabric. This results in an increase in apparent length with little applied stress. Also, multifilament yarns may be twisted and they tend to straighten as they are pulled. Once the fibers have been straightened out, additional straining of the fabric requires an actual stressing of the fibers. Beyond this point, the stress-strain curve of the fabric is controlled by the stress-strain relationship of the fiber. Because of the relatively simple geometry of woven fabrics, the mechanical properties of a woven fabric can be directly related to the mechanical properties of the fibers or yarn.

Woven fabrics can be subdivided according to the nature of the components which are woven together to form the fabric. The three classes discussed here are monofilament, multifilament and ribbon filament fabrics.

2.2.1.1 Monofilament Fabrics

Monofilament fabrics are woven from strands which are single filaments of a polymer. Most of these are manufactured from polyester or polypropylene, and there is at least one monofilament fabric manufactured from polyvinylidene chloride. These filaments are extruded and are usually circular in cross-section, although some of them tend to be oblong. The manufacturing process and relatively high cost of these fabrics make it convenient and reasonable to use carbon black for ultraviolet light stabilization; therefore, most of these fabrics are black. Some fabrics are calendered after weaving so that the individual filaments are bonded together by heat at the contacts giving considerable stability to the fabric structure. These fabrics have discrete simple openings.

Most monofilament fabrics for geotechnical uses are woven in weights such that they have medium strengths relative to other geotechnical fabrics. The production of fabrics of very high strength is not efficient by the monofilament method. Differential cooling creates problems in extruding filaments of very large diameters and does not allow for drawing of the filaments to develop maximum orientation of the polymer chains which would produce the maximum strength and modulus for the materials.

While they have been used for other purposes, they were adapted for and their main use is for filters where moderately high strength is also required as under riprap. Some engineers also believe that because of their simple pore structure the monofilament fabrics are more reliable filter materials and use them in critical installations where their higher cost can be justified.

2.2.1.2 Multifilament Fabrics

Multifilament fabrics are woven from yarns composed of many fine fibers or fibrillated film filaments. The strongest fabrics produced are manufactured by this method and are usually fabrics especially designed for reinforcement. Great strength can be obtained by using yarns consisting of many filaments. Polypropylene and polyester are more common than nylon in the geotechnical field because of their lower cost. The fabrics incorporating fibrillated films are polyethylene. Strength is obtained not only by using a large number of filaments, but the filaments themselves are small diameter and may be drawn to a high ratio, thereby developing the maximum orientation and the greatest possible strength available from the polymer used.

In most reinforcing functions, the stresses applied to the fabrics are greater in one direction than in the other; therefore, many multifilament fabrics manufactured for reinforcing purposes are anisotropic. Anisotropic multifilament fabrics are among the most efficient in placing high strength in the plane of the fabric and in the direction of the maximum stress and therefore are used where reinforcing applications demand superior mechanical characteristics. Their high cost will usually limit their use in other applications.

2.2.1.3 Ribbon Filament Fabrics

As used in this report, ribbon filament fabric refers to fabrics woven of filaments which have a width many times the thickness of the filament. Some class these in the monofilament class but they are considered separately in this report.

The most common ribbon fabrics in the United States and the only ones considered in this report are the slit-film polypropylene fabrics. These fabrics are woven from ribbons slit from a polypropylene sheet. They are sometimes referred to as slit-tape fabrics. These fabrics are very inexpensive by woven standards and are comparable in cost to the nonwoven fabrics. The slit-film fabrics are produced in light and medium weight and offer a moderately high strength and high modulus. Their main applications to date have been as separators. These fabrics are less uniform than the monofilament fabrics; the ribbons are not bonded together, and in service the films are easily split so that the pore characteristics may be variable. Their use as filters has been relatively limited.

2.2.1.4 Summary

As a group, the woven fabrics offer moderately high to very high strengths with moderately high modulus and relatively low strain at failure. They also have simple pore structures.

2.2.2 Knitted Fabrics

While in woven fabrics the strands of the fabric are essentially straight, knitted fabrics are made up of loops of fibers or yarns connected by straight segments. Because of this structure, the knitted fabric may stretch in one or both directions without significantly stressing the fibers. Knitted fabrics may be either monofilament or multifilament, as discussed above. The knitting process has two advantages over weaving. First, it is less expensive, and second, it is possible to knit tubes.

Knitted fabrics have not been widely used in the civil engineering field; however, there are two applications worthy of mention. First, knitted tubes have been used as filters around drain tiles in agricultural applications for some time, and this use is now being recognized in the highway field [17].

Second, one company has developed a special knitted fabric for reinforcement applications (18). In this knitting procedure, the main multifilament yarns are placed not only straight in the direction of the fabric, but flat in the plane of the fabric so they are not crimped over and under the cross fibers, as in the woven fabrics. This fabric, unlike the woven fabric, has a stress-strain curve which starts out with a high initial modulus controlled strictly by the modulus of elasticity of the yarn and does not have the S-shaped curve characteristic of the woven fabric.

2.2.3 Nonwoven Fabrics

Nonwoven fabrics, with the exception of some special fabrics, include all materials which are not woven or knitted. They consist of discrete fibers which are arranged in some manner to form a fabric. They may show some preferred orientation or may be placed in a random manner and do not form a simple repetitive pattern as do the woven and knitted fabrics.

To date, nearly all nonwoven fabrics marketed in the United States have been manufactured from polyester, polypropylene or polypropylene-nylon hetero-filaments. As a group, the nonwovens are relatively inexpensive, have low to medium strengths and high to medium elongations to failure. They are widely used as filter materials, separation materials, and for light reinforcement.

The properties of nonwoven fabrics are controlled by the fiber properties the geometric relationships of the fibers and the methods of bonding.

2.2.3.1 Fiber Filaments

The fiber filaments are divided into two groups of staple and continuous filaments. The continuous filaments are extruded, drawn, and laid in the fabric in one continuous fiber. The staple filaments are cut to the desired length before use in the fabric. Staple filaments may vary from less than an inch to several inches in length.

Staple Filaments. Staple filaments are formed into a fabric mat or web by either wet or dry methods. In the wet method, the staple fiber pieces are mixed in water, and the slurry is pumped onto a supporting screen or belt. The water is then removed by squeezing or suction, leaving the fiber elements in a mat or web. The web is then dried and bonded into a fabric by one of the bonding methods described below. In the wet-laid process, the fibers are all more or less parallel to the plane of the fabric, but otherwise oriented randomly.

In the dry-laid process, staple fibers are applied to a supporting screen or belt by air or some mechanical means. In some processes, the fibers are carded so that they are all more or less prallel. In this case, the resulting fabric will have a significant anisotropy. Other processes result in the fibers being placed in a random manner. They may be parallel to the plane of the fabric and random in the other two directions, or they may be random in three dimensions. It is even possible in some processes to place the staple fibers with a strong orientation normal to the plane of the fabric. In this construction, the ends rather than the sides of the fibers are exposed at the surface of the fabric. Finally, the fabric is finished by bonding the mat or web by one or more of the bonding methods described below.

The final fabric weight may be produced by laying a single web of the desired weight or it may be produced by taking several webs of lesser weights and bonding them together. In the case of the anisotropic dry-laid webs, layers may be cross-laid so that the finished fabric may have essentially the same mechanical properties in the machine and cross-machine directions. In this case, the mechanical properties at other angles would be different, as mentioned with woven fabrics.

In many cases, staple fibers are used to permit use of equipment which was developed for production of fabrics from natural fibers of finite lengths. However, there are special orientations of the fibers which can only be achieved by using staple fibers, and in some instances these techniques have been used to produce fabrics with special properties.

Continuous Filaments. Continuous filaments are formed by extruding the polymer from dies at high temperatures. The extruded filament is then drawn to the final dimension in one continuous thread. This drawing develops the orientation in the filament and has a strong influence on controlling the mechanical properties. Different processes have different degrees of drawing and therefore relatively different strengths, elongations at failure and elastic moduli. The staple fibers are produced by chopping the continuous filament into the desired length and used in the processes described above. In the continuous filament process, the filaments are laid on continuously moving belts, usually by means of air jets. The filaments so placed are oriented in the plane of the fabric, but essentially random in the other directions. Some processes may produce a slight anisotropy of the fabric mat. The strongest direction may be either the machine direction or cross-machine direction, depending on the details of the process.

2.2.3.2 Bonding Methods

The filaments in the nonwoven fabrics are bonded together by one of four general methods. These methods are: needle punching, heat bonding, resin bonding, and various combinations of the above three methods.

Needle Punching. Needling is accomplished by punching many barbed needles through the fabric web normal to the plane of the fabric. This action causes the fibers to be mechanically entangled. This technique results in a loose fabric which has the appearance of a felt mat. Such fabrics are frequently called felts or mats. The needling may be accomplished on a single web, or several layers may be needled together to form a thicker fabric. Needle punching is very difficult to control for very lightweight materials, but works very well for the heavier fabrics.

The needled fabrics are thick for their weight and have very complex pore structures. Also, they are compressible, so the nature of the pores may change depending upon the stresses on the fabric. Further, the fabric fibers have considerable freedom of movement relative to each other.

Heat Bonding. Heat or melt bonding is accomplished by subjecting the fabric web to a relatively high temperature. This results in the filaments welding themselves together at the contact points. From this, a relatively thin fabric is formed with the individual fibers physically attached to each other so they may not move unless the fibers or the bonds are broken. Melt bonding works very well with the lightweight fabrics, but is difficult to apply to heavyweight fabrics. The melt bonding process results in a fabric with relatively discrete and simple pores. Further, the pore size and configuration are relatively independent of the stresses applied to the fabric.

For polyester and polypropylene fibers to have high tenacity and high moduli, it is necessary that their polymer be highly oriented. This orientation is developed in the fiber by drawing. First, the fiber is extruded in a molten form through a die and as the fiber is cooled, it is mechanically stretched to produce the high orientation in the polymer. If the fiber is subsequently melted or even heated to a temperature very close to its melting temperature, much of the structure will be destroyed and the fiber will lose these desirable properties. This creates a problem in heat bonding, in that if the fabric web is heated to a temperature high enough to bond the fibers together, it will reduce the orientation and degrade the mechanical properties. To overcome this, it is necessary to include fibers in the fabric web which will melt at lower temperatures and will serve as a bonding agent to hold the higher tenacity fibers together, or to introduce a second material which will melt at a lower temperature than the primary fibers and accomplish the same purpose.

In polyester fabrics, it is common to utilize two slightly different polyester formulations in the fibers. One of these has a slightly lower melting point and serves to bond the fibers together. Strong bonds occur only where two low melting point fibers contact each other. It is apparent that if the mixture is fifty-fifty between the fiber types, bonds will occur at one quarter of the contact points.

In polypropylene fabrics, it is possible to take advantage of the fact that the melting temperature increases with the orientation of the fiber. Therefore, it is possible to produce fibers in the web with different melting temperatures by using different draw ratios during the fiber forming process [7]. When the heat is applied to such a web, the fibers with the lowest draw ratio and hence the least polymer orientation serve to bond the other higher tenacity fibers to form the fabric.

A third approach is to incorporate an additional binding material. This has been done by using co-axial filaments. These have been either a nylon or polyethylene sheath around a polypropylene core. When heat is applied to the web containing these filaments, the sheath material melts and bonds together leaving the core material intact. Using polyethylene, the heat may be applied dry because polyethylene has a lower melting temperature than polypropylene. However, nylon has a higher dry melting temperature than polypropylene; therefore, when nylon sheaths are used, the heat must be applied with steam. In the presence of steam, nylon has a lower melting temperature than polypropylene [3].

The system using co-axial heterofilaments is more complex and therefore slightly more expensive. However, it offers greater flexibility in controlling fabric properties. An obvious advantage is that it allows all of the homofilaments to have a high draw ratio and hence a relatively high tenacity. Some other heat bonding methods require that at least a significant percentage of the fibers be lower tenacity so that they have lower melting temperatures. Also, with the co-axial filaments, the percentage of contacts between filaments which will be bonded can be controlled by controlling the ratio of co-axial hetero-filaments to simple homogeneous filaments. If the ratio is fifty-fifty, then 25% of the contact points will be bonded. If 100% of the filaments are co-axial heterofilaments, then 100% of the contacts will be bonded. This will have a significant influence on the mechanical properties of the resulting fabric.

Resin Bonding. Resin bonded fabrics are produced by impregnating the fabric web with a resin which serves to coat and cement the fibers together. The thickness and structure of these fabrics are intermediate between that of the needled fabrics and the melt bonded fabrics. The thickness depends upon the pressure used to compress the mat during the bonding process. The resulting fabric may be quite thick and open or fairly thin and dense. Resin bonding is more expensive than the other methods. Also, other things equal, resin bonded fabrics will have less voids and permeability.

2.2.3.3 Combination Bonding Techniques

A number of geotechnical fabrics use two or more of the above techniques. Sometimes this is done simply to expedite manufacture, and other times it is to produce special combinations of mechanical and pore characteristics. Resin bonded fabrics are frequently also needled. In some instances the needling is simply an intermediate step to facilitate the other bonding process and the final fabric properties do not reflect the needle punching. One fabric which is produced for the drain function is a thick needled polyester fabric which then is given special resin bonding treatment to product two outside resin bonded layers with a thicker central high-permeability layer. Another fabric is a staple polypropylene fabric which is needle punched and then heat bonded on one side only.

2.2.4 Combination Fabrics

A number of fabrics have been produced by using more than one of the various construction and bonding techniques discussed above. The practice of needling a mat onto a woven scrim is relatively common. In this construction, the scrim is usually to provide the mechanical strength and the needled mat is to provide filtering capabilities and abrasion resistance. The lightweight fabrics of this type are manufactured by needling a light mat, usually of nylon onto a slit film polypropylene woven material. The heavier fabrics of this type usually use woven polyester fabrics as the scrim and heavy needled mats of polypropylene, polyester or nylon.

In most of these applications, a staple fiber is used, and the needling process is such that the fibers are oriented so that their ends are exposed on the face of the fabric. Where a very high abrasion resistance is desired, the mat may also be resin bonded. This results in a resin bonded needle punched mat on a woven scrim or backing.

In some instances, the mat is needled on one side of the scrim only. In other instances, a mat is needled on both sides of the scrim, forming a sand-which type of construction. In this latter case, the two mats may be different.

The heavy combination fabrics are expensive, but they offer great flexibility for manufacture of fabrics for special uses. They are usually used where very high strength and/or very high abrasion resistance is required in connection with good filtration characteristics. They may also be designed for other special needs. Possible variables include the strength of the scrim and the polymer and fiber orientation in the mat. Hundreds of combinations are possible.

A number of special fabrics to serve as drains have also been fabricated. These have consisted of a thick permeable fabric sandwiched between two thinner filter layers. The filter layers have commonly been melt bonded nonwovens with the permeable layer consisting of one of the heavy needled fabrics or one of the special fabrics discussed below.

2.2.5 Special Fabrics

Two materials which do not fit into any of the above classifications but which have been applied to geotechnical problems are briefly discussed below.

The first is an extruded plastic mesh. This material is formed of polyethylene, is a single layer, and has the appearance of a net. Both the elements forming the net and the openings are significantly larger than in the fabrics previously discussed. The openings are uniform in a given mesh and vary from about 7 to 70 mm for the meshes manufactured. The elements are welded at each contact. These materials have been used to a limited extent in the United States, but have been used rather extensively in Japan [14]. Applications have been mainly separation, reinforcement and erosion control

A second special fabric is a three-dimensional structure of entangled nylon monofilaments melt bonded at their intersections [19]. This material is quite coarse, the resulting fabric is very thick, and the openings are large. To date, this material has been used most frequently in erosion control installations.

2.2.6 Summary

The important factors in fabric construction are indicated in Table 2-4. It is apparent that a wide variety of fabrics are available. It is equally obvious that a much wider range of fabric types is possible with the development of new materials and techniques. The range of characteristics of these fabrics is very wide. This is true both with respect to pore characteristics and mechanical properties. Fabric durability characteristics may also be quite different. The engineer must recognize these differences and select those fabrics which are most likely to be suitable for his particular application.

It must also be noted that even for a given polymer and general type of fabric construction, certain variations are possible. For example, the denier of the fibers may be changed and the total weight of material per unit area can

TABLE 2-4. Fabric Construction Groups

STRUCTURE	FILAMENT	BONDING
Woven	Monofilament	Heat Bonded None
	Multifilament	None
	Ribbon Filament	None
Knitted	Multifilament	None
Nonwoven	Staple Filament	Needle Punched Heat Bonded Resin Bonded Combination
	Continuous Filament	Needle Punched Heat Bonded Resin Bonded Combination
Combination and Woven Nonwoven	Combinations of above	Combinations of above
Special	Other Methods	Other Methods

be varied. Changing either of these factors can change both the pore and mechanical characteristics.

It is further important to bear in mind that the manufacturer may change his production processes from time to time. Therefore, the properties of a fabric with a given trade name purchased at one time may vary somewhat from previously published data.

2.3 FABRIC PROPERTIES

Some of the more prominent fabric properties which are significantly affected by polymer fiber or construction are listed in Table 2-5. The relative importance of the polymer fiber and the construction method are indicated with a number in this table. Zero indicates that there is insignificant or no effect on the variable and three indicates a strong effect. In some instances, there are very few data to support the rating given. When a rating cannot be determined for a factor, a question mark is indicated.

The influences of polymer fiber type and fabric construction on different fabric properties are discussed in the following paragraphs. An effort is made to highlight those factors which would be important in fabric selection, and also those factors which would be important in the selection and/or development of test methods and procedures. The discussions are relative to those polymers and construction methods which are most common in the United States at this time. Special situations are mentioned only where they appear to be important. Therefore, the discussions and relative ratings relate only to polypropylene, polyester and to a limited extent, nylon polymers. Both continuous filament and staple fibers are considered. Construction methods are essentially limited to woven fabrics and needled, heat bonded and resin bonded nonwoven fabrics. Knitted, combination and special fabrics are only mentioned where appropriate.

It is apparent from Table 2-5 that either the polymer fiber or the construction dominate the property in most instances. This is particularly true with respect to general, hydraulic and durability properties. It is only in the mechanical properties where both the polymer fiber and the construction appear to be significant. When dealing with the mechanical properties, it is also necessary to distinguish between those properties of the fabrics in isolation and the properties of the fabrics when imbedded in the soil. This is a factor which may be very important but about which, at this point, little is known.

Fabric weight or mass per unit area is not in itself an important fabric property. It does, however, strongly influence many fabric properties which are indeed important. For example, in many instances, the ultimate breaking strength of a given fabric is almost linearly proportional to the weight of the fabric. Also, the amount of material in the fabric will have a strong influence on the pore geometry and hence on the hydraulic characteristics. Therefore, unless otherwise stated, all comparisons are on a constant weight basis. That is, it is assumed that all fabrics, regardless of the polymer-construction combination, are the same weight.

TABLE 2-5. Relative Effects of Polymer Fiber and Fabric Construction on Fabric Properties*

PROPERTY	CONTROLLING FACTOR**	
	POLYMER FIBER	CONSTRUCTION
GENERAL PROPERTIES		
Cost	2	3
Specific Gravity	3	0
Thickness	1	3
Absorption	1	3
Surface Properties	3	?
Uniformity	-	3
Isotropy	0	3
MECHANICAL PROPERTIES***		
Peak Strength	2	3
Elongation at Rupture	2	3
Stress-Strain Relationships	2	3
Creep	3	2
Fatigue	?	3
Tear Resistance	1	3
Puncture Resistance	1	3
Burst Strength	2	3
Cutting Resistance	3	?
Abrasion Resistance	2	3
Friction	1	2
HYDRAULIC PROPERTIES		
Transverse Permeability	0	3
In-Plane Permeability	0	3
Filtering Ability	0	3
Clogging and Blinding Resistance	?	3
Capillary Siphoning	0	3
Threshold Pressure	?	3
DURABILITY PROPERTIES		
Thermal Stability	3	1
Biological Stability	3	1
Chemical Stability	3	1
Ultraviolet Light Stability	3	1

* Comparisons for fabrics of the same weight per unit area

** Rating Scale: 3 - Great Effect
2 - Significant Effect
1 - Slight Effect
0 - Insignificant Effect
? - Effect Unknown

*** May be greatly different for fabric in soil than for fabric in isolation

It is also interesting to note in the following discussions that there are few clear advantages or disadvantages to a specific fabric type. A characteristic of a polymer or a fabric construction method which is an advantage in one instance may be a disadvantage in another application. This further supports the argument that there is no ultimate fabric which is best for all applications. Rather, the fabric type which offers the best compromise of properties should be selected for each specific application.

2.3.1 General Properties

2.3.1.1 Cost

In general, nylon is the most expensive polymer, followed by polyester and polypropylene in that order. Staple fibers should add a slight cost to the manufacture over continuous fibers because they involve an additional step in the preparation of the fibers and another in the laying of the mat. As for construction, weaving is usually more expensive than the nonwoven forming processes. With respect to the nonwoven methods, needle punching is the least expensive process and resin bonding the most expensive, with heat bonding intermediate.

With the exception of the polypropylene slit film woven fabrics, woven fabrics are considerably more expensive than corresponding nonwoven fabrics. The slit film polypropylene fabrics, however, are very competitive price-wise with the corresponding nonwovens. Within the nonwoven group, because of the materials and operations involved, it would be expected that the needle punched continuous filament polypropylene fabrics would be the least expensive, while the resin bonded staple filament polyester fabrics would be the most expensive. Fabrics incorporating two or more bonding methods tend to be more expensive, because of the additional steps.

While there are certain trends, similar fabrics tend to be competitively priced, and frequently competition, variations in the market supply and other factors often override the considerations outlined above and reverse the expected order of prices.

2.3.1.2 Specific Gravity

The specific gravity of a fabric is the specific gravity of the polymer. Fabric construction techniques do not alter this value. The specific gravities of the various fibers range between about 0.9 and 1.35. Nylon and polyester have specific gravities greater than 1 and polypropylene and polyethylene have specific gravities less than 1. This is usually not a major consideration except where fabrics are to be placed under water. For this operation, depending upon the construction procedure, a fabric which floats or a fabric which does not float may be more desirable than the other. Also, if a fabric of high bulk is desired, low specific gravity polymer would tend to be more economical.

2.3.1.3 Absorption

Absorption of water within the fibers themselves is controlled by the polymer and not by the construction method. All of the common polymers have very low water absorption. With the exception of polyethylene there is, however, a finite absorption and fabrics should normally be tested after conditioning in the presence of water. Of the common polymers, nylon has the greatest absorption and its mechanical properties are significantly reduced in the presence of water [1]. It is probable, however, that this reduction occurs upon initial wetting and is not progressive. Discrepancies, however, have been found between actual test results and expected test results for the effect of moisture and salt water on the properties of various fabric types [8]. Further studies are required to more completely determine a fabric's response to moisture.

The water absorption within the fabric fibers is very small. Therefore, the total water absorbed by a fabric is dominated by its structure rather than its polymer. The woven and thin heat bonded fabrics absorb relatively modest amounts of water. However, the thick needled fabrics may absorb several times their weight in water. After installation, this is rarely a consideration; however, during construction it may be something to consider. Should the fabrics become waterlogged during handling, they become very heavy and difficult to manage.

2.3.1.4 Surface Characteristics

The surface characteristics of the fabric fibers, with respect to electrical charge and wetting angle may be significant with respect to certain fabric characteristics. This is a question which has been given very little attention concerning civil engineering fabrics. It is possible that the tendency for clogging by electrically charged, very fine soil particles may be related to the electrical charge of the fabric surface. Also, the wetting angle of the polymer would tend to influence the ease of wetting of the fabric and the pressure necessary to initiate flow. The relationships between fibers and the ability to control these properties should be investigated.

2.3.1.5 Uniformity

The woven fabrics tend to have more uniform structures than do the nonwoven fabrics. Within the nonwoven group, the bonded fabrics tend to be more uniform than the needle punched fabrics. However, there may be considerable variation within the groups. When considering fabric variations, it is necessary to consider not only the variations within a piece of fabric produced at a given time, but to consider the variations between fabrics produced at different times. In designing tests for fabrics, it is necessary to consider not only the magnitude of the variations of the property being measured, but also to consider the physical scale of inhomogeneities within the fabric. It is also necessary to consider how the property will be used in the fabric selection and design. If averages are desired, then it would be desirable to select relatively large fabric specimens so that the scale of the test specimen would be greater than the scale of the inhomogeneities or test a large number of specimens. However, on the other hand, if maximum or minimum values were desired, than it would be necessary to select smaller test specimens so that their scale would be equal to or less than the scale of inhomogeneities.

While it is true that there may be significant variations within and between fabric samples, it is also true that there are significant variations within the soils which will be used in connection with the fabrics. It is probable that the soil variability will be greater than the fabric variability in many applications.

2.3.1.6 Isotropy

This property is controlled exclusively by the construction. Almost all fabrics have some difference in their mechanical properties in the different directions. Most monofilament woven fabrics manufactured specifically to be used as filters are similar in the warp and fill directions, and therefore have similar mechanical properties in these two directions. However, the mechanical properties of woven fabrics in the diagonal directions are considerably different than in either the warp or fill drections [1]. Fabrics manufactured for reinforcement applications frequently have more and stronger fibers in the warp direction than in the fill direction. This is one of the most efficient methods of orienting the strength in the direction that it is required. The multifilament woven fabrics are often of this type. The slit film woven fabrics may be either isotropic or anisotropic.

At first, continuous filament nonwoven fabrics appear isotropic. However, on closer inspection most are slightly anisotropic. In some, the fibers are truly random, in others they are oriented in the machine and cross-machine direction. In this latter case, the properties may be essentially the same in the machine and cross-machine directions, but different in the diagonal directions. In other cases, it may be that more fibers are oriented in the machine direction than cross-machine, so that the fabric will be stronger in the machine direction. In some nonwoven fabrics, the greatest strength is in the cross-machine direction.

Isotropy may be important in selecting a fabric, depending upon the magnitude and orientation of the stresses which will be imposed on the fabric during service.

2.3.2 Mechanical Properties

Mechanical properties, unlike the properties previously discussed, are strongly influenced by both the polymer fiber type and the method of construction. Also, care must be taken in judging between fabric types on the basis of published test data. Nearly all of the data available to date have been determined from mechanical tests of the fabrics in isolation, that is, of the fabrics themselves. In application, the fabric and the soil will frequently behave as a reinforced soil, which will have properties different than either the soil by itself or the fabric by itself. Tests of fabrics in isolation probably greatly exaggerate the differences between fabrics. The relative differences in the behaviors of two reinforced soils with different fabric reinforcements would probably be much less than the relative differences between the mechanical behavior of the two fabrics themselves. There are still many questions relative to the hydraulic characteristics of the fabric and performance, but we are probably better able to relate these properties and performance than we are mechanical properties and performance. In almost all cases where theory is used to relate mechanical properties of the fabric to performance controlled by mechanical characteristics such as reinforcement or separation, the theory almost invariably fails to predict the benefits observed in practice. This is most likely due to the inability to properly evaluate mechanical property coefficients to use in the analysis. These thoughts are discussed further in Chapter 3.

2.3.2.1 Maximum Tensile Strengths

Both the polymer fiber and the construction characteristics of the fabric control maximum strength. For the same weight fabrics with the same orientation of fibers, the stronger fiber will, of course, result in a greater failure strength. However, if the fabric has a higher percentage of its fibers aligned in the direction of the tensile stress at failure, it may be possible that a weaker polymer could produce a greater strength. This preferred orientation could either be built into the fabric by initially orienting more of the fibers in the warp or in the machine direction. Also in the very high elongation needle punched fabrics, the fibers are free to re-orient themselves in the direction of the applied tensile stress during the application of the load. This is particularly true of continuous filament fabrics. This is the case at least for the fabrics in isolation.

The fiber forming process is also important because in addition to the polymer type, the amount of crystalline orientation in the fibers is important to the ultimate strength. The higher the crystalline orientation, the higher the strength. Some heat bonded fabrics require some low orientation fibers so they will have a lower melting temperature for bonding. This means that only part of the fibers can be truly high tenacity fibers. Resin bonding and needle punched fabrics would appear to have some advantage over this type of fabric. Also, woven fabrics can be constructed solely of high tenacity fibers. For needle punched fabrics, where bonding is by entanglement, it would appear that a continuous filament would give a greater strength than a staple filament, because it would allow greater interaction of the fibers and would require that they fail by breaking, rather than by separation of one fiber from another.

The above comments refer to strengths of the fabrics in isolation. It is probable that when the fabrics are confined within the soil mass, the soil particles and friction between the fibers resulting from the normal stresses applied to the fabrics will so restrict the individual fiber movements so that the needled fabrics will behave more like the bonded fabrics. This question needs additional research. Very preliminary results of research in progress suggest that at least to a degree this is true [20].

It would appear that if high strength is desired in one direction, an anisotropic woven fabric would be most efficient. The least effective would be an isotropic bonded fabric. Bonding would be low because the high degree of bonding would prevent re-orientation of the fibers and would cause the fibers to fail individually without the ability to re-orient and act together to resist the applied stresses.

2.3.2.2 Elongation at Rupture

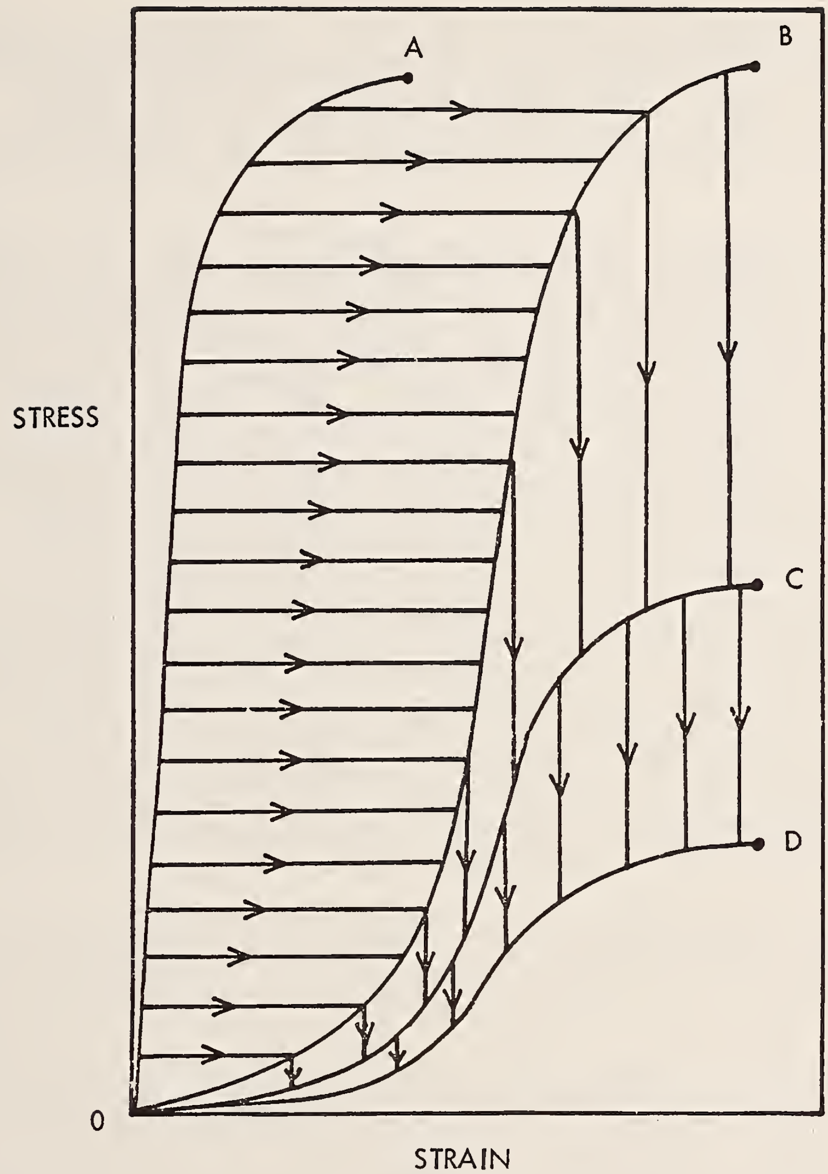
For this property, both polymer fiber and construction are important, but construction is more important than the fiber. In this case, a big factor is the ability of the fibers to re-orient during the application of the stress. If they are free to move, then much of the strain is the result of the fiber movement rather than the actual stretching of the fiber itself. The various components of a stress-strain diagram for a nonwoven needled fabric are shown in Figure 2-2. If the fibers are fixed as in a woven or strongly bonded fabric, then the fibers cannot re-orient and the elongation of the fabric is controlled by the elongation of the fibers themselves. This is the situation for woven fabrics in the warp and fill directions where the fabric elongation is dominated by the elongation characteristics of the polymer.

Again, these comments are relative to fabrics in isolation. It is probable that for woven fabrics contained in a soil, their elongations at failure would be very similar to that in isolation. However, the confinement of the soil would serve to greatly reduce the elongation at rupture for the extensible fibers, such as the needle punched mats [20].

2.3.2.3 Stress-Strain Relationship

As with most mechanical properties, tensile stress-strain relationships of the fabrics are functions of both the fiber and the construction type. Again, however, the details of the fabric construction tend to dominate. The stronger polymers with high moduli tend to give higher maximum strengths and steeper initial moduli. However, at least for fabrics tested in isolation, these factors can be dominated by the construction of the fabric. The woven fabrics have relatively low elongation at failure. The needle punched fabrics have very low initial moduli, and the curves increase gradually, reaching a peak at high strains. Bonded nonwoven fabrics are intermediate. The resin bonded fabrics tend to have moduli greater than those of the heat bonded. Some composite fabrics with a fiber needle punched onto a woven scrim have stress-strain curves with a high initial modulus and a peak at low strains controlled by the properties of the woven scrim. For these fabrics, the stress level then drops as strain continues and is controlled by the properties of the nonwoven mat. This second part of the curve usually builds to a peak at a relatively high strain. For some of these fabrics the first peak, controlled by the scrim, is higher and in others the second peak, controlled by the mat, is greater. Woven fabrics have different relationships on the bias than in the warp and fill directions.

Stress-strain curves are also greatly influenced by the conditions of the test. Factors which are significant are temperature, specimen geometry, specimen size and rate of loading. All of the polymers are temperature sensitive. Except at extreme high temperatures, the modulus is more variable than the ultimate strength. The modulus decreases as temperature increases and increases at low temperature [21]. Materials which are quite flexible at room temperature may be stiff and brittle at very low temperature [11]. Also, the strength decreases at high temperatures approaching the softening point. Most laboratory tests are performed at room temperature which is considerably



OA - Fiber curve
OB - Allows for slippage at cross-overs and straightening of fibers
OC - Allows for fiber obliquity
OC - Allows for slippage from fiber ends

FIGURE 2-2. Development of Stress-Strain Curves of Needled Fabric (10) higher than the ambient temperature for fabrics imbedded in the ground. Therefore, the modulus of the fabric in-situ may be appreciably different from that indicated by the test. Fabrics used in installations in northern regions will also usually be loaded under conditions of rather low temperatures and may behave significantly differently than indicated by the standard laboratory conditions.

In many applications where tensile strength is important, such as reinforcing uses, the loading condition of the fabric in-service is essentially plane strain. The standard strip and grab tensile testing methods do not create a plane strain test condition for many fabrics. As the fabric is pulled in one direction, there is a contraction or necking in the other direction. This phenomenon is very pronounced in the needled nonwoven fabrics. It is of somewhat less concern in the bonded fabrics and may be insignificant in the woven fabrics, as the perpendicular fibers tend to hold the stressed fibers apart [8]. As discussed earlier, with the associated realignment of the fibers, this will possibly increase the ultimate strength of the fabrics. It will also have a much more profound effect on the strain characteristics of the fabric. Several investigations of plane strain tests have shown that the elongation to failure is very significantly reduced in the nonwoven fabrics and somewhat reduced in the woven fabrics [12]. In the woven fabrics, the necking of the specimen is not so obvious, however, if the transverse fibers are not held in tension, decrimping of the longitudinal fibers as they are pulled will be easier and the modulus of the material will be somewhat lower. It would appear, especially if information concerning strain is desired, that every effort should be made to use test procedures approaching plane strain conditions, particularly for the nonwoven fabrics.

The size of the sample can also be important in indicating the stress-strain characteristics of the material. First, the size of the test specimen will influence the variability in the specimen. Large samples will tend to average out variations in the fabric and will tend to show a smaller variability between test results. However, as the sample dimensions decrease and approach the size of the defects or variations within the fabric itself, the variations between individual test results will become much larger. The population mean should be the same, but the standard deviation will be considerably higher. The sample size should be selected to provide data desired. If averages are desired, larger samples would provide them with fewer tests. If maximum and minimum are required, the samples must be selected to be of a scale similar to the variation.

The stress-strain curves for woven fabrics are relatively independent of the width of the sample. There is very little interaction between the various fibers. However, with nonwoven fabrics, there is a great deal of interaction between the fibers. For these fabrics, sample width becomes important and is related to the lengths of the fibers. This is particularly true for needle punched fabrics, where the interaction is through entanglements rather than direct bonding. For very long staple fibers or especially for continuous filament needle punched fabrics, the interaction may be very long-ranged. If a very narrow specimen is used, the advantage of the long filament is lost and the specimen would behave essentially as if a staple fiber had been used.

With bonded fabrics, the specimen width is not as important, because the strong bonds prevent interactions between the surrounding fibers. The bonds tend to prevent rearrangement of the fibers and the strength gained by entanglement with surrounding fibers effectively requiring the filaments to fail one by one. The bonds do tend to prevent movement and develop stresses in the fibers at smaller strains so that the bonded fibers will have a higher initial modulus but possibly a lower peak strength. The magnitude of this effect depends upon the number of possible bonds which are actually produced in the fabric. In some heat bonded fabrics, approximately a quarter of the possible bonds are formed, in others nearly 100% of the bonds are achieved. With the same original orientation of the fibers and with the same polymers, these two bonded materials would exhibit different stress-strain curves. The high number of bonds would give a higher modulus and lower peak strength in conventional strip tensile tests. Much of the apparent strength advantage of the fabric with the smaller number of bonds would probably be lost in plane strain tests. The plane strain test would not allow the same degree of orientation of the fibers. The resin bonded fabrics tend to have the highest moduli of the nonwovens due to the very high degree of bonding of the fibers.

How failure is defined also influences the strength of the fabric. If failure in simple tension tests for nonwovens is defined as rupture of the fabric, a needle punched fabric would tend to show the highest strength. However, if failure is defined as some strain significantly less than rupture, then a resin bonded material would show the best strength. If relatively high strength at small strains is required, then woven fabrics or very highly bonded nonwoven fabrics would appear best from conventional test methods. As explained before, plane strain testing would improve the initial modulus of the loose mat type fabrics. There is also preliminary evidence to suggest that nonwoven fabrics contained within the soil mass will have a much higher modulus than those tested in isolation [20]. This area needs additional study, and it may be necessary to reconsider some of the conclusions drawn on the basis of fabric tests in isolation. Holtz [26] also reports that the modulus of a woven fabric in sand is 2.5 times the value in isolation.

The rate at which the load is applied to a fabric is also very important. Civil engineering applications were not considered when the rates of loading were selected for the standard strength tests on fabrics. There are only limited data concerning the rate of loading on these tests, and this should be investigated further. The general trends are much the same for all fabrics; that is, that within rather wide limits, the ultimate strength is not greatly affected, but the modulus is very sensitive to rate of loading as modulus increases with loading rate [22]. The relative change seems to be greatest for those fabrics with random orientation and loose bondings such as the needle punched fabrics and less for the bonded nonwovens and still less for the woven fabrics where the response of the fabric is essentially directly related to the response of the polymer.

Three general loading conditions should be considered with respect to rate. One is the loading during the construction period. This may be relatively rapid, and the standard tests may be appropriate for this loading condition. However, in many instances, the main forces on the fabric are relatively constant with time and long-term creep considerations are important. This will be discussed in the next section. In many applications, the dead loads are relatively modest, and the major stresses in the fabric are induced by live loads. For example, this would be the case in a relatively thin embankment supporting a construction road over soft subgrades. In these cases, the repetitive and rapidly applied live load might be the controlling factor. One of the reasons for difficulty in relating theory to experience in these cases may be that the analyses are based on a modulus of elasticity determined at standard rates of loading, where a dynamic or resilient modulus should possibly be used.

2.3.2.4 Creep

Creep is the continual strain of a fabric or fiber under a constant stress. Creep rate is strongly temperature dependent and is greater at high temperatures than at low temperatures [22]. Therefore, creep should be measured for appropriate temperature values. Creep rate is also strongly stress dependent and should be determined for a given material at the stress level appropriate for the particular application. Considering the same weights of fabrics and the same construction, the polyesters have superior creep characteristics, that is, lower creep than polypropylene. The influence on creep of the type of fabric construction is not clear. Indications are that woven fabrics and bonded nonwovens have less creep, all other things being equal, than the needle punched fabrics. If this is true, it must result from the fact that as creep occurs, the fabric fibers are also free to change their orientation and induce an additional strain. Again, these observations are on fabrics in isolation.

Closely related to creep is stress relaxation. Creep occurs when a constant stress is applied. Stress relaxation will occur when the fabric is strained to a fixed value. The creep prone fabrics will tend to relax the stress induced in the fabric. Very little is known about the effect of repeated applications of fixed strain and stress relaxation. There is some information relative to a cyclic creep where a constant stress is repetitively applied to the fabric [13]. In this case, there is a certain elastic and inelastic strain occurring with each application of stress. Until failure is approached, the elastic strain component for each stress application is approximately constant. The plastic or inelastic irreversible component tends to decrease slightly with each application. The net effect, however, is to accumulate a large permanent deformation of the fabric [13]. Failure in this mode of loading usually occurs at much higher total strains than for the single standard load application test. This may be the mode of failure that occurs in some heavy separation installations and is a question which needs to be investigated further.

2.3.2.4 Fatigue

Fatigue refers to failure due to the application of a repetitive load less than the normal failure load. Very limited information is published on this phenomenon. The only information available is for nonwoven fabrics [13]. If fatigue limit is defined as the maximum load that the fabric would support for an infinite number of applications, the fatigue limit ranges from about 40 to 60% of the single load strength [13]. It appears that the needled fabrics have a larger relative fatigue limit than do the bonded nonwovens. This is probably because the bonded fabrics do not allow the fibers to realign and work collectively to resist the applied stresses. Rather, between bonding points, an individual fiber must carry the stress by itself, and the fibers can essentially be failed one by one. It should be pointed out, however, that these results are for simple strip tensile tests. Plane strain tests and expecially plane strain tests with confinement of the sample within a soil may not substantiate this trend.

2.3.2.6 Tear Resistance

Tear resistance refers to the resistance against the propagation or enlargement of a hole or rip in the fabric after the initial tearing or breaking of the fibers. Tear resistance of a fabric is related to the anisotropy or orientation in the fabric and bonding. Fabrics with distinct fiber orientations such as the woven fabrics and certain staple nonwovens tend to have different tear resistance parallel and perpendicular to the direction of the fiber orientation. For the nonwoven fabrics, the bonded fabrics have lower tear resistance than the needle punched fabrics. This is because as the stresses are applied to propagate the tear, the fibers in the loose fabric mats will orient themselves across the tear and act as a group to resist further tearing. This is enhanced by long continuous fibers rather than shorter staple fibers. In the bonded fabrics, this re-orientation of the fibers is not possible, and the tearing force can cause the fibers to break between the bond points one by one. The greater the percentage of contact points that are bonded, the lower will be the tear resistance of the fabric.

2.3.2.7 Puncture Resistance

Puncture resistance implies penetration of the fabric by a relatively pointed object which forms a hole in the fabric by spreading of the fibers and tearing action. For very small objects, puncture resistance may be provided simply by the resistance of the fibers to lateral displacement by bonding. At this scale, the fabrics which are strongly bonded would offer the higher penetration resistance, as would those with the denser packing of fibers. However, as the size of the penetrating object becomes larger, resistance to tearing is a combined effect of bonding and polymer. In a manner analogous to tear resistance for the nonwovens, needle punched fabrics would tend to have the greater resistance to penetration. Again, the fibers would orient to form a concentrated ring of fibers around the penetrating object, and the resistance to penetration would increase as the diameter of the penetration became greater. In the bonded fabrics, the fibers would not be permitted to re-orient themselves around the penetrating object, but would be forced to resist the penetration one fiber at a time acting between the bond points. Therefore, it is probable that the greater the degree of bonding, the lower the puncture resistance, other things being equal. Since the ultimate puncture resistance in any case is partially controlled by the breaking strength of the fibers, the high strength fibers would have a greater penetration resistance for the same structure than would the lower strength fibers. As strength is a factor, all of the conditions such as temperature, rate of loading, etc. which would control fiber strength would also influence the penetration resistance.

2.3.2.8 Burst Strength

Burst is the condition where the fabric fails due to a uniformly applied pressure acting over a significant area of the fabric surface. If the pressure is applied over a circular area, the fabric tends to deform into a segment of a hemisphere. Neglecting the small effect of bending, the fabric is essentially in pure tension acting more or less uniformly in all directions. An anisotropic fabric or an inhomogeneous fabric would be somewhat distorted, failure occurring by the fabric fibers failing essentially in simple tension with the main stress acting radially from the center of the load. This is quite different from the puncture situation, where the fabric is penetrated by a concentrated force, and the fibers fail in tension with the main stress acting tangential to the penetrating object.

Since burst is essentially a specialized tension failure, all of the polymer types which would have higher tensile strengths would offer higher bursting resistance. Bursting resistance would also be affected by all of the factors such as rate of loading, temperature, etc. which influence strength. As far as fabric construction is concerned, the most important characteristic would be isotropy. Since the stresses are applied in all directions, the failure will be initiated in the direction of least resistance. Therefore, other factors being equal, an isotropic homogeneous material should offer the greatest resistance to bursting. The needle punched materials with their low degree of bonding would at least in isolation, offer a greater burst resistance than the bonded fibers. This would result from the fact that during the straining of the fabric, a higher percentage of the fibers would be free to orient themselves radially in the specimen so that the maximum number of fibers would be available in every direction to resist the induced tensile forces.

2.3.2.9 Cutting Resistance

As used here, cutting resistance refers to the resistance of the fabric to fiber cutting when the fabric is placed on a hard surface and struck or pressed very hard by some other hard object. It is a distinctly different process from either burst or puncture. This is of concern in some construction processes, as the fabric may be laid over a rock or aggregate material and have more aggregate dropped on top of it. If the fabric is caught between two rock particles, at the point of the impact, the fibers may be cut and a significant hole formed in the fabric. Few data have been found on this subject, but there is some evidence to suggest that polypropylenes are more resistant to this type of cutting than polyesters [16]. With respect to fabric type, cutting resistance is enhanced by large diameter filaments or fabric bulkiness, which provides a cushioning effect.

2.3.2.10 Abrasion Resistance

Abrasion refers to the weakening of a fabric, either by the removal of fibers or the wearing through of fibers by some abrading action. Of the common polymers, nylon appears to have the highest individual abrasion resistance [1]. Abrasion resistance is enhanced by the bonding of the filaments to make them more difficult to remove from the fabric. Resin bonding appears to have the best abrasion resistance in this respect. The abrasion resistance of individual fibers is higher for coarse fibers than for fine fibers. Bulky fabrics are also more effective in protecting the filaments. Special needle punched stable fabrics with the fibers oriented normal to the plane of the fabric are particularly resistant to abrasion. As in a brush, this presents the end of the fibers to abrasion rather than the sides of the fibers. This construction has been used in connection with a woven scrim where one of the main functions of the needled mat was to provide high abrasion, protection for the scrim which then provided the strength to the fabric system. For extra abrasion resistance, the fiber mat can also be resin bonded.

2.3.2.11 Friction

During construction, the ends of the fabrics are frequently anchored simply by over lapping or by embedment in the soil. The fabrics are held in place by friction, either between the two pieces of fabric or between the fabric and the soil. Stability of the system depends upon the friction developed. Fabric to fabric friction seems to depend more upon the finish of the fabric than upon the polymer used. The smoother, slicker bonded fabrics seem to have less friction than do the rougher mats or woven fabrics.

Soil to fabric friction or adhesion is controlled primarily by the fabric construction, the soil type and the normal stress. Thin fabrics with relatively large holes, such as some of the woven fabrics and the special fabrics, develop very high friction. The soil grains are free to penetrate into the openings in the fabric and there is actual physical interlocking between the grains on the opposite side of the fabric. In these instances, the friction will be at least as great as the soil friction itself. The very lightweight heat bonded nonwoven fabrics tend to behave in much the same way. The heavier multifilament woven fabrics and the heavier heat bonded and resin bonded nonwovens will behave somewhat differently. In these fabrics, the soil grains are not permitted to penetrate the fabric and contact the grains on the other side of the fabric. Also, some of these fabrics tend to be fairly stiff, so that for fine-grained soils and relatively modest normal forces, the friction is strictly due to grain sliding on the relatively smooth fabric surface. In these situations, the soil-fabric friction may be significantly less than the soil friction itself. With the thick fabrics, the amount of distortion of the fabric-soil surface, the penetration of the soil grains into the fabric itself, and any possible interlocking of grains across the fabric depend upon the relative weight of the fabric, the size and shape of the soil grains, and the normal force. For these cases, the soil-fabric friction can vary from a value almost equal to that of the soil to a value significantly below that of the soil [23]. Tests available suggest that the friction angle between the soil and the fabric is almost always greater than 2/3 the friction angle of the soil itself.

Very little information concerning the adhesion between cohesive soils and the various fabrics are available. One would suspect for cohesive soils that the construction operation would result in remolding the soil immediately adjacent to the fabric and that the bond between the fabric and the soil would be equal to either the remolded or undisturbed strength of the natural soil, whichever was smaller. Soft organic or sensitive soils would probably reconsolidate immedately under the fabric after remolding to densities greater than their original in-situ strength. Therefore, the disturbed layer of soil would be stronger than the natural soil immediately under the fabric after remolding to densities greater than their original in-situ strength. Therefore, the disturbed layer of soil would be stronger than the natural soil immediately under it, and the shearing resistance would be controlled by the natural strength of the in-situ soil. Very dense, stiff, overconsolidated clay soils upon remolding and reconsolidating would probably take up water and have a lower strength than their initial in-situ strength. In this case, the adhesion should be estimated on the basis of the remolded strength of the soil, which would develop immediately under the fabric.

In some instances for slopes, especially those under water, it is expected that the construction process will leave a thin layer of very soft disturbed sediment. Special fabrics with a very thick, stiff, open, brushy mat needled to the surface of the fabric are sometimes used. It is believed that when this material is against the soft soil and weighted with the overlying erosion protection material, the stiff bristly web of the fabric will penetrate in the soft, disturbed soil and assist in developing a higher adhesion between the fabric and the soil.

2.3.3 Hydraulic Properties

2.3.3.1 Permeability

The fabrics considered in this report have moderately high permeabilities. Typically, they are 10^{-3} to 10^{-2} cm/sec. This is comparable to a clean, medium to fine sand. The special fabrics described earlier and the coarse monofilament woven fabrics have permeabilities greater than fine gravels. The other woven fabrics have lower permeabilities, depending on the tightness of the weave. However, rarely is their permeability too low for their usual intended function as a reinforcement or separation. For the nonwoven fabrics, the needled fabrics tend to have higher permeabilities with the resin bonded fabrics having the lowest and the heat bonded fabrics intermediate. For the bonded fabrics, the permeability may vary with the process and the weight of the fabric. Permeabilities tend to decrease for heavier fabrics. The needle punched fabrics are compressible and their thickness and porosity decrease with pressure. As a result, their permeability also decrease with compression. In all cases, however, the permeabilities for most nonwoven fabrics are so high as to rarely be a consideration. More research is required to more precisely determine what permeability values are required for a fabric material used in a specific function.

It is somewhat misleading to talk about fabrics in terms of their permeability. This results from the fact that the different fabrics will also have signficantly different thicknesses. It is usually more meaningful to consider the quantity of water which would pass through the fabric under a given head or to consider the head loss across the fabric which would be necessary to cause a given flow. In real problems, it is usually desirable to pass some given amount of water under certain conditions or to prevent the pore pressure in the soil from building up above some maximum value. To compare fabrics in these respects, it is necessary to consider both permeability and thickness. The quantity of flow through a fabric under a given gradient and for a given cross-sectional area would be proportional to the ratio of permeability to the thickness. Using this ratio may give an entirely different conclusion with respect to the water-passing ability of fabrics than looking at the permeability alone. For example, some heat bonded nonwovens have permeabilities significantly lower than needle punched nonwovens of a corresponding weight. However, the heat bonded fabric has a much smaller thickness, so that even though its permeability is lower, its ratio of permeability to thickness and hence its water-passing capabilities may be higher than the corresponding needle punched fabric.

The above comments have been relative to the permeability of the fabric to water moving transverse to the plane of the fabric. Some fabrics also have significant permeabilities within the plane of the fabric. Some special fabrics and the needle punched fabrics fall into this category. The thin woven fabrics and the thin bonded fabrics have very low, if any, permeability within the plane of the fabric. For those fabrics which do have significant in-plane permeability, the magnitude of this permeability is usually of the same order as that in the transverse direction. For those fabrics which are compressible, the permeability in the in-plane direction is also a function of the normal pressure and decreases with compression of the fabric. For these situations, compression has a double effect in that it reduces both the permeability and the cross-sectional area available for flow. In the transverse direction, it is probably more instructive to talk about a factor of combining permeability and thickness of the fabric than permeability alone. In this case, the quantity of water which would pass through the fabric would be proportional to the product of the permeability and the thickness, so that for the same permeability, the thicker fabric would have the greater water-carrying capability.

Although the basic permeability of a needled fabric is probably not a function of the polymer, the water carrying capability may be slightly different for different polymers, considering the same weight of fabric. This results from the different specific gravities of the polymers. The lighter weight polymers would be of more bulk per unit weight, and hence yield a fabric of a different water carrying capability. In this same vein, the denier of the fiber might be significant in that finer denier would give more fibers, and hence greater bulk and higher water carrying capability. This might be offset by the fact that larger denier would tend to give larger pores and hence higher permeability.

With respect to flow across the fabric, it is probable that permeability of the fabric will rarely be a controlling property in the selection of fabric types for a given application.

2.3.3.2 Clogging and Blinding Resistance

When a fabric is used to prevent piping, it must maintain an adequate permeability to perform its function. This requires that the fabric not blind or clog. This requires that the fabric either have large enough pores to allow the fine material removed from the soil by flowing water to pass through the fabric or the fabric must have pores too small to permit entry of soil particles.

As with permeability, the clogging and blinding resistance of a fabric are controlled almost exclusively by its construction. The polymer may have a slight effect in that for electrically charged clay size soil particles, there may be a greater affinity to some polymers than others. This question has not been investigated. Also for the same weight of fabric, the lower specific gravity polymers will give slightly greater bulk than the higher specific gravity polymers, and this may have some minor affect on the clogging and blinding resistance of the fabric. However, for the most part, this property is controlled by the structure of the fabric which is controlled by the fabric details and construction methods.

Clogging and blinding behavior are related to the permeability of the fabric, in that they are only important because they reduce the permeability of the fabric. Therefore, in setting the final criteria with respect to fabric clogging and blinding resistance or potentials, it is necessary to be able to determine the minimum permeability permissible for a given application. Clogging is a term usually applied to the trapping of particles within the fabric and hence reducing its permeability by clogging the pores. Blinding usually refers to the plugging of the entrances to the pores by soil particles at the fabric surface. Plugging is used to indicate either clogging and/or blinding without implying which.

It can be argued that monofilament woven fabrics are best with respect to filtering. They are relatively thin and therefore clogging is eliminated virtually by definition. Their pore structure is uniform and simple, and therefore it is easy to evaluate and relate to corresponding soil characteristics. Because these woven fabrics are relatively expensive, it has been desirable to use nonwoven fabrics as filters in many instances. The bonded thin nonwoven fabrics also have a relatively simple pore structure; however, they have a range of pore sizes where a monofilament woven fabric has essentially one size of pores. This distribution of sizes complicates the problem of defining and measuring some characteristic pore size or coefficient for the nonwoven fabrics compared to these woven fabrics.

There is considerable controversy concerning the nature of the fabric which is best suited to perform this function. It is argued that because of the simple structure of the woven fabrics and the heat bonded nonwoven fabrics, these materials perform the best because they do not trap the soil particles, but allow them to pass through the fabric so that the fabrics do not clog. It is suggested that the thick, nonwoven fabrics tend to trap particles within the mat and clog the fabric. The counter argument is that the thin woven and bonded nonwovens do tend to blind and that a particle trapped in a pore of these materials completely blocks that pore. On the other hand, because of the complex pore structure in the thick matted filter fabrics, the particle does not completely block a pore but merely requires the water to flow around through adjacent passages. This argument suggests that the thick fabrics can trap many more particles without significant loss of permeability than can the thin fabrics. It is further suggested that when the soil to be protected is not particularly well graded, the complex structure of the matted fabric interacts with the soil particles to form a more integrated soil-fabric filter network that is more effective in preventing piping. Some special layered fabrics are even constructed with a coarser mat on the side adjacent to the soil and a finer mat on the side towards the drain. This is designed to allow more soil and coarser soil particles to enter the first layer of the fabric, where they are trapped to form an integrated structure with the fabric fibers themselves. This is felt, by some, to be particularly important under rip-rap and other such installations, where the direction of the flow may be reversed. Where there is flow reversal, it is possible that the normal soil bridge development does not occur and that there will be progressive erosion of the fine soil particles through the fabric, and equilibrium will not be established. The coarse fabric layer adjacent to the soil is intended to counter this problem.

It is also suggested that when the woven fabrics with uniform openings are used to filter a uniform material of appropriate and uniform grain size, the grains may fit into the fabric openings and effectively blind the fabric. One instance is reported where a slope protection installation with a woven fabric filter failed, presumably from the cause described above [24]. It is further argued that for the nonwoven fabrics, the range of pore sizes available in the fabric would prevent this from occurring, since the uniform soil grains could not all fit neatly into the pore openings of the fabric. This argument appears to be logical, but it has not been proven by controlled experiments.

There is very little documentation of experiments or tests specifically designed to prove these various arguments. A wide range of fabrics has apparently been used successfully as filters; however, it is not always clear as to why the fabrics work in a given installation.

The problem of determining the effective fabric characteristics to prevent piping is very difficult for the fabrics with complex structures, especially for the multilayer fabrics. The problem of establishing appropriate test methods to measure these characteristics is also more difficult for these materials than for the simpler woven or heat bonded nonwovens. It is probable that if a fabric of appropriate pore size relative to the soil grain size is selected, either a woven or nonwoven fabric will satisfactorily provide sufficient resistance to blinding, and the final choice of fabric will be influenced by other considerations.

2.3.3.2 Filtering Ability

To filter implies the removal of solid particles suspended in a fluid. In practice, fabrics are only employed as filters in this sense in special cases. Examples are a silt fence or a situation where dirty water approaches a filter through a granular material. When dirty water is caused to flow through a filter fabric, one of two things happens. Either the pores of the filter are significantly larger than the particles in suspension and the solids move through the fabric without filtering, or the pores of the fabric are smaller and the movement of the particles is stopped by the fabric. The particles may be trapped partly within the fabric and/or as a deposit building up on the face of the fabric. In either case, the filter will eventually plug. By definition, if a fabric actually filters the water, it will in sufficient time plug, and the fabric must either be replaced or cleaned. This is the same phenomenon as in the use of an air filter or any other filter application. The life of a filter is limited.

When a fabric is used in contact with a soil as a replacement for a graded granular filter, its purpose is not filtration as usually defined. The use of the term filter in this case may be misleading. The function of the so-called filter is to retain the soil in place. It is not to remove the soil particles from a suspension. The filter must, of course, also allow the water to pass without producing an excessive water pressure. The purpose in this case is not to filter, but to prevent piping of the soil particles through the fabric into the drain.

The problem is very simple for a uniform soil. All that is required is that the openings in the filter be slightly less than the particle size of the soil. In this case, it will be impossible for the soil particles to move, and the permeability of the filter will be sufficiently high. Virtually any type of fabric with appropriate pore size would perform this function. Monofilament woven fabrics, having a uniform and simple pore structure, are attractive because of the ease of evaluating the fabric pore size and matching it to the grain size of the soil. These fabrics, however, are relatively expensive, and so it is frequently desirable to use lightweight nonwoven fabrics. The bonded nonwovens have a simple pore structure, but they have a range of pore sizes. This makes it somewhat more difficult to evaluate the effective characteristic pore size for the fabric and somewhat obscures the relationship between the fabric pores and the soil grain sizes. The problem is made more complex when thick nonwoven fabrics are introduced because of their complex pore characteristics. However, appropriately chosen, virtually any of the fabric types should serve as an adequate filter for uniform soils.

When the soil to be protected is graded and has a wide range of particle sizes, the problem is somewhat more complex. In this situation, it is usually not feasible to select a fabric with pores smaller than the smallest sized soil particles. This would possibly result in a fabric with such low permeability that the head required to cause flow across the fabric would be excessive. With the pores in the fabric slightly larger than the finer soil grains, the water will erode some of the finer soil particles and cause them to move into or through the fabric. This will leave a layer adjacent to the fabric of soil particles slightly larger than the fabric pores. This layer of coarser soil grains will have the same effect on the next layer of soil as the fabric had on it. It will allow a few fine particles, in this case slightly finer than those which originally passed through the fabric, to move through the first layer of coarse soil particles and then through the fabric. This will leave a second layer of soil grains slightly smaller than the first layer. The second layer will have a similar effect on the next layer of soil particles, etc. until a filter system consisting of the fabric and a graded layer of soil will be developed. If the soil to be protected is reasonably well graded, the process will stabilize itself in a short time. This so-called soil bridge network will have a finite thickness, and movement of soil grains into or through the fabric will essentially stop. The prevention of further piping by the soil is the combined effect of the fabric and the soil itself.

The relative suitability of the filter fabrics with respect to reasonably well graded soil are essentially the same as for the uniform soil. The main difference is that the relationship between the characteristic fabric pore dimension and the effective characteristic soil grain size or coefficient is complicated by the effect of gradation.

If the soil to be protected is gap graded, the finer soil particles will always be capable of moving through the pores between the coarser grains and contact fabric itself. In this type of situation, if the fabric is to prevent piping, it must indeed act as a filter, in which case it will have a finite life before it clogs.

2.3.3.3 Capillary Siphoning Ability

Some fabrics, such as the thick needle punched types, have the capability of moving considerable quantities of water by capillary siphoning. It is suggested that this is beneficial in certain applications; for example, to remove water from the surface of a subgrade which would otherwise accumulate in ruts and depressions in the subgrade under the base course materials. The effectiveness of this remains to be proven; however, it may be of significant benefit in certain cases.

For the fabric to have significant capillary siphoning ability, it needs both a reasonably high permeability within the plane of the fabric and also a significant capillary potential. As discussed previously, only the thick needle punched and some special fabrics would have adequate permeability within the plane of the fabric to be effective. High capillary potential would be enhanced by a relatively fine pore size and a small wetting angle for the polymer.

2.3.3.4 Bubbling Pressure

All of the fabrics have significant permeability once saturated. However, it is observed that when dry it takes an initial gradient across the fabric to initiate flow. The pressure required to initiate flow would be a function of the pore size and the wettability of the fibers. Pore size can be controlled by the construction process and wettability by the polymer and additives incorporated. The bonded nonwoven fabrics usually have the smallest pore sizes and consequently the greatest initial pressure requirement. It has been suggested that this could be a problem in situations where it is required that the fabrics allow water to flow or drain out of soils under very low gradients.

2.3.4 Durability Properties

2.3.4.1 Thermal Stability

At normal temperatures, all of the common fabrics are relatively stable and this will not in general be a major consideration. There are changes in certain of the mechanical properties which may in some instances be significant, however, as discussed under Mechanical Properties (2.3.2). As far as the basic durability of the fabrics is concerned, they are only likely to be affected under extreme conditions.

At high temperatures, fabrics will melt. At temperatures approaching

20°C below the melting temperatures, there could be effects on the molecular structure of the polymer which will in most cases reduce the ultimate strength and modulus of the material. The melting temperatures for polypropylene and polyethylene are about 175°C and 135°C, respectively. Polyester and nylon are higher with values of about 250°C. These values are high enough so that temperature effects will rarely be a problem and need be considered only for special applications.

2.3.4.2 Biological Stability

There is very little reason to believe that the common polymers in geotextiles will be attacked by biological activity when buried in the ground. There is very little information on this relative to fabrics; however, bacteria are highly specialized in the materials they feed on and the polymers used in fabrics have not been in the environment long enough to expect that there would be significant colonies of bacteria depending on the presence of these polymers for their existence. There is some speculation that if any of the polymers were to be degraded by biological activity, it would be nylon [6]. However, even here, there is limited evidence, and the probability of this being a major problem is low. It is possible that, depending on the resin used, resin bonded fabrics can have poorer resistance to biological agents.

2.3.4.3 Chemical Stability

All of the polymers in common use are highly resistant to chemical activity [4]. This is probably also true of most of the binders which would be used in resin bonding. It is unlikely that these materials will be degraded by the normal chemical environment found in soils. Chemical stability probably needs only be considered for unusual circumstances. Some applications may subject the fabric to exceedingly high or low pH conditions or to prolonged exposure to various solvents such as diesel fuel. All of the materials are generally resistant to these conditions, but for extreme conditions there are significant differences between the various polymers and polypropylene is weakened somewhat by diesel fuel. This area needs additional study. It is not always possible to extrapolate the data from plastic films which have been used extensively in the past to the fabrics. This is because the structure of the polymers will be different in fibers than in film because of the manufacturing processes.

2.3.4.4 Ultraviolet Light Stability

All of the common unstabilized polymers are adversely affected by ultraviolet (UV) light. In some, the oxidation under these conditions is very rapid, resulting in almost complete destruction of the fabric in a very few weeks when exposed to continual, direct sunlight. Of the common polymers, unstabilized polypropylene and polyethylene have the poorest UV stability, while nylon and polyester has greater resistance [3]. When buried in the ground, this is not a problem; however, in certain applications such as silt fences or other erosion control devices, the UV life of the fabric may be important. Also, with certain of the fabrics, it is necessary to assure that they are not unduly exposed during the construction period. This degradation is normally a disadvantage. However, in some temporary erosion control devices, it may be desirable to have the materials degrade and be removed from the environment.

Stability of the fabrics can be increased by the addition of carbon black or other pigmentation to the fibers or by chemical stabilizers. Carbon black can be incorporated during the extrusion process and is a relatively effective and inexpensive treatment.

For UV stability, fabric construction is significant. Those fabric construction processes resulting in larger denier filaments tend to yield fabrics more resistant to UV because the surface area per unit weight exposed to the sun is less. Other things being equal, the monofilament woven fabrics are most resistant and slit film fabrics the least resistant. Multifilament wovens and the nonwovens are intermediate depending on fiber denier.

2.4 FABRIC CLASSIFICATION

Fabrics can be classified in a variety of ways depending upon the general purpose of the classification. In the following sections, the fabrics are classified and discussed with respect to:

(1) Polymer type,
(2) Fabric construction method, and
(3) Fabric use.

2.4.1 Classification by Polymer Type

As shown in the previous discussions, the polymer is only important in influencing certain of the properties. The relative ratings of the importance of polymer and the construction types for a variety of properties have been indicated in Table 2-5. The properties which are significantly influenced by the polymer are taken from Table 2-5 and listed in Table 2-6. In this latter table, they are given a numerical rank. The ranking of 4 is given to the polymer which has the highest value for the given factor. The 3 indicates a slightly lower value and a 2 a considerably lower value. One indicates that the polymer has a very much lower value than the value for the highest polymer. Zero is used to indicate that the factor is either not applicable or insignificant. It should be recognized that these rankings represent the general or typical case. The variety of fabrics is so large that it is possible to find some exception to almost any ranking given. The rankings have been made on the basis of fabrics with the same weight per unit area.

Care must be exercised in interpreting Table 2-6. A high value is not always desirable. An obvious example is cost. Other cases where high values are undesirable are in absorption and creep. There are some cases where a high value may be desirable sometimes and a low value desirable other times, such as specific gravity and elongation at failure. Also, not all properties are important for all applications. For example, high strength and low creep are usually only necessary in reinforcing applications and are not particularly significant with respect to filter problems.

Since the comparisons in Table 2-6 are made on a weight basis rather than cost, the rankings of some items with respect to cost might be different.

TABLE 2-6. Relative Fabric Polymer Fiber Properties

Property	Relative Value*	
	Polypropylene	Polyester
Cost	2	4
Specific Gravity	2	4
U.V. Stability**	2	4
Thermal Stability	2	4
Chemical and Biological Stability	2+-4	3-4
Strength	2-4	4
Failure Elongation	4	2
Elastic Modulus	2	4
Creep Susceptibility	4	2
Impact Cutting Resistance	4	2

* Comparison for fibers currently (1979) common in geotechnical fabrics. The scale is 4 Highest - 3 Slightly Lower - 2 Considerably Lower. It is important to note that a high rating is not necessarily desirable. Also, in many instances the fabric properties will be controlled more by the fabric construction than by the polymer fiber.

** Unstabilized.

In considering polymer strength, the weaker polymer is less expensive; therefore, it would be possible to use more of it for the same cost and the relative strength per dollar might be very nearly equal or possibly even reversed.

Considering the two most common polymers, polypropylene and polyester, the most expensive polyester has the better combination of mechanical properties. Polypropylene has some advantage with respect to cutting resistance and possibly has a slightly greater chemical and biological stability. However, in other properties, the polyester tends to be superior. Polyester has a significant disadvantage in its relatively higher cost. The problem for any specific application is to determine whether or not the superior properties justify the higher cost. It will be noted that many important properties of fabrics are not listed in this table. This results from the fact that they are controlled by the fabric construction rather than the fabric polymer. If these factors tend to control the overall performance installation, it may be that the less expensive polymer would serve well and would be the economical choice. If, on the other hand, the factors listed in this table control the performance of the installation, the more expensive polymer may be justified.

2.4.2 Classification by Fabric Construction

The fabric properties which are controlled to a significant measure by the fabric construction are summarized in Table 2-7. Here the properties are compared with the major fabric types and are rated by the same scale discussed previously. This table includes a number of entries having ranges of values because there is a considerable variation possible within a given fabric construction. For example, the bonded fabrics are manufactured by a variety of techniques which result in different strengths of bonds and greater percentage of possible bonds than are actually formed. The cautions in interpreting this table are essentially the same as discussed previously. In addition, with fabric construction, the range of properties which are affected is so broad that it is not possible to rate any construction type as superior to any other. To use this table, it is necessary to isolate those factors which are important for any given application and consider them to determine which type of fabric might be most suitable. The final evaluation would require combining the ratings from Tables 2-6 and 2-7.

A very simple example would be for an application where the fabric itself was to perform as a drain, where the water would be intended to flow through the fabric. In this case, the needle punched and some special fabrics are the only types with great enough in-plane permeability to suffice. Also, the fabric would be buried and would not be subjected to high temperatures so UV and thermal stabilities would not be problems. In most applications, strength would not be particularly critical. Therefore, it would appear that the particular benefits of the more expensive polymers would not be justified. In this case, as a general rule, it would seem that a needle punched polypropylene would be the most economical fabric.

For another example, consider a heavy duty reinforcing application. In this case, great strength, high modulus, and low creep susceptibility would probably be the more critical properties. Looking at the fabric construction

TABLE 2-7. Fabric Properties Related to Fabric Construction

Property	Value*				
	Woven			Nonwoven	
	Mono-Filament	Multi-Filament	Slit Film	Needled	Bonded
Cost	3	4	1+	1+	2
Thickness	2	2	1	4	2
Absorption	1	2	1	4	2
Permeability					
Transverse-Flow	2-4	2-4	1-2	4	2
In-plane-Flow	0	1	0	4	0-1
Clogging and Blinding Resistance	-- Trends not clear --				
Filtering Ability	2-3	2-3	3	4	3+
Siphoning Ability	0	1	0	4	1
Strength	3-4	4	4	2-3	2-3
Rupture Elongation	1-2	1	1	4	2-3
Elastic Modulus	3	3	4	1	2
Flexibility	2	2-3	2	4	1-2
Creep Susceptibility	-- Trends not clear --				
Fatigue Resistance (Tensile)	-- Trends not clear --				
Burst Strength	3-4	4	4	2-3	2-3
Tear Resistance	2	2	2	4	1-3
Puncture Resistance	-- Trends not clear --				
Friction	-- Trends not clear --				
Impact Cutting Resistance	-- Trends not clear --				

*Compared for fabrics of similar unit weight per area and polymer fiber
4 Highest - 3 Slightly Lower - 2 Considerably Lower - 1 Very Much Lower - 0 Insignificant.
Note that a high value is not necessarily desirable

types, it would appear that the logical choice would be a polyester multifilament woven fabric.

As a third example, consider a light duty subgrade stabilization layer. This application would require good filtering characteristics, moderately high permeability, and reasonable resistance to clogging. At the same time, the requirements for strength, creep resistance, penetration resistance and abrasion resistance would be relatively modest. Further, in this application it would appear that virtually any of the fabrics would suffice, and so the objective would be to look for the one which could be provided at the minimum cost. This would include the nonwoven heat bonded fabrics, the light needle punched fabrics, and the woven slit film fabrics. It would also appear that the polypropylene would be the most economical filament because the superior mechanical properties and the UV and thermal stabilities of the more expensive polymers are not necessary.

2.4.3 Use Classification of Fabrics

By the process illustrated in the examples in the previous paragraphs, the fabrics are classified according to their appropriate use in Table 2-8. These classifications are also supported by reported usage.

Classifications such as those in Table 2-8 must, of course, be very general. There may be specific cases where an indicated fabric would not perform satisfactorily for the use indicated. The engineer must apply this with judgment. Also, the fabrics listed are those which are deemed to be the fabric which would provide the minimum satisfactory characteristics and therefore the most economical cost. There will in most cases be a variety of fabrics which would have superior properties to those recommended and which clearly would perform the functions satisfactorily. However, as a general rule, their cost would be higher, and therefore they would be less economical. There are, however, any number of cases where the economics may be changed by the requirement for special characteristics or availability of a given fabric, among other reasons. Also, in many important structures, the cost of the fabric is relatively very small; therefore, quality may be more important than cost.

In silt fences, either polypropylene or polyester might be suitable. For fabrics not UV stabilized, the polyester has a clear advantage with respect to its ultraviolet light resistance which would be a definite factor in the selection of material for silt fences. However, polyethylene, polypropylene and other polymers can be stabilized to improve UV resistance at very low cost and might be less expensive.

2.5 SUMMARY

This chapter has outlined and discussed the major polymers and fabric construction methods in common usage today. The technology is changing almost daily, and new materials and techniques are being applied. Therefore, the discussions and conclusions in this chapter will need to be modified as the state-of-the-art continues to develop. The influence of the polymer used in the fabric is significant in many instances, but in most cases, the

TABLE 2-8. Likely Practical Fabrics for Various Application

USE	FABRIC
Drain Filter	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film and Monofilament Woven
Separation: Light Duty	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film Woven
Separation: Heavy Duty	Mediumweight Bonded and Mediumweight Needled Nonwoven and Slit Film Woven
Reinforcement: Light Duty	Monofilament and Slit Film Woven and Heavy Needled Nonwoven
Reinforcement: Heavy Duty	Multifilament Woven
Erosion Control: Light Duty	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film and Monofilament Woven
Erosion Control: Medium Duty	Slit Film and Monofilament Woven and Mediumweight Bonded and Mediumweight Needled Nonwoven
Erosion Control: Heavy Duty	Very Heavyweight Needled Nonwoven, Heavyweight Woven, and Special Heavyweight Combination Woven-Nonwoven Fabrics
Silt Fences	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film Woven
Drainage	Heavyweight Needled Nonwoven

technique of the fabric construction is overriding and will control the significant engineering properties of the resulting material. The polymers, construction, and usage of fabrics are so diverse that it is not possible to rank any given fabric as superior for all applications. Decisions must be made as to which fabric is likely to be most suitable and most economical for each application.

The fabrics are classified and ranked by polymer, fabric construction and fabric use. These classifications are intended to be only general, and their respective rankings may be changed by special conditions. Also, the properties of the polymers can be modified from what is presented here by different manufacturing processes. Thought must be given to this and the fact that costs of the fabrics are often based more on supply and demand trends rather than actual production costs. The tables must be used with engineering judgment.

CHAPTER 2.0 REFERENCES

1. ________________, "The Use of Non-woven Fabrics in Civil Engineering Structures," Rhone-Poulenc-Textile Co., Non-woven Development Division, Lyons, France, 1975.

2. ________________, "Comparisons of Reinforcing Fibres," Civil Engineering, England, March 1977, 26-28.

3. ________________, "Modern Plastics Encyclopedia," Plastics Catalogue Corporation, New York, New York, 1964.

4. Herman, Mark, "Plastics," Colliers Encyclopedia, Volume 19, MacMillan Educational Corporation, New York, 1976.

5. Information supplied by I.C.I. Fibres, Herrogate, England, 1978.

6. Colin, Georgette and Mitton, M.T., Personal communication, National Research Council fo Canada, Ottawa, 1978.

7. Krcma, Radko, Non-woven Textiles, Textile Trade Press, Manchester, 1962. (Translated in 1967).

8. Haliburton, T. Allan, Anglin, Cyc C., and Lawmaster, Jack D., "Selection of Geotechnical Fabrics for Embankment Reinforcement," School of Civil Engineering, Oklahoma State University, Stillwater, OK, May 1978.

9. Guillet, James, "Polymers and Ecological Problems," Symposium on Polymers and Ecological Problems, Plenum Press, 1973.

10. Lennox-Ken, Peter, Needle-Felted Fabrics, Textile Trade Press, Manchester, England, 1972.

11. Calhoun, C.C., "Development of Design Criteria and Acceptance Specifications for Plastic Filter Cloths," Technical Report S-72-7, U.S. Army Engineers, Waterways Experiment Station, Vicksburg, Miss., 1972.

12. Sissons, C.R., "Strength Testing of Fabrics for Use in Civil Engineering," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 287-292.

13. Greenway, D.R. and Bell, J.R., "The Role of Fabric in Low Embankments," paper presented at the 17th Muskeg Research Conference, Saskatoon, Saskatchewan, Canada, October 7, 1977.

14. Yamanouchi, T., "Experimental Study on the Improvement of the Bearing Capacity of Soft Ground by Laying a Resinous Net," Proceedings, Symposium on Foundations in Interbedded Sands, CSIRO, Perth, Australia, 1970, pp. 144-150.

15. Yamanouchi, T., "Structural Effect of Restraint Layer on Subgrade of Low Bearing Capacity in Flexible Pavement," Proceedings, Second International Conference on Structural Design of Asphalt Pavements, Ann Arbor, MI, 1967.

16. Bell, J.R. and Steward, J.E., "Construction and Observations of Fabric Retained Soil Walls," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 123-128.

17. Barsvary, A.K., Personal Communication, Ontario Ministry of Transportation and Communications, Toronto, Ontario, Canada, 1978.

18. ________________, "Designing with Terram," Imperial Chemical Industries, Ltd, Harrogate, England, 1977.

19. ________________, "Enkamat," America Enka Company, Enka, NC, 1976.

20. McGown, A., Personal Communication, University of Strathclyde, Glasgow, Scotland, 1978.

21. ________________, "Polyfelt TS 300 Fabric," Advance Construction Company, Memphis, Tennessee, 1975.

22. Raumann, G., Personal Communication, Monsanto Triangle Park Development Center, Inc., Triangle Park, NC, 1978.

23. Stilley, A.N., "A Model Study of Fabric Reinforced Earth Walls," Master of Science Thesis Presented to Oregon State University, Corvallis, Oregon, 1974.

24. Crowe, R.E., Personal Communication, Terrafix Erosion Control Products, Inc., Toronto, Ontario, Canada, 1978.

25. Steger, T.R., "A Multiaxial Impact Test for Measuring the Puncture Resistance of Engineering Fabrics," Monsanto Company, St. Louis, MO, 1977.

26. Holtz, R.D., Personal Communication, Purdue University, West Lafayette, Indiana, 1978.

3.0 CRITERIA, PROPERTIES AND TESTS FOR VARIOUS APPLICATIONS

Fabrics have been employed in a variety of ways in the areas of drainage, erosion control and soil reinforcement. In the development of criteria for each application, it is most important to consider the function(s) the fabric performs in each application and then consider those properties which control the performance of the fabric in a given function. It is for these properties that tests should be performed to ensure that the fabric will perform in the fashion intended. Table 3-1 describes the possible functions a fabric may serve.

Most applications of fabrics (Table 3-2) will require a combination of these functions; however, one will normally control. For example, a fabric placed between the base course and the subgrade might be expected to perform as a drain and carry the water away from the subgrade surface. At the same time, it would be expected to be a filter layer to allow dissipation of excess pore pressures due to the wheel loads, while at the same time to prevent pumping. It could also serve as a separation layer to prevent the intrusion due to plastic flow of the subgrade into the base course. Finally, it might be expected to serve as reinforcement to reduce tensile stresses in the bottom of the base course layer.

The purpose of this chapter is to present for each fabric function, a description of selected use applications, and then indicate the important criteria and fabric properties which need to be evaluated. The approach used to identify important properties for all applications is to:

(1) Describe the purpose of the fabric for each application,

(2) Indicate how the fabric installation is constructed,

(3) Identify how the fabric might fail (or continue to perform its intended function), and

(4) Select appropriate criteria and properties to protect the installation against failure.

Following the discussion of all applications for a given function, current tests which might be used to evaluate the properties are identified. Finally, additional tests or modifications to existing tests are identified where needed.

3.1 FABRICS FOR FILTERS

3.1.1 Introduction

The purpose of fabrics as filters is to allow removal of ground water without the buildup of excessive seepage forces or water pressures. In addition, the fabric must be able to prevent piping or subsurface erosion of the soil mass being drained. In these applications, water flows across the filter into a water conducting medium which is specially selected drainage aggregate, pipes or other devices that can quickly remove the water.

TABLE 3-1. Description of Fabric Functions

Function	Description
Filter	The process of allowing water to escape easily from a soil unit while retaining the soil in place. The water is carried away by some other drain (e.g. rock or rock with pipe).
Drain	The situation where the fabric itself is to carry the water away from the soil to be drained.
Separation	The process of preventing two dissimilar materials from mixing. This is distinct from the filtration function, in that in separation it is not necessary that water be allowed to pass through the fabric.
Reinforcement	The process of adding mechanical strength to the soil-fabric system.
Armor	The process of protecting the soil from surface erosion by some tractive force. Usually in these situations, the fabric serves only for a limited time.

TABLE 3-2. Applications and Controlling Function of Fabrics

CATEGORY	APPLICATIONS	CONTROLLING FUNCTION	SECONDARY FUNCTION(S)
Filter	Trench Drains	Filter	
	Pipe Wrapping	Filter	
	Base Course Drains	Filter	Separation Drain
	Frost Protection	Filter	Separation, Reinforcement
	Structural Drain	Filter	Drain
	High Embankments	Filter	
Drainage	Retaining Walls	Drain	
	Vertical Drains	Drain	
	Horizontal Drains	Drain	Reinforcement
Erosion Control	Silt Fence	Filter	
	Silt Screen (Dredging)	Filter	
	Culvert Outlets	Armor	
	Seeding, Mulching	Armor	Filter
	Ditch Armoring	Armor	Filter
	Embankment Protection	Filter	
	Scour	Armor	Filter
Reinforcement	Reinforcement over soft ground	Reinforcement	Drain, Separation
	Retaining Structures	Reinforcement	
	Fill Reinforcement	Reinforcement	Drain, Separation
Separation	Paved Roads	Separation	
	Working Platform	Separation	Reinforcement
	Railroad	Separation	Reinforcement
	Aggregate Surfaced Roads	Separation	Reinforcement

3.1.2 Theory of Filtration

When water flows from the soil into the fabric filter, some of the finest soil particles will move into and through the filter (piping), and some will be trapped in the filter (clogging), leaving a more porous media adjacent to the fabric. This layer then serves as a filter for smaller particles. Under this idealized condition, continued migration eventually leads to the creation of an internally graded filter system or soil bridge structure as shown in Figure 3-1 [1]. In most soil-fabric systems, barring clogging by biological growth or blinding, the overall permeability will normally be governed by the filter cake permeability. In these cases, the fabric serves only as an instigator for the soil bridge formation, which actually filters the soil. In some cases a thin filter cake of fine soil grains may form near the fabric and actually reduce the permeability of the system. The filter cake does not always form. The conditions leading to a filter cake are not fully understood.

The tendency of a fabric to clog or blind over a period of time may result in a reduction of the permeability of the fabric. Reduction of the permeability may occur in one or more of the following ways:

(1) Through deposition of particles within the fabric by suspended solids (Figure 3-2). Deposited particles originate either from chemical or organic compounds suspended in the water or from soil particles of the filtered soil being transported by the water. This type of clogging normally occurs within the first three to four weeks [1].

(2) Blinding by plugging the openings in the fabric as shown in Figure 3-2.

(3) As a result of biological growth or vegetation which blocks the pores.

(4) Compression of the fabric structure thereby reducing the void ratio and permeability.

Failure of the fabric-soil system will depend on the reduction in permeability that can be tolerated. Reduction in permeability can occur as a result of fabric clogging, blinding and/or lessening of soil permeability owing to filter cake effects.

3.1.2.1 Factors Affecting Filtration

Several factors may affect the fabric performance. These factors may be categorized as:

(1) Fabric characteristics,

(2) Soil characteristics,

(3) Flow conditions, and

(4) External conditions.

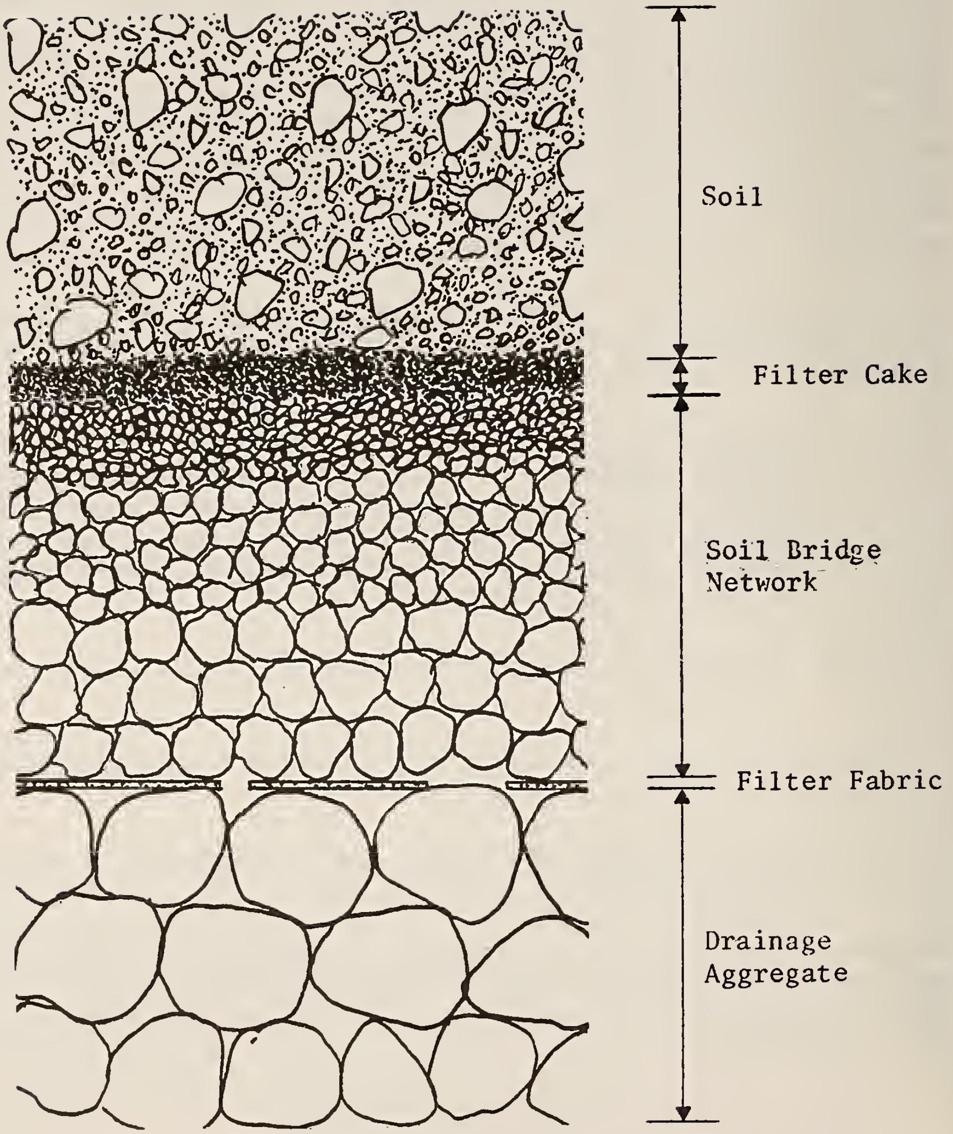


FIGURE 3-1. Filter Formation
(not to scale)

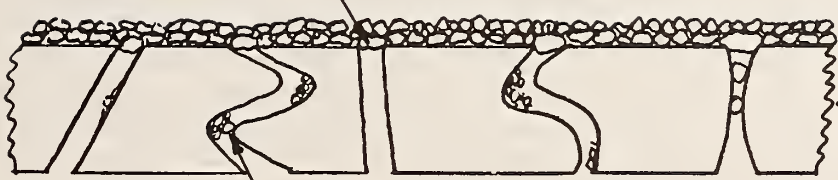


FIGURE 3-2. Methods of Clogging and Binding
(not to scale)

(1) Fabric Characteristics. The fabric characteristics that may influence fabric performance are:

(a) Pore Size Distribution. The largest pore size controls the maximum size soil particle which can possibly migrate through the fabric. The distribution of pore sizes can cause non-uniform flow at the fabric-soil interface and a large variation in velocity. Since the larger fabric openings will take more fluid, areas of turbulence may be prevalent near these pores, rather than near the smaller ones [3].

(b) Percentage Open Area. The percentage of open area influences the likelihood that soil particles will be aligned with the opening. The percent of open area depends on the construction of the fabric. The probability of the occurrence of piping increases with increasing open area and with increasing size of individual openings. The probability of clogging increases with reduced percentage of open area.

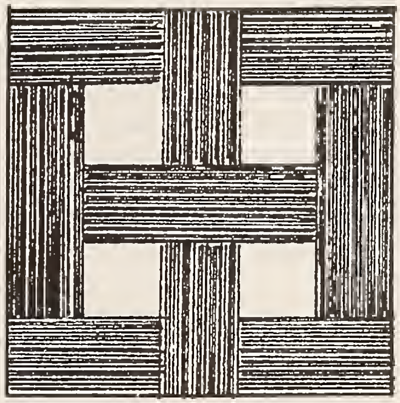
(c) Thickness. Soil particle migration depends on the size of the continuous fabric opening. For thicker fabrics, particularly non-woven, the continuous openings may be tortuous and reduce the maximum size of migratory particles. As soil particles become entrapped within the fabric structure, the effective area for flow is reduced and the potential for clogging is increased [3]. Thicker fabrics may be more likely to clog than thinner fabrics, because there is a greater opportunity for soil particles to clog, since the fabric flow path is longer and hydraulic gradients are smaller.

(d) Rigidity of Structure. For less rigid fabrics, pores may tend to close up under compression loading and clogging may occur. If the fabric stretches, pore sizes may increase and the likelihood of piping may increase.

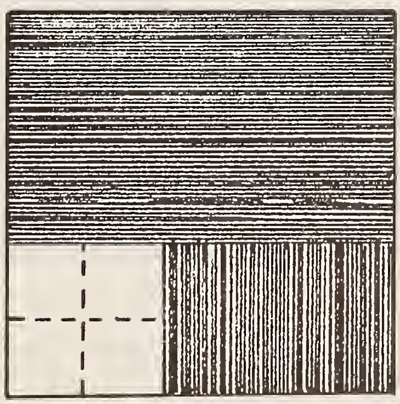
(e) Fiber Characteristics. Fiber diameter may affect the pore size, as illustrated in Figure 3-3. For a unit area, two fabrics may have the same percent open area, but the fabric with wider fibers will have fewer but larger openings, while the fabric with smaller fibers will have more openings that are smaller in size. The likelihood of piping would be greater for the fabric with the larger fibers.

(2) Soil Characteristics. The performance of the fabric filter system may be influenced by the following soil characteristics:

(a) Soil Mineralogy Characteristics. The soil's mineral composition (i.e., cohesive or cohesionless) may influence the permeability of the system. Clay particles may be more likely to adhere to the fabric, thereby clogging the fabric. On the other hand, the clay particles may resist piping and consequently resist formation of the filter cake. In this situation, the fabric-soil system permeability would remain close to the original



(a) Smaller fibers -- smaller openings



(b) Larger fibers -- larger openings

FIGURE 3-3. Effect of Fiber Diameter on Opening Size soil permeability.

(b) Particle Shape. Shape may influence a particle's ability to become aligned with a fabric pore such that it could migrate. The fabric may clog or the soil bridge formation may not be initiated.

(c) Grain Size Distribution. The grading characteristics of the soil may affect the amount of soil loss due to piping and consequently the soil bridge and filter cake formation. If the filter cake formation is affected, the soil-fabric system permeability may be affected depending on the grain size distribution. Clogging may also be affected by the grain size distribution of the soil.

In selecting a fabric to filter a uniform soil, it is only necessary to choose a fabric with pore sizes smaller than the grain size. In this case, there can be no soil migration and therefore, no soil bridge formation. The soil-fabric system permeability would simply be controlled by the least permeable member, which is normally the soil, assuming there is no blinding.

For gap graded and well graded soils, the choice of fabric is not so obvious. The soil bridge formation depends to a large extent on the grain size distribution of the soil. For example, if soil migration occurs for a gap graded soil, it is very likely that all of the fine particles will be removed, since there sould not be sufficient particle size variation to permit the formation of a soil bridge structure if the fabric pores are larger than the fines. If the pores are smaller, a filter cake will form on the fabric blinding it.

(d) Void Ratio. If a soil is in a loose state, smaller particles may be able to migrate through the voids in the soil and possibly through the filter fabric. In a dense condition, soil migration is less likely to occur, since the pores are smaller. In the process of densifying the soil, particles may be forced into the fabric pores, thereby blinding the fabric. As a result of density variations, the soil bridge network and filter cake formations may be affected.

(3) Flow Conditions. The fabric filter system performance may be influenced by the water quality, as well as by the flow conditions. These factors are discussed below:

(a) Water Quality. Water containing suspended solids may clog or blind a fabric [4]. Suspended solids may exist as soil particles carried as a result of construction activity. In addition, precipitation of chemicals in solution may clog the fabric.

(b) Hydraulic Gradient. The seepage force, a controlling factor in soil migration, is directly related to the hydraulic gradient. Also some fabrics, when dry, require a significant head to initiate flow through the fabric and will not allow water to pass initially under low hydraulic gradients.

(c) Flow Pattern. If the flow is pulsating (as in shoreline structures exposed to wave action), there could be a tendency towards disruption of the internal grading system or possibly removal of clogged particles. Most likely, there would be an increase in loss of soil due to piping.

As the flow direction deviates from transverse, the available pore size diminishes and the probability of particles accumulating on the fabric surface may increase. The net result is a reduction in piping tendencies and an increase in clogging potential [2]. The filter cake formation may also be affected by the pattern of flow.

(d) Void Behind Fabric. Variations in soil conditions may contribute to an irregular soil surface as in irregular trenches caused by boulders, cave-ins, etc. If the fabric bridges over the depression without stretching, there will be a void behind the fabric. This void area may take more flow and possibly create a turbulent condition. Soil migration may increase and/or the void may fill if the adjacent soil collapses, the suspended soil particles will tend to clog or blind the fabric.

(4) External Conditions. The following external conditions may affect the performance of the fabric filter system:

(a) Static Surcharge. The surcharge may compress the fabric, thereby reducing pore sizes and possibly creating a more tortuous flow path. The surcharge load may contribute to fabric blinding by forcing soil particles into the fabric surface pores. The soil bridge structure and filter cake formation may also be affected by static surcharge load. Because of these possibilities, the filtration characteristics of fabrics should probably be determined for the surcharge loads that will be applied under project conditions.

(b) Dynamic Loading. The introduction of a dynamic load may disrupt the internal filter system [5]. Soil loss due to piping would probably also occur.

The above factors affecting filtration performance are summarized in Table 3-3. In addition, it has been found that time is a factor that should be considered in evaluating a filter fabric's performance [1,6]. Fabric-soil system permeability tends to decrease for a relatively short period of time and then remains at a constant value. This transition period can probably be associated with the clogging, blinding, and filter cake formation during the formation of the soil bridge structure. Figure 3-4 illustrates a typical time-versus-permeability relationship for two different fabrics.

TABLE 3-3. Factors That May Affect Fabric Filter Performance

CATEGORY	FABRIC
Fabric	Pore Size Distribution Percentage Open Area Thickness Rigidity of Structure Fiber Characteristics
Soil	Soil Mineralogy Particle Shape Grain Size Distribution Void Ratio
Flow Conditions	Water Quality Hydraulic Gradient Flow Pattern Void Behind Fabric
External Conditions	Static Surcharge Dynamic Loading

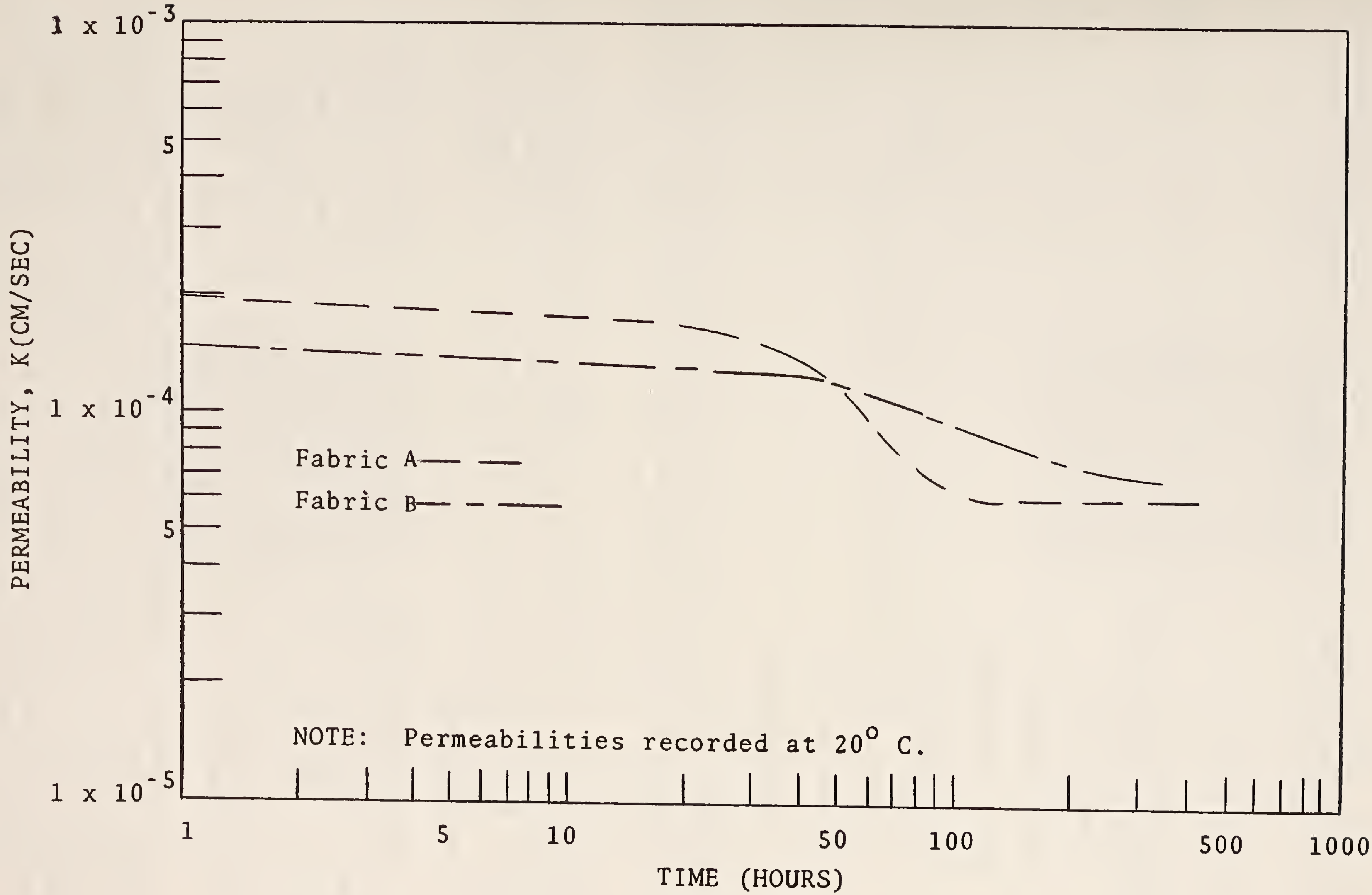


FIGURE 3-4. Permeability Versus Log Time - Soil No. S-15 [1]

Although no experimental evidence is available at this time, fabrics may deteriorate or rot with time as a result of biological activity. Such degradation may reduce the fabric's ability to function as a filter.

3.1.3 Applications

There are many kinds of filtration applications for fabrics. Some of the more predominant are as follows:

(1) Trench drains,

(2) Pipe wrapping,

(3) Base course drains,

(4) Frost protection,

(5) Structural drains (retaining wall, rock buttress), and

(6) High embankments.

3.1.3.1 Trench Drains

(1) Purpose. Figure 3-5 shows the use of fabric in French drain construction. The fabric prevents soil fines from moving into the stone-filled trench and clogging it, while allowing the water to pass through. The fabric acts as a filter for the transport medium.

Figure 3-6 shows a use similar to the French drains, but with a pipe included within the drain. The backfill is simply a porous aggregate larger than the perforations in the pipe. The fabric acts as a filter for the transport medium. When substantial quantities of water need to be removed by drains, it is usually more economical to include a pipe rather than depend only on porous aggregate.

(2) Construction Procedure. In both of the above instances, the construction procedures are similar. Once the trench is excavated to the required depth, leveled and smoothed such that no large sticks or rocks are protruding, the fabric is rolled out and draped into the trench without shoring [7,8]. The cloth should not be stretched so tight that it will tear when the aggregate is placed. Whenever more than one section of fabric is used, the fabric must be overlapped to assure continuity of the filter. Enough fabric should remain exposed to allow for fabric overlap at the top.

For French drains, the stone is backfilled into the lined trench. For trench drains, a shallow layer of the specified open aggregate should be backfilled into the trench. The slotted or perforated pipe is then placed on top of the aggregate layer. Additional aggregate is backfilled into the trench to the desired depth. To avoid tearing or puncture during backfilling with angular rocks, it is better to carefully place a six-inch cushion of stone or gravel material over the filter cloth before end dumping large stone out of trucks or front end loaders. Following aggregate placement, the fabric is

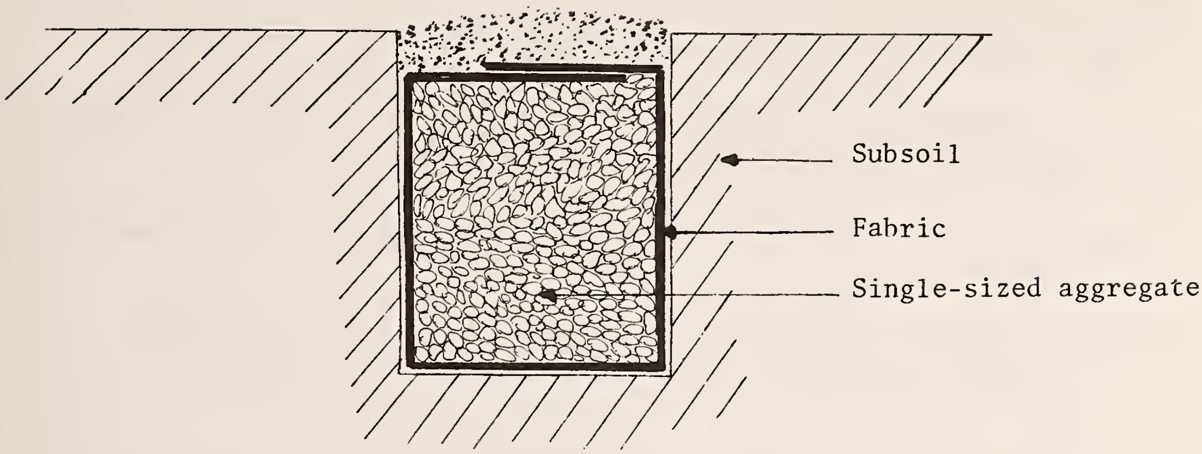


FIGURE 3-5. French Trench Drain Constructed with a Fabric

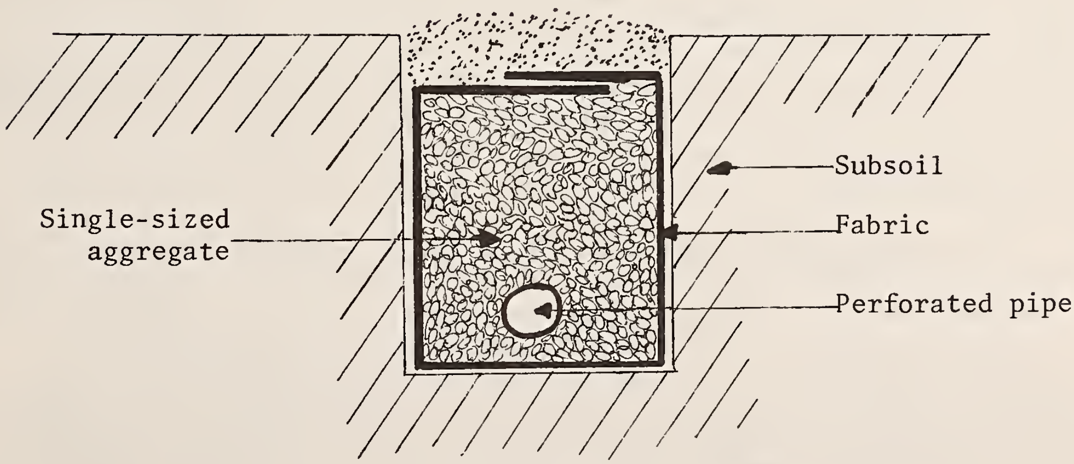


FIGURE 3-6. Pipe Trench Drain Constructed with a Fabric

lapped over the top. No special joining techniques are required. The drain is simply covered with another specified material.

(e) Possible Failure Modes. In trench drains, the fabric can fail in a number of ways if proper conditions do not prevail or unsuitable fabrics are used. Likely modes of failure are listed below.

(a) The initial fabric permeability may be inadequate to remove the water.

(b) The fabric may clog by either particle deposition, blinding, biological growth, or chemical deposits, as described in Section 3.1.2.

(c) Soil particles may pass through the filter fabric, thereby clogging the drain such that it cannot effectively remove water. In addition, the piping may cause subsidence of the adjacent soil as a result of soil erosion.

(d) The fabric may be torn or punctured during construction, either by aggregate placement or construction equipment. In this case, excessive piping may occur and produce the same effect as in (c).

(e) The fabric may fail by biological deterioration. In this case, the fabric could tear easily and fail as in (c). Under repetitive loading, the fabric would most likely fail by piping.

(f) The fabric may fail as a result of thermal effects (i.e., high temperatures during asphalt placement, freeze-thaw cycles). The fabric may deteriorate as in (e).

(4) Performance Experience. The earliest reported use of wrapped trench drains in a significant structure was in 1965 in Toledo, Ohio. Woven monofilament filter cloth was used. The same materials were also used for trench drains at the Shelbyville reservoir dam in 1966 [46].

In highway applications, the New York State Department of Transportation has used non-woven fabrics in trench drain applications since 1974 [9]. The overall performance has been good. A few construction comments, as listed below are worthy of note.

(a) Due to variations in soil conditions, it is common to have irregular trenches caused by boulders, cave-ins, etc. Since the fabric is of uniform width, the fabric must be patched to ensure top overlap. If pavement drainage is not required it may be possible to lower the top of the stone, overlap the fabric and fill the remaining space above the overlap with stone. The fabric can be cut and placed transverse to the trench to guarantee top overlap, but this usually results in a waste of material and time.

(b) If the fabric bridges voids beneath the pavement or shoulder, pavement subsidence and cracking may later occur. To prevent this, stone can be compacted to stretch the fabric to fill small voids. However, larger voids must be filled with stone outside the trench.

The Illinois Department of Transportation, after observing a trench drain installation for nearly two years, found the drain to be effective in removing ground water from a saturated clay subgrade [10]. The original design specified placement of a pipe. However, due to seepage pressure, the trench tended to collapse before the pipe could be placed. Therefore, the pipe was deleted and the granular material could be placed immediately after lining the trench with a nonwoven fabric. Deletion of the pipe cut costs considerably. Water flowing out of the system was very clear, with an estimated capacity flow of 0.06 m^3/s (2 ft^3/sec) of water per second. The maximum flow that the soil could provide was about 0.04 m^3/s (1.4 ft^3/sec). No settlement was noted on the shoulder along the underdrain system.

The Alabama, Pennsylvania and Georgia Departments of Transportation have also noted success with filter fabrics in trench drains [54].

(5) Criteria and Properties. To select the fabric for a trench drain, the criteria and properties listed in Table 3-4 should be considered. In connection with these fabric properties, the following information should be quantified:

(a) Grain size distribution of the subsoil,

(b) Permeability of the subsoil,

(c) Flow conditions -- hydraulic gradient, direction of flow, water quality and anticipated water level fluctuations.

3.1.3.2 Pipe Wrapping

(1) Purpose. Fabrics can be used as a filter around a drain pipe. This system is useful for draining surface water in sandy or gravelly soils. This type of drain can be used in clayey or silty soils, but with a lower efficiency.

(2) Construction Procedure. The drain pipe is wrapped with the fabric. The fabric may be a knitted tube or it may be fastened by either stitching (Figure 3-7), or by lapping and gluing the fabric edges (Figure 3-8). The wrapped pipe is then placed directly into a previously dug trench and backfilled with soil.

(3) Possible Failure Modes. The failure modes are similar to those identified for trench drains (Section 3.1.3.1). Too low fabric permeability would result in failure to drain the soil. Excessive piping would result in soil erosion and drain plugging. In addition, pipe wrapping can be damaged by abrasion during construction if the wrapped pipe is dragged along the ground, thereby causing excessive piping.

(4) Performance Experience. Woven filter cloths were used as early as 1963 in the Holt Lock and Dam and later in the Sam Reyburn Dam. Nonwoven

TABLE 3-4. Design Criteria and Properties for a Trench Drain

CRITERIA	PROPERTIES
Permeability	Initial Permeability Particle Clogging Resistance
Filtration	Piping Resistance
Durability	Chemical Stability Biological Stability Thermal Stability
Constructability	Bulkiness (Storage) Weight and Size Flexibility Tensile Strength Puncture Resistance Tear Resistance Cutting Resistance

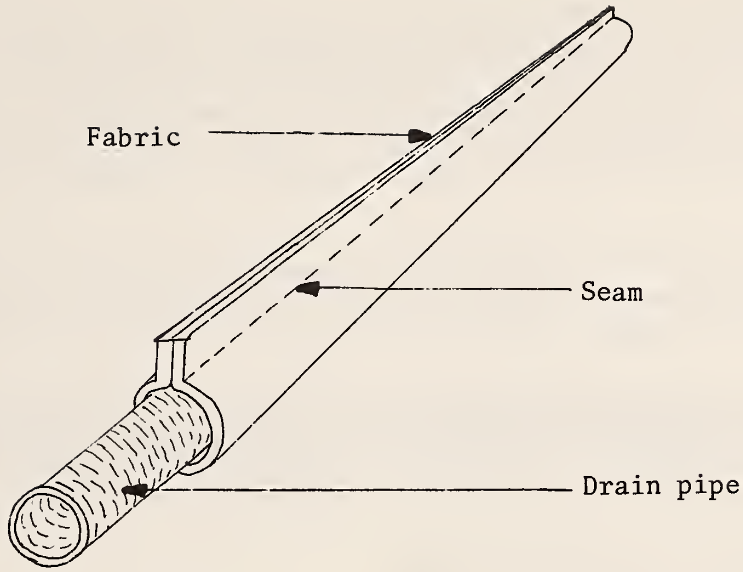


FIGURE 3-7. Fabric Stitched on to the Pipe

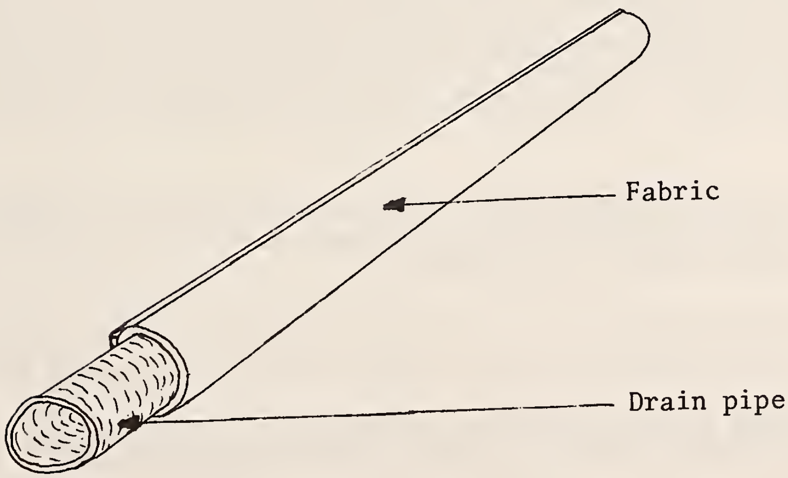


FIGURE 3-8. Fabric Wound around the Pipe

pipe wrapping has been used mainly in agricultural applications. Through the Department of Agricultural Engineering, McGill University [16], a field evaluation of drain tube filter materials was conducted. The lighter weight nonwoven fabrics suffered much abrasion damage prior to installation. In addition, when tubing was dug up, the heavier fabrics had good strength and were bridging over the corrugation valleys. The heavier fabrics performed best.

The Illinois Department of Transportation has used wrapped pipes in sandfilled trenches. Rather than line the trench, the pipe is wrapped. Sand is used because there is a shortage of suitable coarse aggregate.

(5) Criteria and Properties. The criteria and properties identified for the trench drain (Table 3-4) are applicable to pipe wrapping design, with two exceptions. First, it is important to know the seam strength for stitched or glued installations. Second, abrasion resistance should be known.

3.1.3.3 Base Course Drains

(1) Purpose. Fabric can be used as a replacement for the graded aggregate filter subbase in road or railway works (Figure 3-9). The fabric prevents soil migration into the open graded aggregate drainage layer between the natural soil and the base. The fabric allows water to escape, thereby preventing the buildup of hydrostatic or seepage pressures. The fabric can also be considered as serving a separation function. Note that for some conditions, the fabric may be used on top of the open-graded layer, for others beneath the layer, and sometimes it may completely enclose the layer, as shown in Figure 3-9.

(2) Construction Procedure. The subgrade is prepared in the usual manner. Fabric is unrolled on the subgrade either in overlapping strips or stapled, sewn or welded to assure continuity of the filter. Next, the aggregate is directly backfilled on the fabric to the designed depth and a second layer of fabric is placed in the same manner on the top of the drainage aggregate layer. The remaining base and pavement are placed in the normal manner.

(3) Possible Failure Modes. The failure modes for trench drains (Section 3.1.3.1) also apply to base course drains. In addition, the following failure modes are possible:

(a) Failure may occur as a result of abrasion under traffic loads. Eventual fabric tearing would result in increased piping.

(b) Piping into the drainage aggregate may increase as a result of dynamic effects (pumping) resulting from traffic loads.

(4) Performance Experience. At present, very little is known about how fabrics perform in this application.

(5) Criteria and Properties. The criteria and properties given for trench drains (Section 3.1.3.1), plus the additional durability property of abrasion resistance is necessary for blanket drain design.

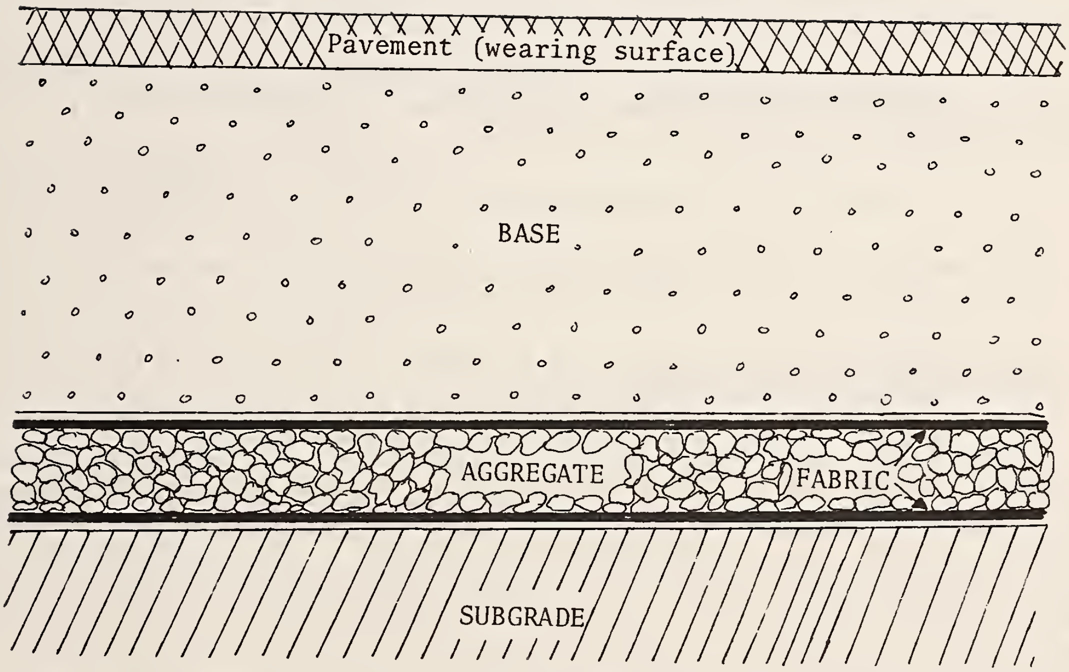


FIGURE 3-9. Base Course Drain Constructed with Two Layers of Fabric

3.1.3.4 Frost Protection

(1) Purpose. In frost protection applications, base course drains, as described in the previous paragraph, prevent the water migration towards the freezing zone [12]. The gravel layer placed below the frost line intercepts the capillary link in the water migration path to the frozen soil, thus preventing frost heave and associated problems. To function correctly year after year, the gravel layer must remain clean and free of contaminating fines. The fabric provides a protective filter between the gravel and the frost-susceptible soil and permits the use of cleaner gravels with low suction and therefore better control over frost action.

(2) Construction Procedure. Fabrics for frost protection are installed in the same manner as base course drains (Section 3.1.3.3).

(3) Possible Failure Modes. The frost protection fabric may fail according to one or more of the modes discussed for trench drains (Section 3.1.3.1). Additional failure modes are listed below:

(a) The fabric may deteriorate as a result of freeze-thaw effects.

(b) The fabric may "break" if it is brittle, as a result of low temperatures.

(4) Performance Experience. At present, very little is known about how fabrics perform in this application.

(5) Criteria and Properties. The criteria and properties outlined for base course drains (Section 3.1.3.3) also apply to frost protection applications. Two additional durability properties should be considered -- cold temperature resistance and freeze-thaw resistance. The average frost penetration must also be estimated. An ideal arrangement for fabrics as frost breaks is shown in Figure 3-10, where the drain is placed at or below the frost line. In this case, ice lenses will not form at the frost line to cause heaving, and the gravel should provide complete protection from ice segregation. However, the depth of the frost line may vary from year to year, and therefore, the ideal location cannot be accurately known. If the frost is greatly above the blanket drain (Figure 3-11), the drain may not provide complete protection from ice segregation. If the frost line extends below the blanket drain (Figure 3-12), the ice lenses can form below the gravel layer, but their effects are reduced because of overburden pressure.

3.1.3.5 Structural Drains

(1) Purpose. A fabric installed behind a retaining wall (Figure 3-13), or around a rock buttress (Figure 3-14) serves as a filter. The fabric behind the retaining wall filters water from the soil that is then removed via the aggregate or pipe. This system helps alleviate hydrostatic and seepage pressures behind the wall. Similarly for the rock buttress, the fabric allows water to escape through the aggregate, but prevents fine particles from being washed away.

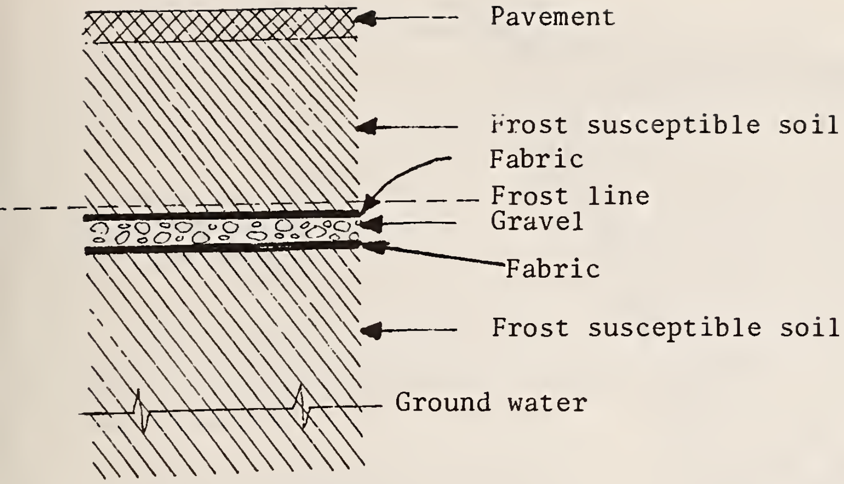


FIGURE 3-10. Frost Protection - Gravel Layer Just Beneath the Frost Line [12]

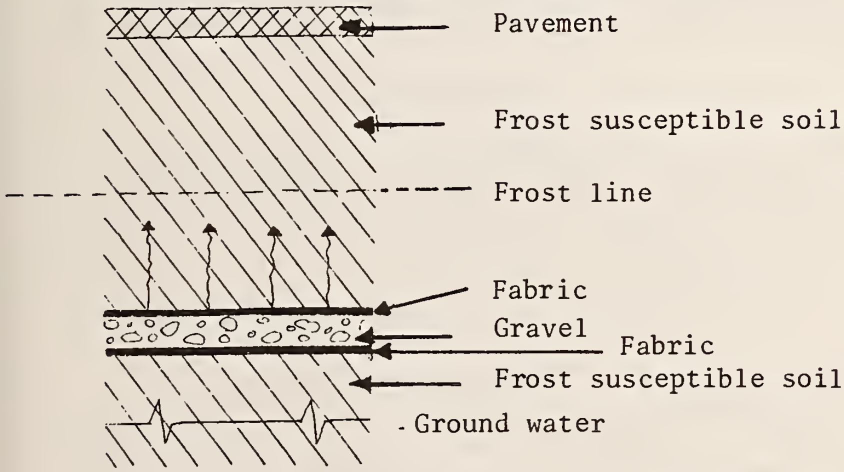


FIGURE 3-11. Frost Protection - Gravel Layer Much Deeper than Frost Line [12]

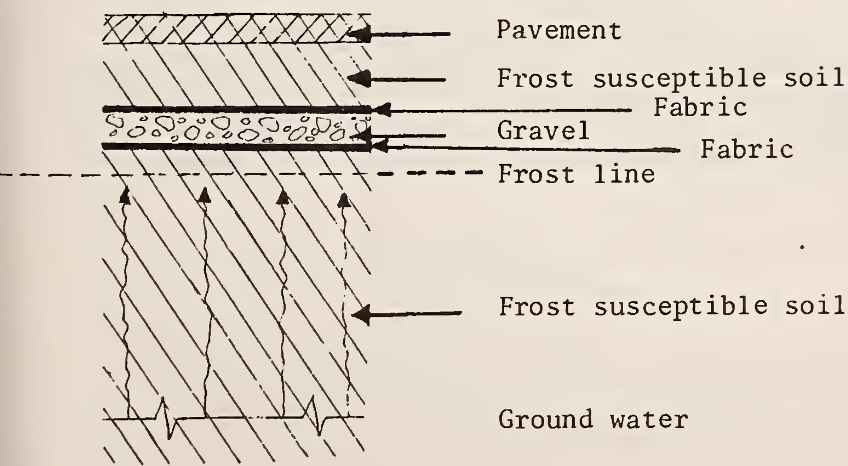


FIGURE 3-12. Frost Protection - Gravel Layer Above the Frost Line [12]

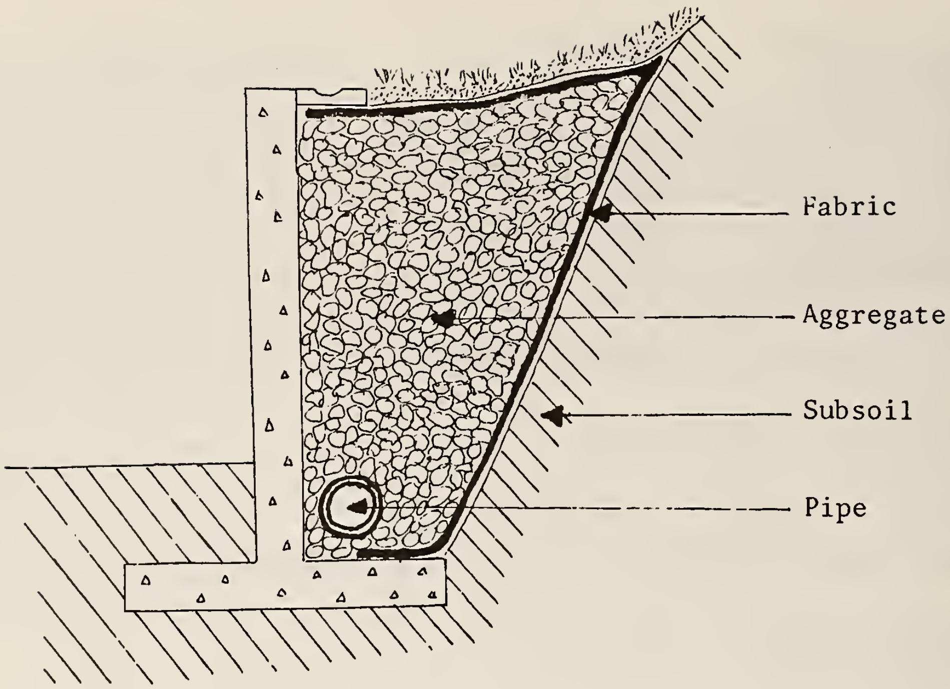


FIGURE 3-13. Drain with Fabric behind a Retaining Wall

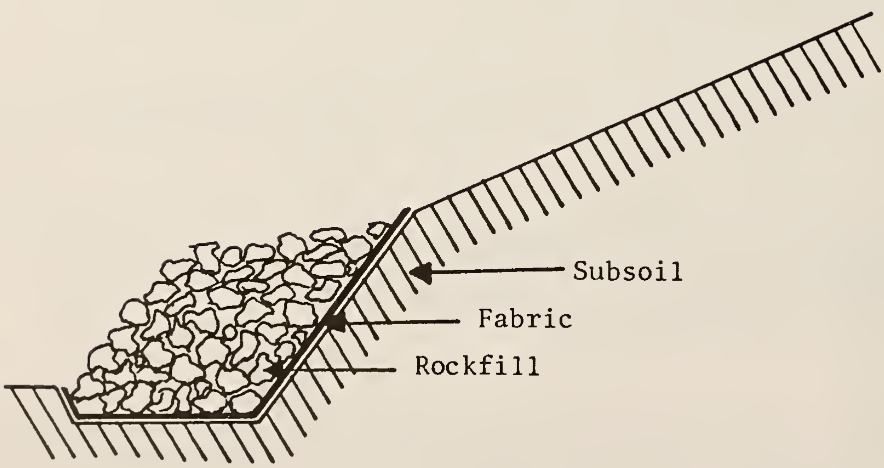


FIGURE 3-14. Rock Buttress

(2) Construction Procedure. For the fabric surrounding the drain behind the retaining wall, the sheet of fabric is rolled out on the slope and can be held in place by means of pins or large nails. After placing the pipe at the bottom of the wall, the aggregate materials are placed and covered with fabric and soil, as shown in Figure 3-13.

For the rock buttress, the filter fabric is placed on the prepared soil slope and pinned in place as indicated in Figure 3-14. After placing the fabric, the rockfill material is placed over the fabric.

(3) Possible Failure Modes. The failure modes identified for the trench drains (Section 3.1.3.1) are similar to those for structural drains. In the event of excessive piping or reduced permeability, the slope could fail and severely damage nearby structures.

(4) Performance Experience. Documented experience summaries for structural drains are unavailable at this time.

(5) Criteria and Properties. The criteria and properties identified for trench drains (3.1.3.1) are also applicable for structural drains.

3.1.3.6 High Embankments

(1) Purpose. High embankments may have fabric filters around vertical or horizontal drains (Figure 3-15). The fabric prevents the impervious fill material from contaminating the aggregate drains during construction while still allowing pore pressure to dissipate. The horizontal drains tend to accelerate consolidation of the high embankments. An additional benefit is the reinforcement derived from the fabric.

(2) Construction Procedure. The first layer of the embankment is placed in the usual manner. Fabric is then unrolled on this layer either in overlapping strips or stapled, sewn or welded to assure continuity of the filter. Next, the aggregate is directly backfilled on the fabric to the designed depth and a second layer of fabric is placed in the same manner on the top of the draining aggregate layer. This process is repeated until the embankment is at the desired height.

(3) Possible Failure Modes. High embankment drains can fail in ways similar to trench drains (Section 3.1.3.1) except that flows are too low for piping to occur. The drain efficiency will be reduced if the fabric is plugged by blinding due to compaction. Earth loads may compress the fabric and reduce its permeability. Special problems may develop for embankments which impound water.

(4) Performance Experience. At present, very little is known about how fabrics perform in this application.

(5) Criteria and Properties. In addition to the criteria and properties specified for trench drains, the abrasion resistance of the fabric should probably be specified. Piping is not a criteria.

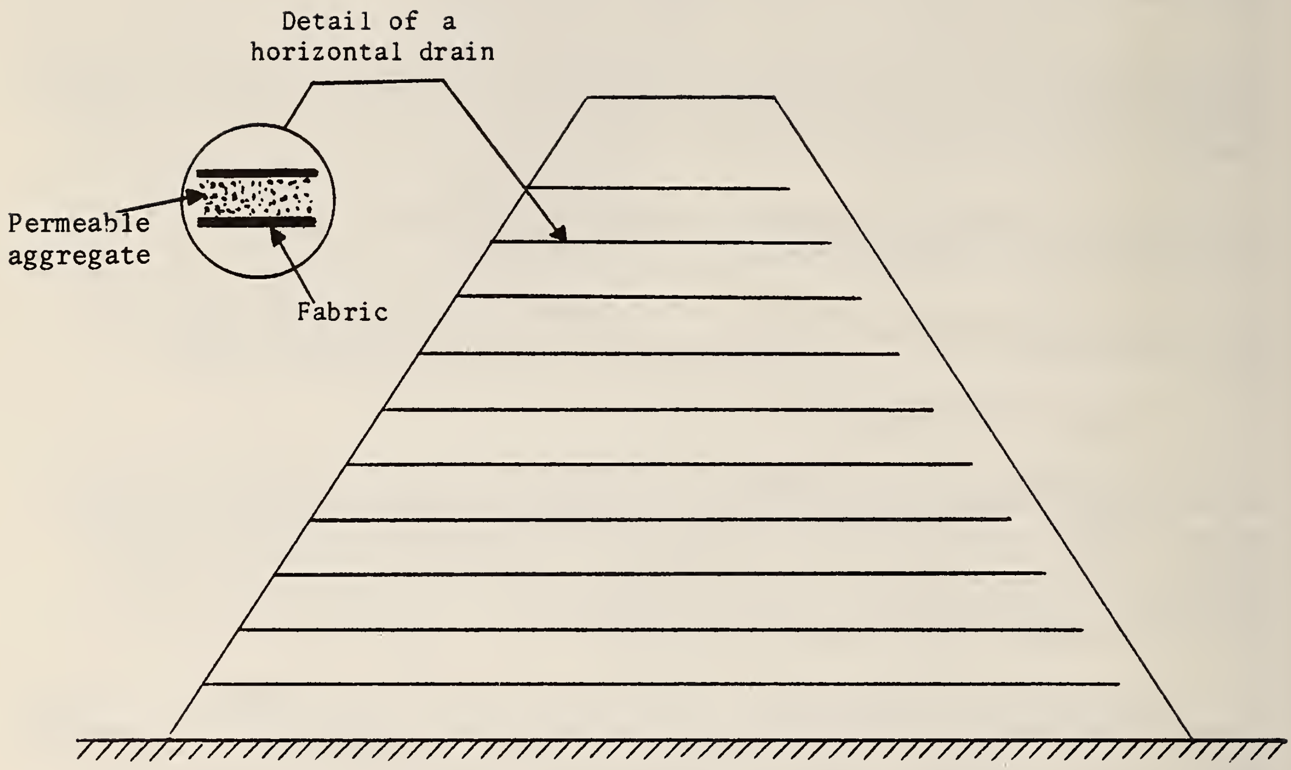


FIGURE 3-15. Filter Fabrics Used Around Drains in High Embankments

3.1.4 Summary of Criteria and Properties

For fabrics to perform satisfactorily in the filtration applications described in Section 3.1.3, they must meet several requirements. First the fabric must be sufficiently permeable to allow removal of ground water without the buildup of excessive seepage forces or water pressures. Second, the fabric must also be able to prevent piping or subsurface erosion of the soil mass being drained. In addition, the fabric must be able to withstand handling stresses during installation such that it does not tear and result in soil loss. Finally, the filter fabric must maintain its characteristics for the life of the installation (durability). Design criteria for filtration applications are summarized in Table 3-5.

To ensure that the criteria are met, a number of fabric properties should be evaluated. The properties to evaluate permeability criteria are initial permeability and particle clogging resistance. The filtration criterion can be evaluated in terms of the fabric's ability to resist piping under initial and working conditions. Properties satisfying the system durability and contructability criteria are listed in Table 3-5. The importance of these has been previously indicated.

3.1.5 Tests and Test Conditions

Several attempts have been made to evaluate fabric filtration properties through laboratory testing. These tests can be categorized as follows:

(1) Fabric pore characterization methods: visual measurement or mechanical analysis, and

(2) Filtration tests.

The following sections will discuss the major tests in terms of their ability to represent field conditions and present significant results.

3.1.5.1 Fabric Characterization Methods

Fabric characterization methods are normally adopted as a means of indirectly determining fabric permeability and/or piping resistance. Table 3-6 summarizes methods commonly used today.

Equivalent Opening Size (EOS) [13]. The EOS is an indication of the effective maximum opening size of a fabric. It is measured by sieving uniform sands through the fabric starting with a size which will pass more than 5 percent and using successively coarser fractions until less than 5 percent passes. The EOS is defined as the U.S. Standard Sieve size for a uniform sand which will have 95 percent retained by the fabric after the standard sieving time.

As mentioned earlier, the purpose of the EOS is to determine the effective maximum pore size of the fabric for use as a measure of piping resistance. However, this determination may not always be entirely accurate. During sieving, particles may become trapped in surface fibers (especially for thick nonwonven fabrics). Soil particles that would normally pass through

TABLE 3-5. Filtration Criteria and Properties

CRITERIA	PROPERTIES
Permeability	Initial Permeability Clogging and Blinding Resistance
Filtration	Piping Resistance
System Durability	Thermal Stability Biological Stability Chemical Stability
Constructability	Abrasion Resistance Bulkiness (Storage) Weight and Size Absorption (Wet Weight) Flexibility Bondability Tensile Strength Puncture Resistance Cutting Resistance Seam Strength Tear Strength

TABLE 3-6. Fabric Characterization Methods

METHOD	REFERENCES	PARAMETER(S) MEASURED
Equivalent Opening Size (EOS)	Charles C. Calhoun [13]	Maximum Opening Size
Delft Sieve Analysis	H.J.M. Ogink [5]	Maximum Opening Size Pore Size Distribution
Image Analysis (Electronic)	A.L. Rollin [14]	Pore and Fiber Size Distribution and Density
Optical	-	Percent Open Area Pore Size Distribution
Sieve Analysis with Glass Beads	E.C. Ruddock [26], Celanese [31]	Pore Size Distribution
Suction	Paute and Chene [99]	Pore Size Distribution

the fabric would remain at the surface. Therefore, the EOS may not represent the effective maximum pore size.

Delft Sieve Analysis [5]. The Delft sieve analysis provides an indication of the pore size distribution and the maximum opening size of the fabric as an evaluation of piping resistance to sands. The test method is similar to that used to determine the EOS by the Corps of Engineers. Ogink [5] defines the maximum pore size as 0_{98}. 0_{98} corresponds to the average sand diameter of the sand fraction of which two percent falls through the fabric. Ogink concluded that for a given fabric, 0_{98} is constant for sieving times greater than 5 minutes. For other pore diameters (i.e. 0_{90}, 0_{50}), sieving time affected the results. Inaccurate test results may result due to surface fibers and other factors as encountered in the EOS determination.

Electronic Image Analysis [14]. Rollin has injected fabrics with resin cut them into thin slices, made electron micrographs, and then analyzed them with an electronic image analyzer. By establishing the average fiber diameter and the number of fibers in the plane of the cut, Rollin approximated the diameter of particles that would be retained on/in the fabric and those that would pass through the fabric. This method, although more difficult in terms of time and equipment required, probably gives the most accurate representation of the fabric morphology. However, this degree of sophistication may not be necessary or practical for design purposes.

Optical Measurement. The maximum opening size, percent open area, and pore size distribution can be evaluated under a microscope with light transmission or with enlarged photos. The values obtained may be fairly accurate for most woven fabrics. Howver, for nonwoven fabrics, the accuracy is very low due to the thickness and tortuosity of openings of most nonwoven fabrics.

Analysis with Glass Beads [26]. Ruddock evaluated the pore size distribution by vibrating spherical glass balls (ballotini) through a fabric sample. The test method is similar to the EOS method, with the exception of the ballotini. Ruddock noted that the energy of vibration of individual particles of the finest grades of ballotini is insufficient to make them penetrate any fabric with a hairy or fleecy consistency. The scatter of results was large for all fabrics.

3.1.5.2 Filtration Tests

Filtration tests have been performed to evaluate one or more of the following:

(1) Fabric permeability,

(2) System permeability before and after various flow periods including clogging, and

(3) Soil loss during filtration.

Filtration tests included in this study are listed in Table 3-7. Identification of the flow direction symbols in Table 3-17 is made in Figure 3-16. Each test is summarized in terms of flow conditions, properties measured,

TABLE 3-7. Filtration Tests

Test Author		Properties Measured			Soil Present	Flow Conditions				Variables
		Permeability	Clogging	Piping		Direction **	Reversible	Constant Head	Falling Head	
ASTM D 737 [15]		X(air)								
A. L. Bell [17]		X				0		X		
J. Hoogendoorn [4]		X	X			0		X		Water quality
M. Bourdillon [18]		X				0		X		
C.C. Calhoun [13]	1/	X			X	↓		X		Hydraulic gradient, surcharge, soil
	2/	X	X		X	↓		X		Hydraulic gradient, soil
B. D. Marks [1]		X	X		X	↓		X		Soil
E. McKeand [6]		X	X		X	↓		X		
H.J.M. Ogink [5]	1/	X				0		X		Hydraulic gradient
	2/	X		X		↑		X		Hydraulic gradient grain size distribution
	3/	X		X	X	↑		X		Dynamic load--frequency, amplitude, grain size distribution
D.B. Sweetland [3]	1/	X			X	↓		X		Hydraulic gradient, surcharge load, soil
	2/	X			X	→		X		Soil
Soil Testing Services, Inc. [19]	1/	X		X	X	↓		X		
	2/	X		X	X	↑		X		Hydraulic gradient
L. F. Hermsmeier [20]	1/	X			X	↓↑→		X		
	2/			X	X(slurry)					
L. Willardson & R. Walker [20]										

**0 - implies no soil is present

TABLE 3-7. Filtration Tests (cont.)

Test Author	Properties Measured			Soil	Flow Conditions				Variables
	Permeability	Clogging	Piping	Present	Direction**	Reversible	Constant Head	Falling Head	
L. Benz (E.J. Doering) [21]	X		X	X	↑		X		
D.G. Carabetta [22]	X			X	↓			X	
G.L. Hoffman [23] 1/	X	X		X	↓		X		Soil
2/	X			X	↓↑→		X		
L. Lockett [24] 1/	X				↓		X		Number of fabric layers
2/	X	X		X	↓			X	
New York State [27]	X			X	↓		X		Hydraulic gradient
Chemie Linz Ag [28]	X			X	↓↑→		X		Inflow pressure
Celanese [29] 1/	X				0			X	
[30] 2/	X		X		↓		X		
Brunswick Corp. [49] 1/	X	X		X	↓		X		
2/	X	X		X(slurry)	↓		X		
3/	X				0		X		Surcharge
4/			X	X(slurry)	↓			X	
Celanese [50]			X	X(slurry)	→				
Fayoux [51]			X	X					
New York DOT [52]	X		X	X(slurry)		← →		X	
H.J. List 1/	X				0			X	
2/	X		X	X		X			
3/		X	X						
Rollin [14]	X	X		X	↓		X		

*AASHTO T-215 Standard Constant Head Permeameter

**0 = implies no soil is present

Figure 3-16

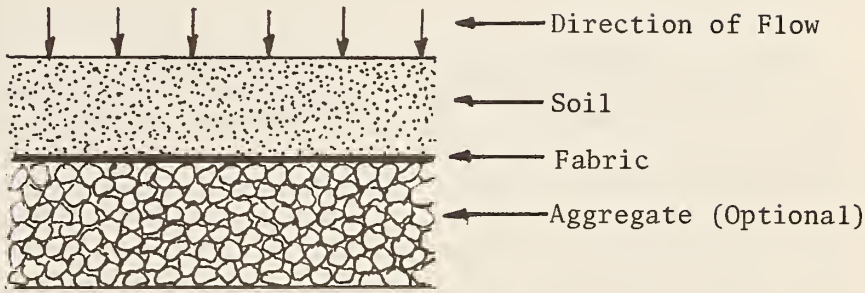
EXPLANATION OF FLOW DIRECTIONAL SYMBOLS

FOR TABLE 3 - 7

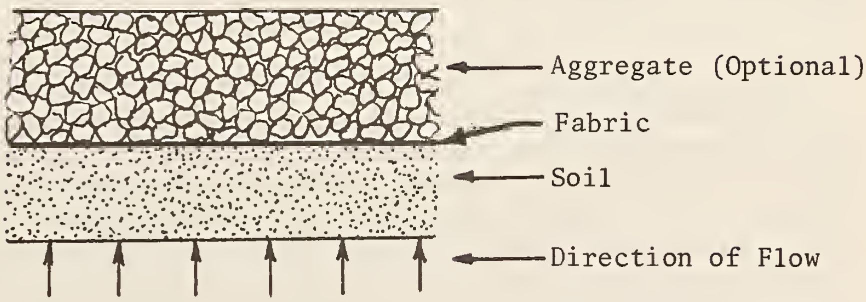
Filtration Tests

Flow symbol direction:

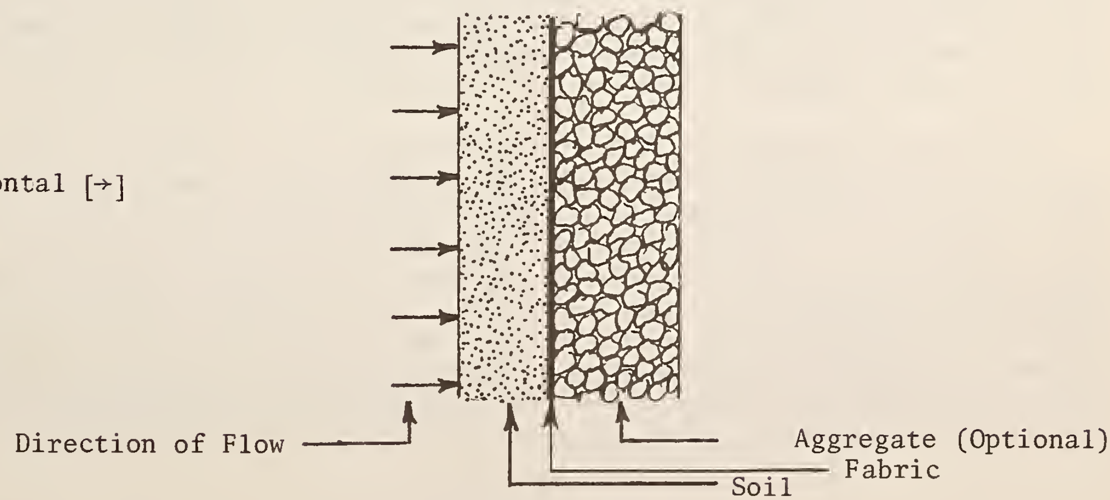
Down [↓]



Up [↑]



Horizontal [→]



soil presence and test variables. The following sections will discuss the major tests in terms of their ability to simulate field conditions and significant results.

Air Permeability [15]. Attempts have been made to correlate air permeability results to soil-fabric permeability test results. Although a relationship exists between air and water permeability of the fabric, Marks concluded that a relationship did not exist between fabric permeability and soil-fabric system permeability [1]. This is because the system permeability is greatly affected by the soil.

A.D. Hoogendoorn [4]. Hoogendoorn performed tests with tap water, ditch water and silty water. No soil was present in the constant head system. By expressing the rate of clogging as the time needed for a reduction of the original flow velocity (i.e., t_{25} is the time required to reach 25 percent of the original flow velocity), Hoogendoorn concluded that all fabrics were sensitive to clogging in a relatively short length of time. t_{25} was less than 5 hours under the test conditions used. However, it was concluded that reductions in permeability due to chemical compounds in tap water was insignificant when compared to those due to tap water with added silt. Although the test conditions are not entirely analogous to the previously discussed applications in which the fabric was in contact with the soil, the test does emphasize that water quality is a factor that should be further researched in filtration. Chemicals in solution or suspended soil particles in the water may clog or blind the fabric. On the other hand, with soil present, the chemical or suspended soil particles may be filtered by the soil bridge formation with no fabric clogging or blinding.

C.C. Calhoun [13]. The U.S. Army Corps of Engineers performed filtration tests on four woven fabrics. Water was allowed to flow through pea gravel, soil, filter fabric and then crushed limestone. Changes in head across the soil and fabric were measured. Soil types included two gradations of uniform rounded to subrounded river sands and a silty sand. It was thought that the silty sand imposed a more severe condition than just silt, because the water velocities through the silty sand would be higher and piping would be more likely to occur. The soil range tested did not permit verification of this hypothesis. Tests were run under constant head conditions with deaired water. By applying a surcharge load, the effect of riprap or other structures was simulated as the fabric was installed over angular aggregate. Under loads of 24.5 and 49 kPa (500 and 1000 psf), no significant punctures or tears from the crushed limestone were noted. Punctures or tears would have possibly promoted excessive piping.

Tests were performed on two woven and one nonwoven fabrics. Water was allowed to flow through pea gravel, soil and then the filter fabric. The soil consisted of Ottawa sand with varying percentages of loess fines (0,5,10 and 20 percent). A constant head was applied utilizing deaired water. Calhoun evaluated "clogging" by introducing the term clogging ratio. Calhoun defined the variable "i" as the average hydraulic gradient measured from the tailwater piezometer to the first piezometer below the top of the soil specimen. The ratio of the average hydraulic gradient through the lowest one inch of soil plus filter cloth, i', to i at the conclusion of the test was termed the clogging ratio. A ratio greater than one would indicate clogging. Values ranged from less than one to almost two. Calhoun concluded the clogging ratio to be a valid indication of the amount of clogging in the fabric. However, he neglected to consider that the "clogging" may be due to the soil and that the fabric may not be clogged at all. It should be noted that the duration of these tests (about 1-1/2 to 5 hours) may not adequately indicate long-range performance characteristics of the filter fabric. In addition, the hydraulic gradients applied were in excess of those normally encountered in highway applications and are more appropriate for erosion control structures along coastlines.

B.D. Marks [1]. Marks performed permeability tests on a range of fabric and soil types. The constant head apparatus directed flow through the soil, fabric and finally the aggregate. No attempts were made to remove air from the system. Pressure drops across the soil and fabric were measured. In determining the performance of filter systems under soil variance, a sandy silt base soil was used. Soil variance was accomplished by adding the following fractions:

SERIES	SOIL ADDED	PERCENTAGES
1	Minus No. 100 Size Particles	0,5,15,25,35,40
2	Kaolinite Clay	0,10,20,30
3	Montmorillonite Clay	2,4

Four weights of heat-bonded heterofilament nonwoven fabric and on woven fabric were used in this portion of the study. From this test program, Marks concluded the following:

(1) The fabric filter behavior as a function of time was found to be closely related to the soil bridge and filter cake formation. By varying the soil depth, it was found that the soil bridge network system was about 5 cm. (2 inches) deep. Soil depths greater than 5 cm. (2 inches) did not affect the system behavior. Later studies using resin injections verified the soil bridge system formation [52]. Because of test conditions, the soil bridge network is probably much greater than could be expected under most field conditions, where it could be almost nonexistent.

(2) The amount of soil clogging the fabric was approximately equal for all soils tested.

(3) Piping was found to decrease significantly with increase in plasticity of soils.

(4) Fabric variance was not great enough to detect any significant differences in filtration performance for a given soil.

The test conditions represented a fairly close approximation of typical field conditions. However, the following deviations are worthy of note.

(1) The soil was placed in a very loose condition (density ≈ 1155 kg/m^3 (75 pcf)). Density may affect soil bridge and filter cake formation. Compaction efforts may tend to blind the fabric.

(2) No surcharge load was applied.

(3) The hydraulic gradient used was relatively high (i = 3). Lesser gradients may result in less piping. If piping is restricted, the filter cake formation may be less pronounced such that the soil-fabric system permeability may be closer to the soil permeability.

H.J.M. Ogink [5]. Ogink investigated the possibility of piping under a static load condition represented by permanent groundwater flow in a direction perpendicular to the fabric. The test equipment was similar to that used by Marks except that water flowed upward through the sand and fabric. Ogink noted only an initial transport of fine material. The initial piping stopped after a while because a natural filter had apparently built up under the fabric. This phenomenon tends to indicate that the soil bridge system formation does not require gravitational assistance. However, further testing may be necessary to verify this phenomenon for other soil types.

Ogink also investigated the effect of reversing flow conditions. Dynamic loads were applied to water which passed through a sand layer sandwiched between two layers of fabric. Under these load conditions, the sand particles with a diameter smaller than O_{98} can be washed out irrespective of fabric type. This is to be expected, since the internally developed filter, which prevents the movement of fines under static load conditions is disrupted. It should be noted that the dynamic loads were extreme. Under less adverse conditions, the results might be more favorable.

Ogink allowed for the possibility of a turbulent flow condition. The hydraulic gradient was expressed by:

$$i = b \cdot (v_f)^n$$

where:
- b = resistance coefficient, $m^{-n} \cdot s^n$
- v_f = velocity of flow through filter
- n = exponent depending on the flow characteristics
- m = meters
- s = seconds

If n = 1, the above equation represents Darcy's flow equation for laminar flow, while for n = 2, this equation gives the relationships between flow velocity and gradient for fully turbulent flow. For a fabric permeability tests involving no soil, n was found to equal 1.4.

D.B. Sweetland [3]. Sweetland tested nonwoven fabrics in a downward flow permeameter under constant head conditions, such that the fabric was placed between two layers of soil. By using the above equation, Sweetland estimated n to equal one. Consequently, laminar flow conditions were assumed to exist, and Darcy's Law was regarded as valid.

Sweetland observed that the soil bridge system formation developed faster with fabrics having a more open, simple cross-section than the thicker felt-like materials. He, therefore, concluded that thin nonwoven fabrics are preferable to the thicker fabrics in filtration applications. It should be noted that Sweetland's test conditions involved very high hydraulic gradients.

Soil Testing Service, Inc. [19]. The effect of laminar vs turbulent flow conditions was investigated for two woven fabrics and three soil gradations. Turbulent flow was accomplished in the downward direction by increasing the hydraulic gradient to values beyond the Darcy flow regime. In the upward direction, a gradient greater than critical was applied through the soil that was not confined by the filter. In the downward direction, soil particle loss was larger for turbulent than laminar flow. In upward flow boiling occurred, and soil loss of fine particles was excessive. However, it should be noted that such a condition may be prevented by providing enough overburden to balance upward water forces such that silty and sandy soils are held in place. A conventional aggregate filter would normally add this weight.

G.L. Hoffman [23]. Hoffman performed constant head permeability tests similar to those run by Marks, except that the fabric was unsupported and therefore its center deflected downward. To estimate the amount of clogging, soiled fabric was removed and tested for permeability without soil. The permeability of the soiled fabric was generally about ten times less than the permeability of the clean fabric. Hoffman also determined the permeability of the sand alone. It should be noted that even with the reduction in fabric permeability, the fabric was still more permeable than the soil for all fabrics investigated except one.

L. Lockett [24]. The Alabama State Highway Department performed constant head permeability tests using several layers of fabric but no soil. Several layers of fabric were required in order to allow a constant 35-inch (89 cm) water head. The University of Alabama's review [25] of this test method concluded that if thickness is used in permeability calculations, the results will bias a thick fabric over a thin fabric. That is, two fabrics of different thickness may pass equal quantities of water per unit layer over a given amount of time, but have different values of permeability (k). In this condition, the permeability of the thick fabric will be greater than the permeability of the thin fabric, even though both are capable of passing the same amount of flow.

Celanese Fibers Marketing Co. [30]. The Celanese test equipment was similar to the permeability equipment used by Marks. Celanese found that the permeability normally stabilized between 600 and 1000 hours. Experience has shown that the majority of soil loss occurs within the first 80 to 120 hours of test operation. This may vary depending on soil type, hydraulic gradient and possibly other factors.

3.1.6 Current Design Standards

Design criteria for filtration applications have been developed by several organizations. Their purpose has been to ensure adequate permeability, while preventing excessive loss of fine soil particles. Current design standards are presented below.

3.1.6.1 U.S. Army Corps of Engineers [13]

Based on laboratory tests (see Sections 3.1.5.1 and 3.1.5.2), the following filter criteria were specified by the U.S. Corps of Engineers.

(1) Adjacent to granular materials containing 50 percent or less by weight of silt (material of little or no plasticity), passing the No. 200 sieve:

(a) (85% size of the material (mm))/(EOS (mm)) > 1.

(b) Open Area not to exceed 40%.

(2) Adjacent to soils having little or no cohesion containing more than 50% silt by weight:

(a) EOS no larger than the opening in the U.S. Standard Sieve No. 70.

(b) Open Area not to exceed 10%.

(3) Cloths used to wrap collector pipes should be surrounded by at least 6 inches (15.24 cm) of clean granular material. If the cloth is used to line a trench, the collector pipe should be separated from the cloth by a minimum of six inches (15.24 cm) of clean granular material.

Only woven filter cloths with distinct openings are recommended.

These standards have been widely used.

3.1.6.2 Delft Hydraulics Laboratory [5]

Ogink recommends the following filtration design criteria for sandy soils to prevent piping.

(1) Under static load conditions, mat, mesh-netting tape and multifilament fabrics should fulfill the following requirement: $O_{98}/D_{90} \leq 1.0$. For nonwovens, the requirement is: $O_{98}/D_{90} \leq 1.8$.

(2) Under dynamic load conditions, if the soil bridge network is not allowed to form, the requirement is: $O_{98}/D_{90} \leq 1.0$. If the dynamic load permits the buildup of a natural filter, piping is minimized if: $O_{98}/D_{90} \leq 1.0$ for woven and 1.8 for nonwoven fabrics.

The above recommendations are noted as being extreme. Under less critical static or dynamic load conditions, the requirements may be relaxed.

3.1.6.3 Celanese Fibers Marketing Co. [32]

The Celanese Co. recommends the following filtration specifications for nonwoven filter cloths for subsurface drainage structures. Filter cloths for subsurface drainage must be composed of strong rotproof polymeric fibers oriented into a stable network such that the fibers retain their relative positions with respect to each other. The fabric should be free of any chemical treatment or coating which might significantly alter its physical properties. The following filtration requirements must be met:

(1) Water Permeability: $(k) > 5\ k_{soil}$ (10^{-2} cm/sec minimum)

(2) Average Pore Size (P_{avg})*:

(a) Soils with < 50% passing a #200 U.S. Standard Sieve -

$$P_{avg} \leq D_{85}\ \text{soil}$$

(b) Soils with > 50% passing a #200 U.S. Standard Sieve -

$$P_{avg} \leq 0.15\ \text{mm (\#100 sieve)}$$

3.1.6.4 Ontario Ministry of Transportation [53]

The Ontario Ministry of Transportation and Communications specifies the following hydraulic requirements for filtration applications.

(1) Pore Size. Filter fabrics shall have an average pore size between sizes D_{30} and D_{85} of the soil being filtered.

(2) Permeability. The coefficient of permeability (k) of the filter fabric shall be at least twice the coefficient of permeability of the soil being filtered ($k_{fabric} \geq 2k_{soil}$) provided that the soil has a uniformity coefficient of $D_{60}/D_{10} \leq 5$. For soils with a uniformity coefficient of $D_{60}/D_{10} \geq 5$, the coefficient of permeability (k) of the filter fabric shall be at least five times the coefficient of permeability of the soil being filtered.

Other agencies specifying permeability include the U.S. Forest Service and the Pennsylvania Department of Transportation. The Alabama and Florida Departments of Transportation specify a maximum and minimum value of permeability and do not specify any pore size limitations.

---

*$P_{avg} = (P_{80} + P_{20})/2$, where: P_{80} = 80% finer pore size
P_{20} = 20% finer pore size

Values obtained by a standard sieving technique using closely graded spherical glass beads similar to Ruddocks method [26], Section 3.1.5.1.

3.1.7 Recommendations

Most engineering designs for filtration applications have been mainly based on trial and error. Design standards that have been applied (Section 3.1.6) have generally resulted in satisfactory performance. However, fabrics that do not meet the design standards have been known to perform equally well in similar field installations. The goal of this study is to determine the significant properties and influencing factors and to identify tests that will measure these properties.

To predict the performance of filtration applications based on soil and/or fabric properties, the topics listed below should be further investigated. In all cases, both permeability and piping should be evaluated.

(1) The effect of flow conditions on filter fabric/soil performance should be more clearly defined. Flow conditions include upward, downward, horizontal and surging flow. An attempt should be made to typify field gradients. Noting variations in the soil bridge and filter cake formations might assist in this study.

(2) The effect of water quality on filtration behavior should be further defined. Tests varying water quality should evaluate the influence of suspended soil as well as chemical composition. Soil should be included in any tests.

(3) The influence of static or dynamic loads on filter fabric-soil performance should be further evaluated. The repetitive loading situation of roads and railroads should be simulated in laboratory testing.

(4) The importance of soil type should be more clearly defined. Grain size distribution, chemical composition and density are factors that should be considered. The effects of compaction on fabric blinding should also be investigated.

(5) The importance of fabric morphology on filtration and permeability behavior requires further definition. The influence of tensile loading on fabric characteristics should be considered. It is assumed that the effect of compressive loading would be observed in static load studies.

3.2 FABRICS FOR DRAINAGE

3.2.1 Introduction

The purpose of fabrics in the drainage function is to transmit water in the plane of the fabric. Although this is its primary purpose, the fabric must also be able to function as a filter. The filtration role is necessary to prevent piping of the drained soil and to ensure that the fabric can function as a drain without clogging. Therefore, the mechanisms involved in filtration (Section 3.1.2) also apply to drainage installations. Although not widely used yet, possible drainage applications include:

(1) Drainage behind retaining walls

(2) Vertical drains for accelerated consolidation of soft foundation soils, and

(3) Horizontal drains in embankments.

These are applicable primarily to thick nonwovens, special fabrics, or composite fabrics.

3.2.2 Theory of Drainage

Fabrics used in drainage applications must serve a dual role as both filter and drainage media. The fabric functions as a filter when the water enters the fabric and as a drain when the water flows in the plane of the fabric. As mentioned earlier, the mechanisms involved in filtration (Section 3.1.2) will also occur in drainage installations. However, a number of the influencing filtration factors become considerably more significant in drainage applications. These factors are:

(1) Fabric thickness and compressibility, and

(2) Surcharge.

Application of Darcy's Law to drainage applications shows that the quantity of flow is directly related to the thickness of the fabric. That is,

$$Q = k \, \Delta h/L \, A$$

where:
- Q = quantity of flow
- Δh = change in head along fabric length
- L = length of flow path
- k = coefficient of permeability
- A = cross-sectional area avaialble to flow
  = fabric width x thickness

If the fabric thickness is reduced under compressive loading, the cross-sectional area available to flow is reduced and consequently the quantity of flow is less. The reduction in quantity of flow is compounded by the reduction in permeability (k) as a result of compression of fabric pores. Fabrics with greater rigidity of strucutre would be more resistant to this phenomenon than those fabrics with a weaker structure. The reduction in quantity of flow is not as pronounced in filtration applications, because in this case, the fabric thickness is the length of the flow path and a reduction in thickness could increase the quantity of flow.

3.2.3 Applications

3.2.3.1 Drainage Behind Retaining Walls

(1) Purpose. The fabric installed behind a retaining wall helps to relieve water pressure behind the wall by allowing water to seep along the fabric (see Figure 3-17). The water is filtered by the fabric. Therefore, the fabric serves as both a drainage and a filtration medium. However, due to the small cross-sectional area available for flow, the fabric would only be effective with backfill soils of low permeability. A positive outlet is needed to assure discharge of water to a free exit.

(2) Construction Procedure. The fabric is secured to the back of the retaining wall. The backfill is placed against the fabric. The fabric may be anchored at the top by folding over and covering with soil.

(3) Possible Failure Modes. Fabrics used for drainage behind a retaining wall may fail in a number of ways. The most likely modes of failure are listed below.

(a) The initial fabric permeability may be inadequate to remove the water. In this case, excessive hydrostatic or seepage forces may cause the wall to fail by cracking or excessive movement accompanied by ground settlement.

(b) The fabric may plug by either clogging, blinding or biological growth, as described in Section 3.1.2 and fail as in (a).

(c) The fabric may be torn or punctured during construction, either by angular rocks or construction equipment. The fabric may essentially clog if the source (rock) remains embedded in the fabric, thereby blocking flow in the plane of the fabric. However, the flow would most likely divert itself around the clogged area.

(d) The fabric may fail by biological deterioration. In this case, the fabric could deteriorate such that it essentially becomes impermeable and fails as in (a).

(e) The fabric may fail as a result of thermal effects (i.e., freeze-thaw cycles). The fabric may deteriorate as in (a).

(4) Performance Experience. No information on performance experience is available at this time.

(5) Criteria and Properties. In order to use fabric as a drain behind a retaining wall, the criteria and properties in Table 3-8 should be considered. Further research should identify the possible effect of intermittent flow as might occur in ground water fluctuations. In addition to these fabric properties, the following properties should be known.

(a) Grain size distribution of the soil to be drained,

(b) Permeability of the drained soil, and

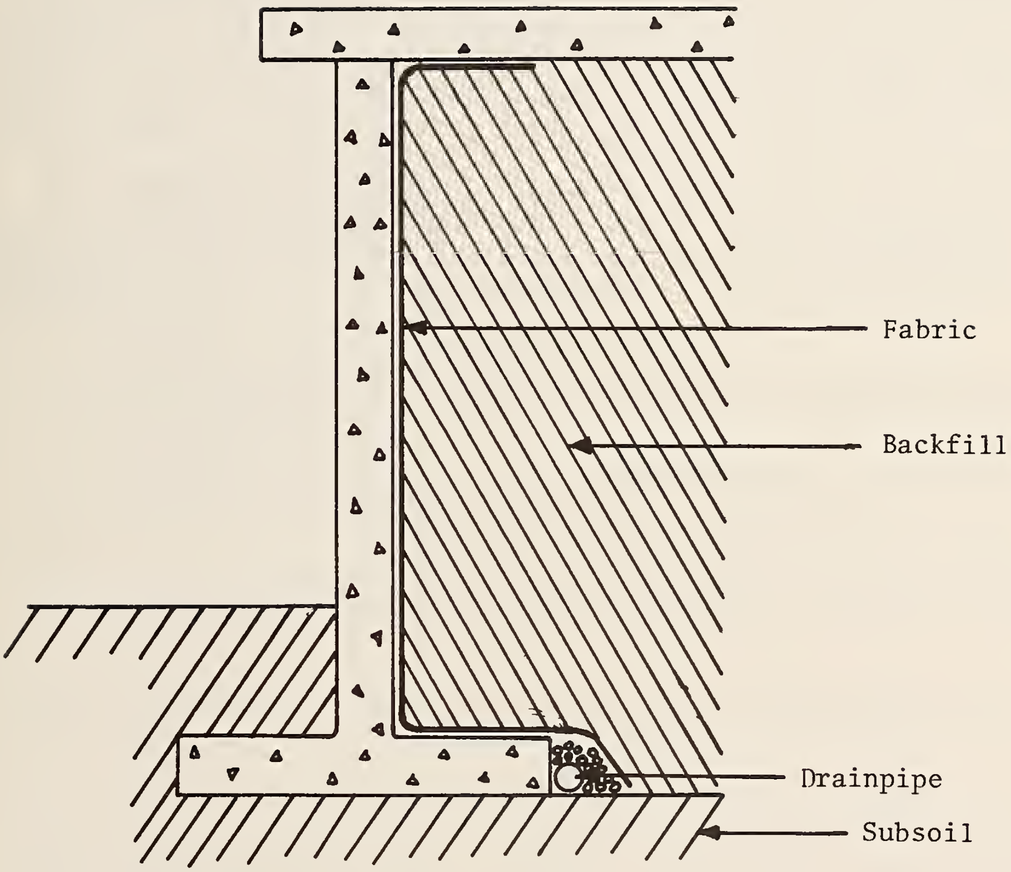


FIGURE 3-17. Use of Fabric for Vertical Retaining Wall

TABLE 3-8. Design Criteria and Properties for a Drainage Fabric Behind a Retaining Wall

CRITERIA	PROPERTIES
Permeability	Initial Permeability Clogging and Blinding Resistance
Filtration	Piping Resistance
Durability	Chemical Stability Biological Stability
Constructability	Bulkiness (Storage) Weight and Size Flexibility Tensile Strength Tear Resistance Puncture Resistance

(c) Flow Conditions -- quantity of flow, water quality, anticipated water level fluctuations.

3.2.3.2 Vertical Drains in Soft Soil

(1) Purpose. The purpose of vertical drains is to shorten the drainage path to water in settlement prone soils such that consolidation is accelerated.

(2) Construction Procedure. The strips of thick nonwoven fabrics are introduced into the soil by means of a lance. Ideally, the fabric should be in contact at the bottom of the compressible layer with a permeable layer (Figure 3-18). Width of the fabric strips and spacing between them can vary, depending on the permeability of the soil. The typical width of the fabric strips is about 30 cm and spacing may vary from 1.50 m to 3.50 m [34].

(3) Possible Failure Modes. Vertical drains may fail in many ways. In all cases, consolidation would not occur as rapidly as expected. The quantity of water flowing out depends on the rate of consolidation and can be estimated using soil mechanics calculatons. The possible failure modes are listed below.

(a) The initial fabric permeability may be inadequate to remove water efficiently.

(b) The system may plug by either particle clogging, blinding or biological growth, as described in Section 3.1.2.

(c) The fabric may be torn during insallation. In this case, a discontinuity may exist in the fabric such that there is not a direct flow path.

(d) The drainage capacity may be reduced by compression of the fabric due to lateral earth pressures.

(e) The fabric may deteriorate by biological or chemical actions.

(4) Performance Experience. Risseeuw and Van Der Elzen [34] observed full scale model installations for over one year. Settlement and pore water pressure measurements were recorded. Comparison of settlements of the non-woven fabric drain installation to the sand drain installation indicated approximately equal performance. Measured settlements for both drain types compared well with calculated values of settlement.

(5) Criteria and Properties. In order to design a vertical drain, the criteria and properties listed in Table 3-9 should be known. In addition, the following conditions should be known.

(a) Grain Size Distribution of the soil to be drained,

(b) Permeability of the drained soil, and

(c) Loading and consolidation characteristics of the soil deposit.

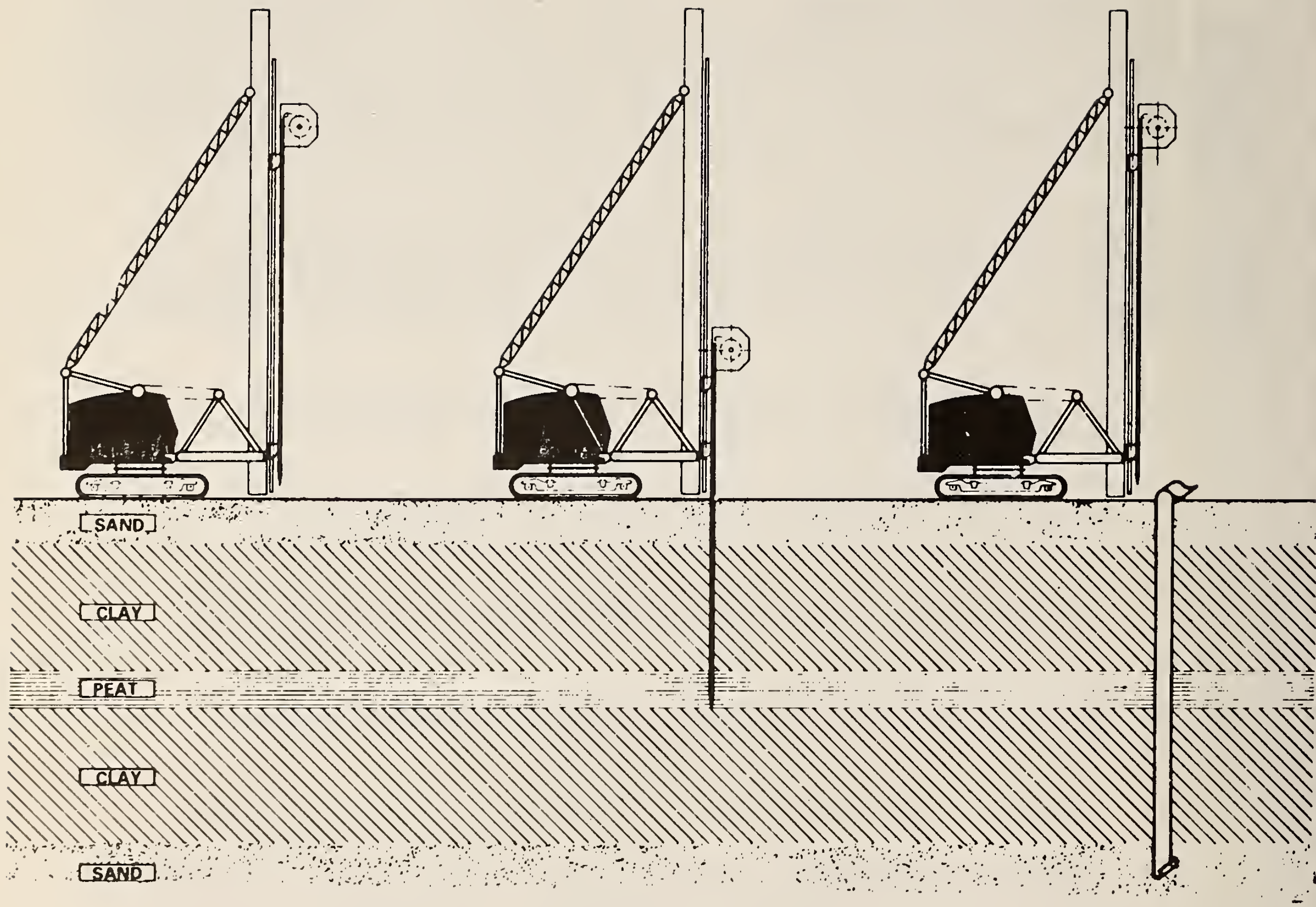


FIGURE 3-18. Procedure for Installation of the Vertical Fabric Drainage Strips [34]

TABLE 3-9. Design Criteria and Properties for Vertical Drains in Soft Soil

CRITERIA	PROPERTIES
Permeability	Initial Permeability Clogging and Blinding Resistance
Durability	Chemical Stability Biological Stability Compressibility
Constructability	Bulkiness (Storage) Weight and Size Tensile Strength Tear Resistance Toughness

3.2.3.3 Horizontal Drains in Embankments

(1) Purpose. The purpose of a horizontal drain in an embankment (Figure 3-19) is to reduce the pore water pressures and accelerate consolidation. An added benefit is derived from the reinforcing properties of the fabric in the role of slope stabilization.

(2) Construction Procedure. The first layer of backfill is placed and compacted as normal. The fabric is then placed on the backfill in overlapping strips. The next layer of backfill is placed on the fabric. The process is repeated until the embankment has reached the desired height.

(3) Possible Failure Modes. Horizontal drains in embankments may fail in a number of ways. The most likely modes of failure are listed below.

(a) The initial fabric permeability and/or thickness may be inadequate to remove the water. The rate of consolidation and embankment stability may be reduced.

(b) The fabric may plug by blinding or biological growth as described in Section 3.1.2, and fail as in (a).

(c) The fabric may be torn or pucntured during construction, either by angular rocks or construction equipment. However, this mode of failure may not be too harmful, as the water would most likely flow around the damaged area.

(d) The fabric may fail by biological deterioration.

(e) The fabric thickness may be reduced by earth loads to such an extent that the water does not drain efficiently. The reduced drainage efficiency may occur as a result of both reduction in thickness and reduction in permeability due to compression of fabric pores.

(f) Special problems may develop for embankments which impound water.

(4) Performance Experience. No documentation on performance experience is available at this time, but there have been some theoretical predictions of their effectiveness [100,101].

(5) Criteria and Properties. To design for a horizontal fabric drain to be used in an embankment, the criteria and properties as listed in Table 3-9 for vertical drains in soft soils should be known. In addition, the following information should be known.

(a) Grain size distribution of the soil.

(b) Loading and consolidation characteristics of the soil deposit.

TABLE 3-10. Drainage Criteria and Properties

CRITERIA	PROPERTIES
Permeability	Initial Permeability Clogging and Blinding Resistance
Durability	Chemical Stability Biological Stability
Constructability	Bulkiness (Storage) Weight and Size Absorption (Wet Weight) Flexibility Bondability Tensile Strength Puncture Resistance Cutting Resistance Seam Strength Tear Strength

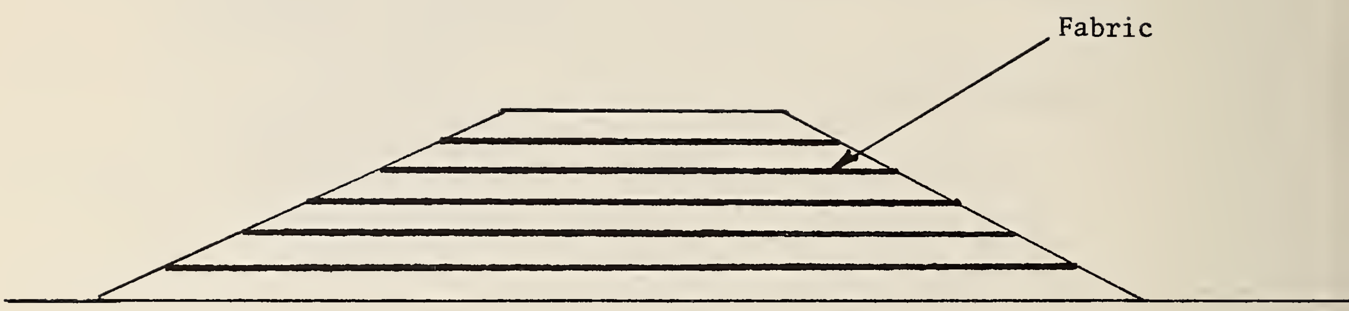


FIGURE 3-19. Horizontal Drains in Embankment

3.2.3 Summary of Criteria and Properties

Criteria and properties for drainage applications are summarized in Table 3-10.

3.2.4 Summary of Tests and Test Conditions

Limited testing has been performed to determine the longitudinal flow rate as required for drainage applications. These tests are listed in Table 3-11 with a brief description of test conditions. The remainder of this section will discuss significant results.

3.2.4.1 P. Risseeuw [34]

Risseeuw investigated the longitudinal fabric permeability under varying compressive loads. Although the test conditions were not entirely analogous to a field situation in that no soil was present, the results did indicate that permeability decreased as the perpendicular load increased.

3.2.4.2 M. Bourdillon [18]

Bourdillon performed tests similar to Risseeuw's. However, the variation of longitudinal permeability with stress did not follow any regular pattern. Bourdillon concluded that the formation of air bubbles in the cylinder prevented the water from flowing freely.

3.3 FABRICS FOR EROSION CONTROL

3.3.1 Introduction

The primary purpose of fabrics used in erosion control is to function as a filter. The mechanisms involved in this type of filtration are similar to those described in Section 3.1.2.

Erosion control may be considered to consist of two distinct elements [35]:

(1) Temporary erosion control during construction activities, and

(2) Permanent erosion control to prevent excessive erosion during post-construction periods.

Temporary erosion control requires that surface runoff be closely controlled by construction procedures and erosion control structures. Not only must the surface runoff from construction sites be controlled, but particulate matter or suspended soil must be filtered from suspension or deposited within the limits of the construction site [35]. Applications of temporary erosion control are listed below:

(1) Silt fences and brush barriers,

(2) Silt screen (dredging),

TABLE 3-11. Drainage Tests in Plane (Longitudinal) Permeability Tests

TEST AUTHOR	EXPRESSION OF TEST RESULTS	TEST CONDITIONS
P. Risseeuw [34]	Total Yield	Constant Head Soil Present
	Permeability	Constant Head No Soil Normal Load Varied
M. Bourdillon [18]	Permeability	Constant Head No Soil Normal Load Varied
A.L. Bell [17]	Permeability	Constant Head No Soil Normal Load Applied

(3) Culvert outlets, and

(4) Seeding and mulching.

Permanent erosion control structures are designed to act as buffers against the natural erosive forces of water movement or against the impact of waves or both. The stability of these structures is totally dependent on the supporting soils that are subject to direct and subsurface water flow. Thus, their design must include a water-permeable filter to prevent backscouring behind the structure and avoid a buildup of hydrostatic pressure that could lead to structural failure [36]. Applications of permanent erosion control are listed below:

(1) Embankment and shoreline stabilization, and

(2) Ditch armoring.

3.3.2 Temporary Erosion Control Applications

3.3.2.1 Silt Fences and Brush Barriers

(1) Purpose. Silt fences and brush barriers are installed to reduce soil erosion with runoff during land-disturbing activities. They retain most soil fines that wash against them and also lower the velocity of the water filtering through the fabric, resulting in less damage to land and streams outside the construction site. Silt fences and brush barriers are not usually utilized where runoff volumes are large.

(2) Construction Procedure. Silt fences are generally fences faced with filter fabric (Figure 3-20). Normally, a stock fence is constructed as shown in Figure 3-20. The fabric roll is cut to the desired height with a chain saw. The fabric is attached to the support system with staples or wire rings with the bottom buried in a trench cut into the ground to prevent sediment from escaping under the fence. The fabric toe can also be backfilled with soil. The height of the fence is from 0.6 - 1.2 m (2 to 4 ft), depending upon the surface area to be drained and the erodability of the soil [37]. Construction in the form of a horseshoe plan aids in the ponding of the runoff and facilitates sedimentation [38]. After construction, the contained sediment is leveled, seeded, and mulched and the fence is removed.

Brush barriers employ branches or similar materials for their support system (Figure 3-21). Fabric is unrolled along the length of the barrier and draped over the brush. The fabric is entrenched or buried to prevent undermining. The fabric covering the brush is secured to the barrier with twine, staples or other suitable devices. Brush barriers do not need to be removed, because deterioration will occur naturally after construction.

(3) Possible Failure Modes. In this application, the fabric can fail in a number of ways. The most likely modes of failure appear to be the following:

(a) The initial fabric permeability may be inadequate to allow

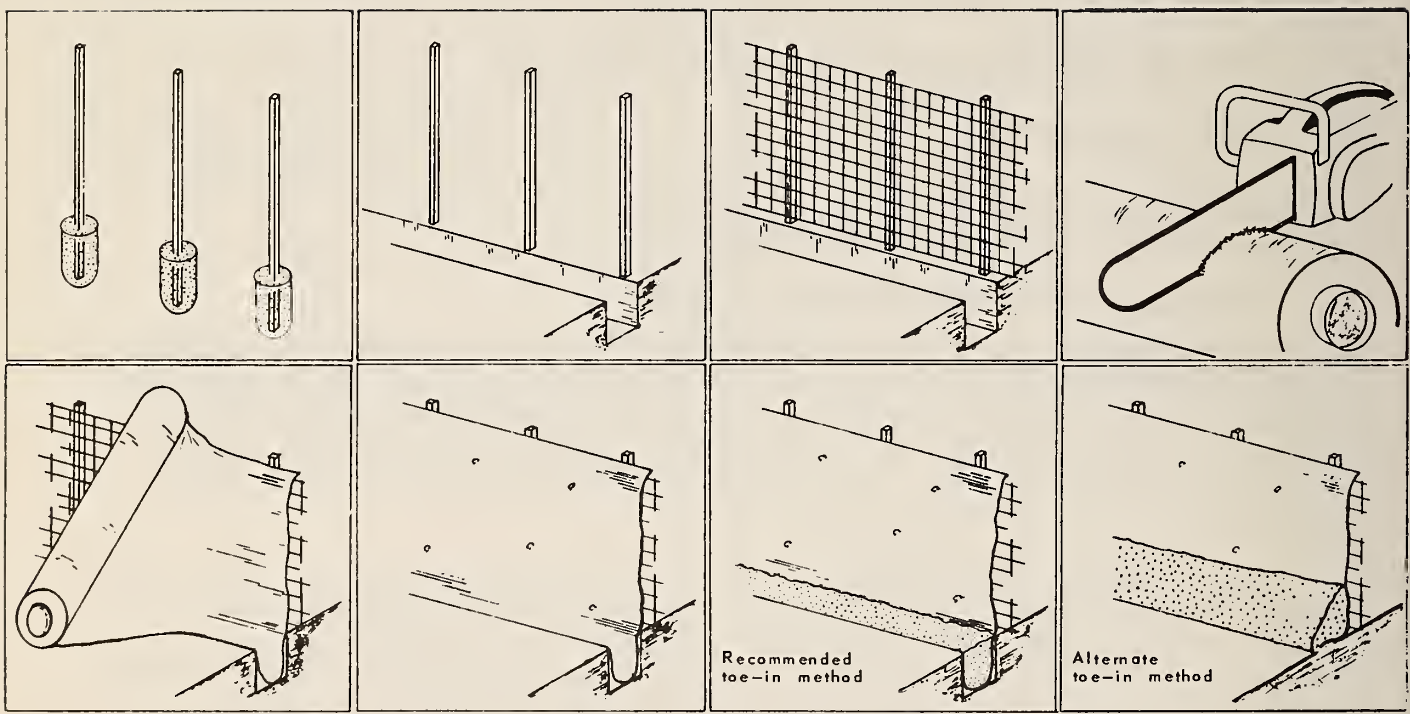


FIGURE 3-20. Installation of a Silt Fence [10]

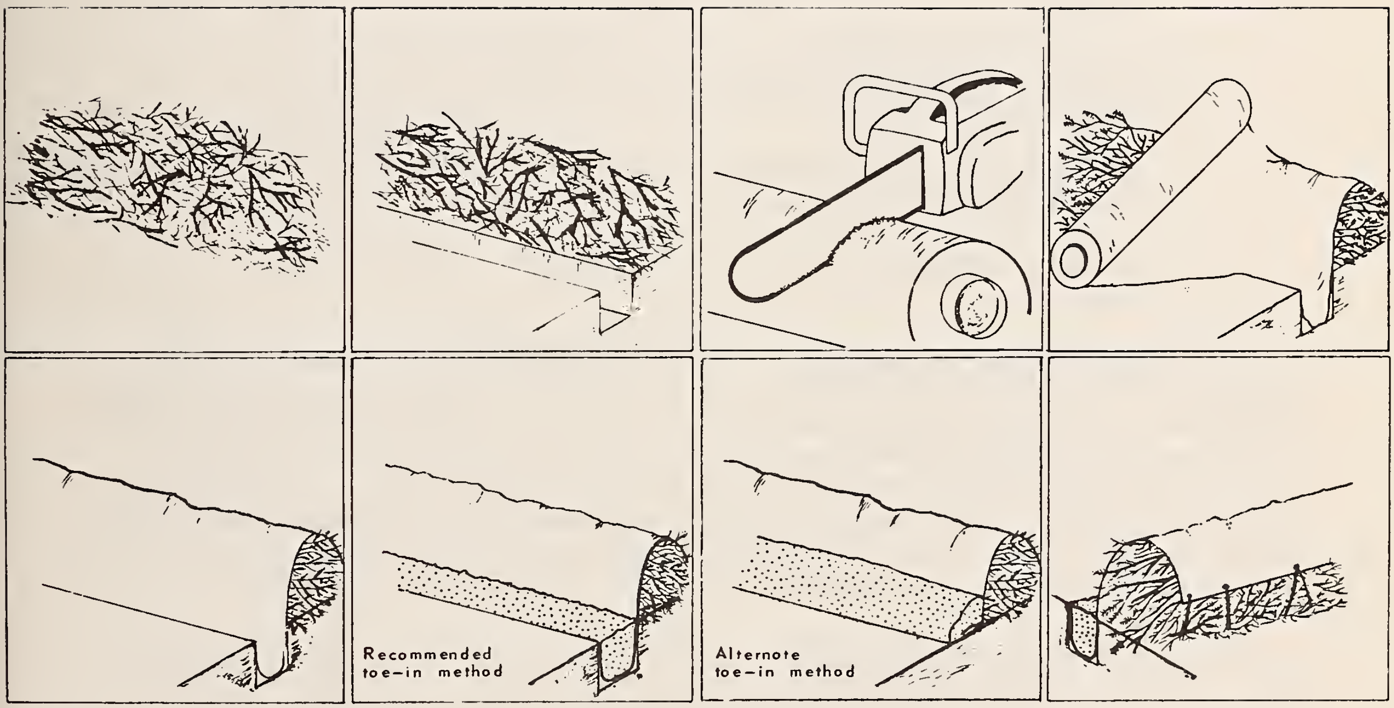


FIGURE 3-21. Installation of a Brush Barrier [10]

the runoff water to pass through it. In this case, the water and suspended soil would build up behind the fence (barrier) and eventually overflow. The fabric may also burst or tear with the same net result or the water pressure may push it over.

(b) Soil particles eroded from the slope may pass through the fence (barrier).

(c) The fabric may deteriorate as a result of exposure to ultraviolet rays. In this case, the fabric would probably lose strength, tear and allow large amounts of soil to be washed away. For short-term control, this ordinarily would not be a problem. It is more likely to occur in longer term applications.

(d) Thermal variations may deteriorate the fabric and cause failure, as in (c).

(e) The fabric may be punctured and/or torn by branches or stones and fail as in (c).

(f) Animals or insects might tear the fabric. Failure would result, as in (c).

(4) Performance Experience. The U.S. Department of Transportation (Region 15) has used silt fences and brush barriers [39]. Early silt fences attempted to utilize burlap, but this was found to deteriorate in about thirty to ninety days. Woven and nonwoven fabrics have both proven to be effective. Both fabrics have been tough, durable and rot-proof. Once one fence is full, a second backup fence is easily constructed. Periodic observation should be made to determine the need for additional fences. Fabrics for silt fences have been used successfully by several agencies [9,35,37,39].

(5) Criteria and Properties. To use fabric for silt fences or brush barriers, the criteria and properties listed in Table 3-12 should be considered. In addition, the following properties should be evaluated:

(a) Grain size distribution of the soil to be filtered,

(b) Estimation of the volume of soil expected to be eroded during construction to determine the number of fences that may eventually be needed to protect the slope,

(c) Flow conditions -- anticipated runoff, water level fluctuations, and

(d) Expected environmental conditions -- temperature and duration of exposure to sunlight.

3.3.2.2 Silt Curtain (Dredging)

(1) Purpose. In the vicinity of open-water pipeline disposal operations, effluent discharges from upland containment areas and small dredging

TABLE 3-12. Design Criteria and Properties for Silt Fences and Brush Barriers

CRITERIA	PROPERTIES
Permeability	Initial Permeability Clogging and Blinding Resistance
Filtration	Piping Resistance
Durability	Chemical Stability Biological Stability Insect and Animal Resistance Thermal Stability Ultraviolet Stability Tensile Strength Tear Resistance Puncture Resistance
Constructability	Weight and Size Flexibility Tensile Strength Tear Resistance Puncture Resistance

operations, installation of a silt curtain is very effective in arresting or controlling turbidity. A silt curtain is a floating vertical barrier designed to be placed around the disturbed portion or the area to be protected. It acts as a temporary dike by interrupting the flow of water and reducing the velocities to the point where suspended solids fall to the bottom or by directing the flow to acceptable areas [40].

(2) Construction Procedure. The fabric forming the curtain is maintained in a vertical position by flotation segments at the top and a ballast along the bottom. A tension cable is often built into the curtain immediately above or below the flotation segments to absorb stress imposed by currents and other hydrodynamic forces. Barrier sections are usually about 30 meters long and of any required width. A system is provided for fastening sections together, as shown in Figure 3-22. Anchor lines hold the curtain in a configuration that is usually U-shaped or circular (Figure 3-23) [41].

(3) Modes of Failure. Silt curtains used for dredging may fail in one or more of the following ways:

(a) The mooring system could be inadequate if such water and particles were allowed to flow freely without filtration.

(b) The fabric could fail due to excessive piping.

(c) The fabric may deteriorate due to ultraviolet exposure. Loss of strength may allow the fabric to tear, thereby permitting water plus suspended solids to flow freely.

(d) The fabric may be torn or punctured by branches or other floating objects and fail as in (c).

(e) High winds or current may damage the curtain.

(4) Performance Experience. Performance experience documentation on silt curtains is not available at this time.

(5) Criteria and Properties. The criteria and properties as listed in Table 3-12 for silt fences and brush barriers also apply to siltscreens. In addition, the following characteristics should be considered.

(a) Grain size distribution and anticipated quantity of soil to be filtered,

(b) Current velocity and direction, quantity of discharge water,

(c) Water depth and levels of turbidity,

(d) Survey of the bottom sediment and vegetation at the site, and

(e) Wind conditions.

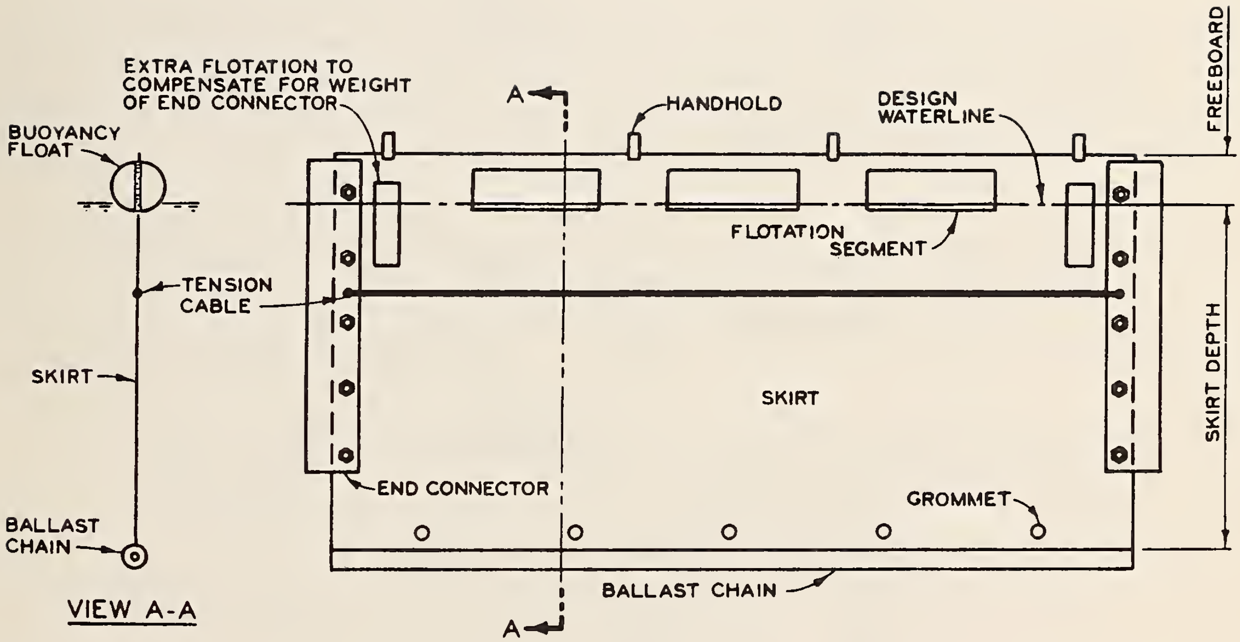


FIGURE 3-22. Typical Center-Tension Silt Curtain [41]

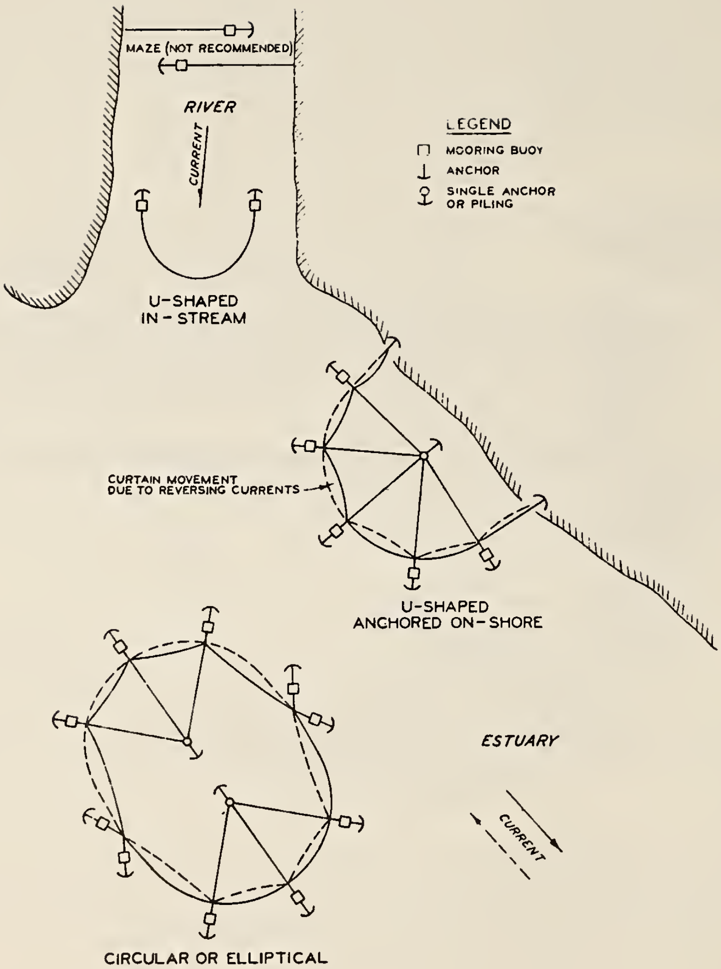


FIGURE 3-23. Typical Silt Curtain Deployment Configurations [41]

Silt curtains cannot be used in all dredging or disposal operations. They are not recommended in the following instances [41]:

(a) Operations in the open ocean,

(b) Operation in currents exceeding one knot,

(c) In areas frequently exposed to high winds and large breaking waves, and

(d) Around hopper or cutterhead dredges where frequent curtain movement would be necessary.

3.3.2.3 Culvert Outlets

(1) Purpose. The use of fabrics below culvert outlets prevents erosion of soils until vegetaion can be established. It prevents sheet and gully erosion and permits the water to soak into the soil. Its role is usually temporary, since without stabilizers, many fabrics degrade in sunlight. Its erosion prevention function is replaced by plant growth or the construction of a permanent protection.

(2) Construction Procedure. A sheet of fabric is placed under the culvert and fixed with stones, staples, pins or other means (Figure 3-24).

(3) Possible Failure Modes. The most likely failure modes for culvert outlets are as listed below.

(a) The fabric can deteriorate due to any of the following factors: exposure to ultraviolet rays, thermal variations, insect or animal invasion. For ultraviolet light resistance, stabilizers should be added.

(b) The fabric could be punctured or torn by branches or stones. Soil erosion would probably increase.

(c) The fabric may be abraded by sediment in the water. Soil erosion may increase.

(4) Performance Experience. The U.S. Forest Service has used fabrics in culvert outlets in several areas. The installations were working adequately when checked after one year [43].

(5) Criteria and Properties. To use fabric for culvert outlets, the information in Table 3-13 should be considered.

3.3.2.4 Seeding and Mulching

(1) Purpose. Synthetic fabrics hold soil and plants firmly in place. They block the force of rain, let needed moisture through, and help control soil temperature and evaporation. After the growth is started, the fabric degrades. (Figure 3-25).

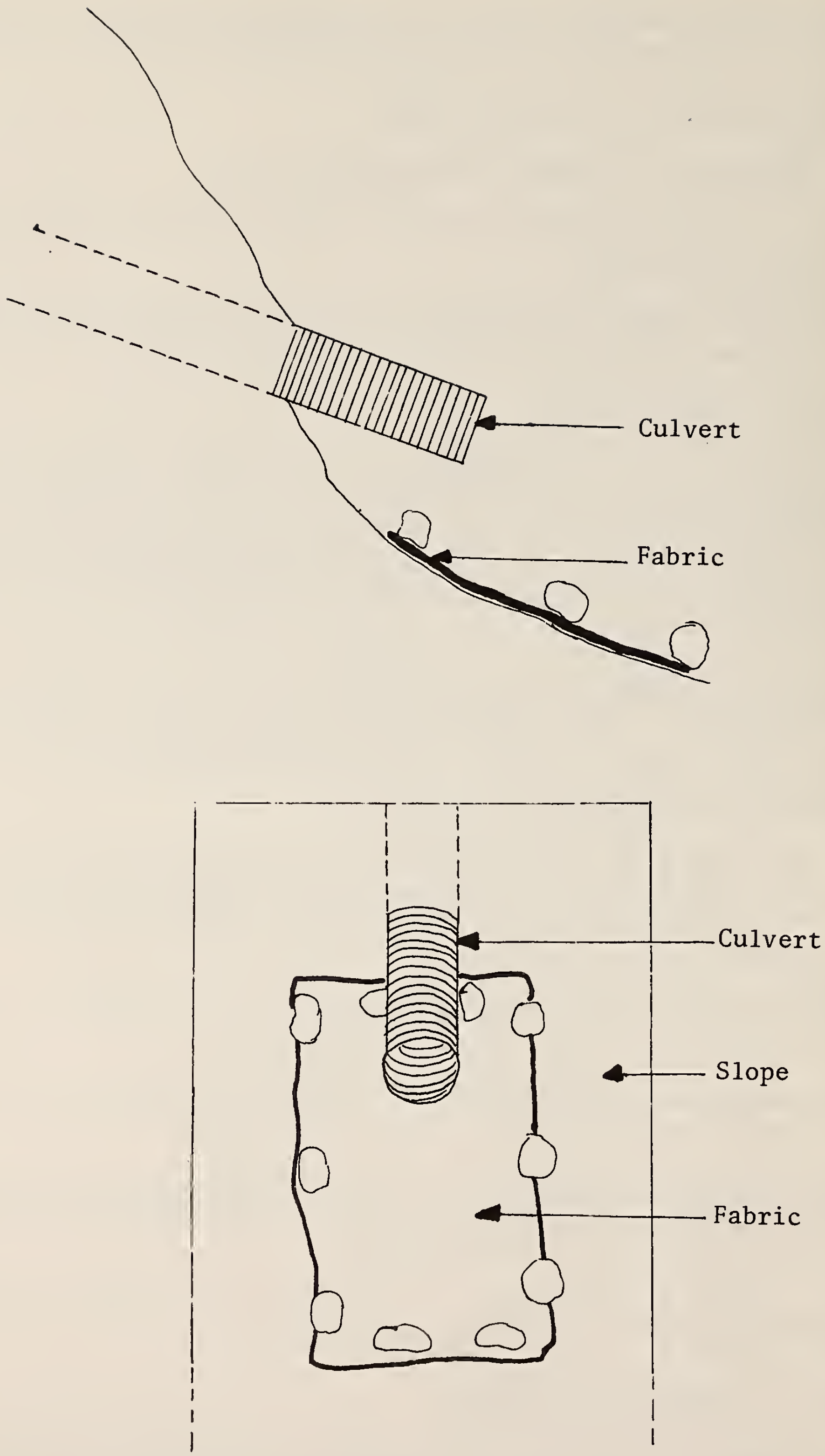
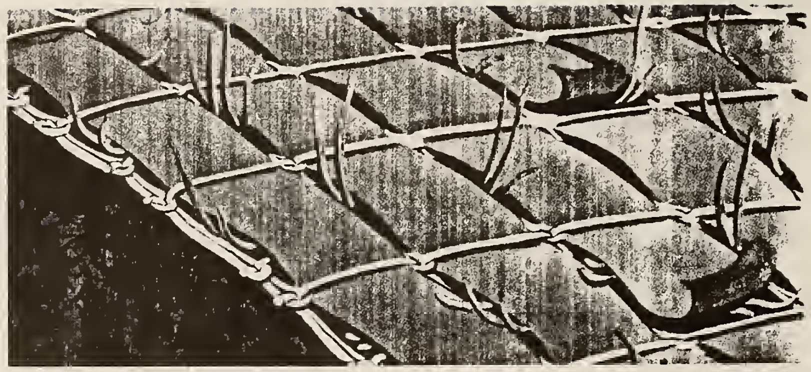


FIGURE 3-24. Fabric used under Culvert Outlets

TABLE 3-13. Design Criteria and Properties for Fabrics used in Culvert Outlets

CRITERIA	PROPERTIES
Durability	Chemical Stability Biological Stability Ultraviolet Stability Abrasion Resistance
Constructability	Tear Resistance Weight and Size



Paper acts as mulch to hold moisture;
it degrades as new growth begins

After paper degrades, the yarn
temporarily supports the root structure

FIGURE 3-25. Fabric Used in Mulching (42)

(2) Construction Procedure. The fabric is laid on the slope that has been previously graded, seeded and fertilized. The fabric ends at the bottom and crown of the slope are tucked into small trenches and secured. It is important that the fabric is in close contact with the soil.

(3) Modes of Failure. The most probable failure modes for fabrics used for mulching are the same as those identified for culvert outlet fabrics (Section 3.3.2.3).

(4) Criteria and Properties. The design criteria and properties recommended for culvert outlet fabrics (Section 3.3.2.3) are also applicable to mulching fabrics, with one exception. Mulching fabrics must be open to allow the vegetation to grow through them.

3.3.3 Permanent Erosion Control Applications

3.3.3.1 Embankment Protection

(1) Purpose. The stability of embankments along coastal shorelines and inland waterways is totally dependent on supporting soils that are subject to both direct and subsurface water flow. The use of fabric filters prevents backscouring behind the structure and avoids a buildup of hydrostatic pressure that could lead to a structural failure. The fabric allows water to pass in and out while retaining soil particles behind it. Fabrics used for embankment and shoreline stabilization include the following applications:

(a) Non-interlocking or interlocking block construction,

(b) Riprap bedding,

(c) Jetties or groins, and

(d) Scour protection around bridge piers.

(2) Construction Procedure. The following recommendations apply for installation of fabrics behind all coastal and riverbank protection structures. Specific instructions for each application will follow.

The fabric is unrolled, loosely laid on the smoothly graded slope, and secured to the embankment. Fabric sections are joined by overlapping and pinning the overlapped strips to the embankment. The fabric may be sewn or stapled in place of overlapping. The fabric should be held firmly in place and conform to the embankment surface irregularities. In rivers, canals and channels, the fabric should be overlapped in the direction of water flow, using the same fastening method above and below the waterline [44]. The fabric must be securely toed in at the top and at the bottom of the embankment, particularly if strong water movements are expected [44]. The revetment is placed on the top of the fabric with care, in order to avoid puncturing or tearing the filter fabric [45].

(a) Non-interlocking and Interlocking Block Construction. Figure 3-26 illustrates the use of fabric beneath an interlocking concrete block revetment. In addition to the plastic filter fabric, there may be a thin layer of crushed rock between the filter cloth and the blocks. The primary function of this layer is to act as a reservoir so that water may be released from the soil and seep through the cracks in the joints of the blocks [45].

(b) Riprap Bedding. Figure 3-27 illustrates the use of a fabric beneath a riprap stone revetment. For severe wave action, a layer of gravel or crushed stone is often placed immediately on top of the filter cloth to act as a pad to prevent rupture of the fabric during placement of the riprap [46,47]. The stone in this pad should be large enough so that it cannot be pulled through the rock layer above it during periods of water level fluctuation. To avoid scour at the toe of the installation, different toe treatments can be applied (see Figure 3-28). Depending on the slope of the embankment and on the material available, revetments can be constructed from gabions (Figure 3-29). The toe is protected by a flexible gabion apron. In this application, it may not be necessary to install a bedding blanket between the filter fabric and gabions [44]. Similarly, riprap can also be placed around bridge piers for scour protection (Figure 3-30).

(c) Jetties or Groins. For jetties or groins, placement of filter fabrics is underwater (Figure 3-31). One of two installation procedures is commonly employed. Both procedures are illustrated in Figures 3-32 and 3-33. In the first method, tubes are sewn in the ends of fabric sheets by lapping the cloth back upon itself. After inserting pipes, the filter sheet is rolled into a roll on the beach. The first roll is secured to the beach at the shoreward terminus of the jetty and is unrolled by use of a yoke on a barge. The operation is repeated by lowering the next roll into position from the barge. Unrolling continues after a 0.6 m (2 ft) overlap has been ensured. Small stones are dropped onto the filter cloth to hold it in position until ensuing steps of construction are undertaken [47].

The second method involves sewing the cloth to a frame of reinforcing material. The frames are picked up by a dragline and placed into position beneath water level. After that, the dragline places the required base course of rubble and uses this as a roadway to walk upon as the construction continues seaward. When the seaward end of the jetty is reached, the dragline places the upper portion of the structure as it goes back to the shore [47]. This method of placement may subject the fabric to additional abrasion or puncture forces from dragline traffic over the fabric.

When rocks and other natural materials are not locally available, considerable savings can be realized by pumping a sand core, covering it with a plastic filter, then a gravel layer, and finally the riprap (Figure 3-34). The

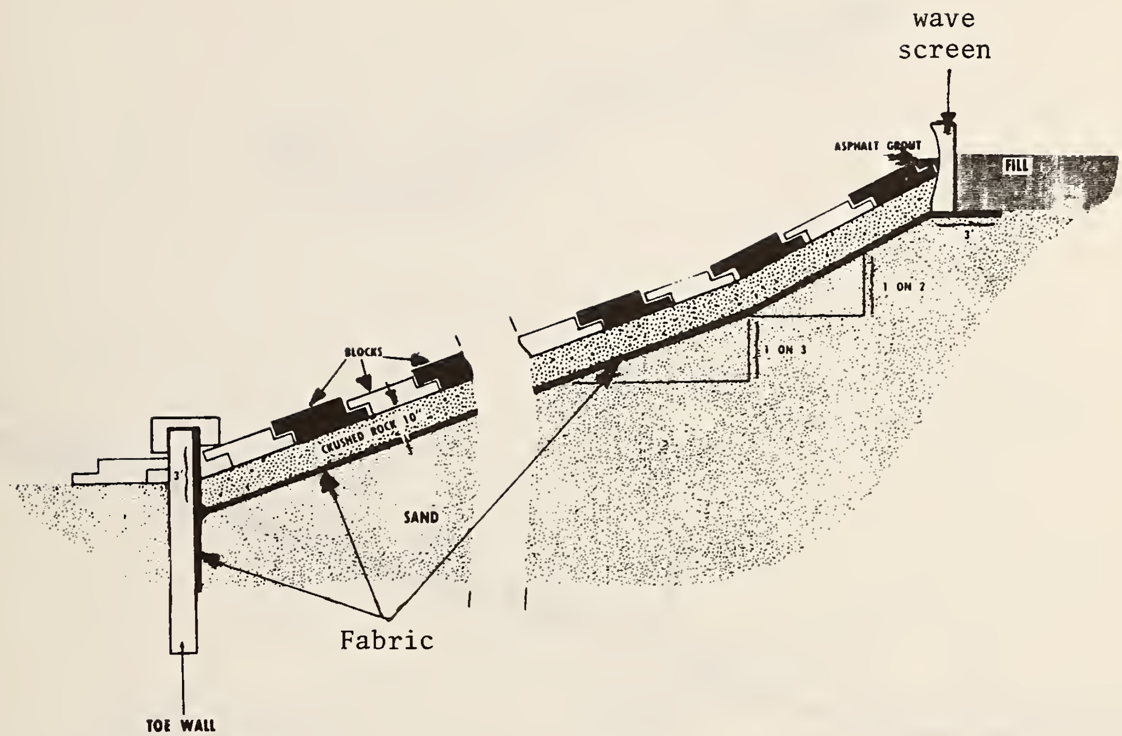


FIGURE 3-26. Example of Interlocking Block Construction [45]

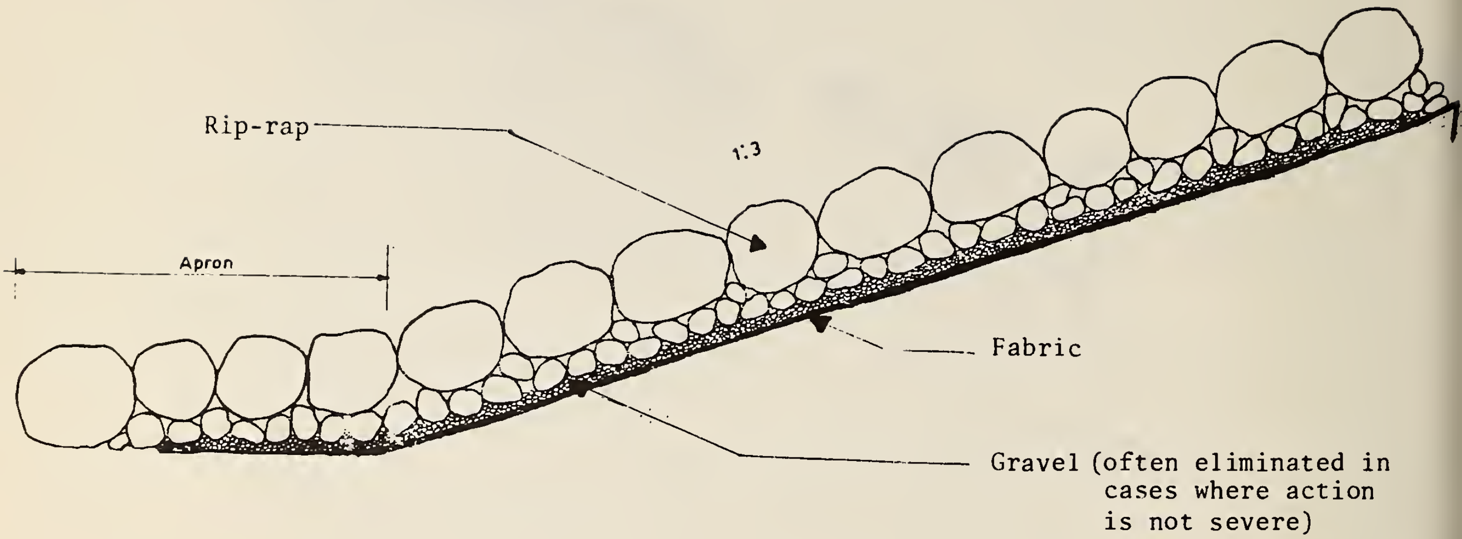


FIGURE 3-27. Example of Fabric Under Rip-Rap for A Revetment with Heavy Armor Stone [46]

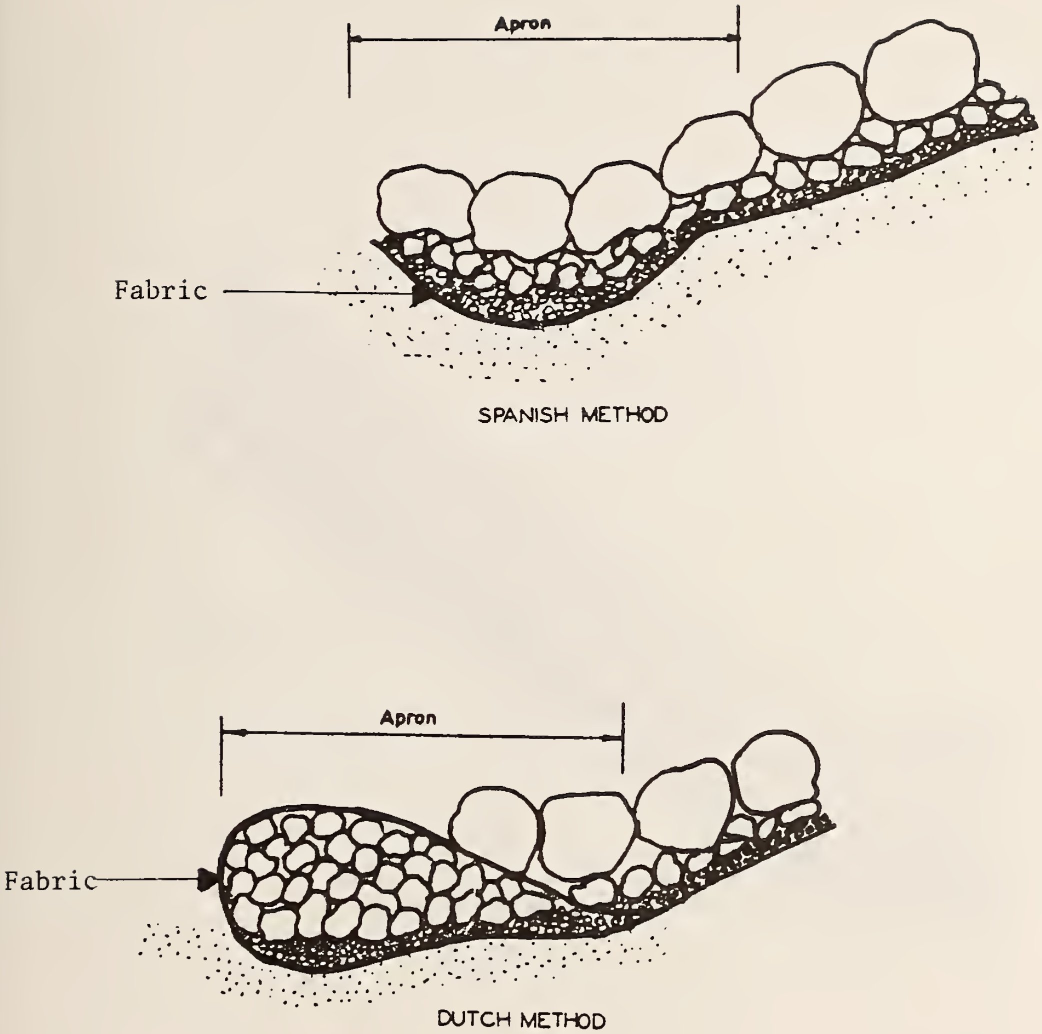


FIGURE 3-28. Alternate Toe Treatments for Rip-Rap Bedding [46]

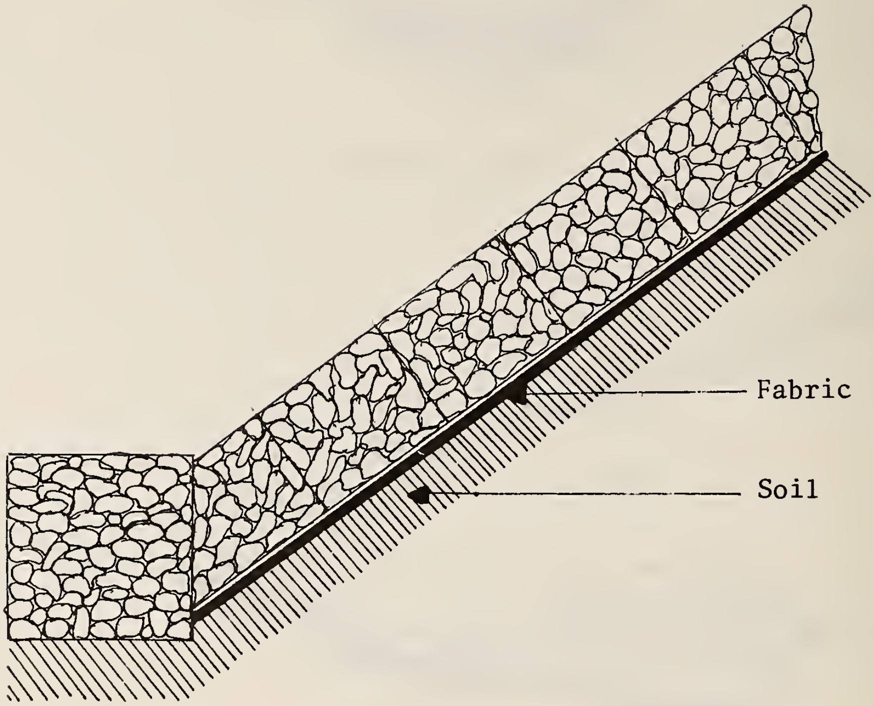


FIGURE 3-29. Section of Gabion Revetment with Fabric [46]

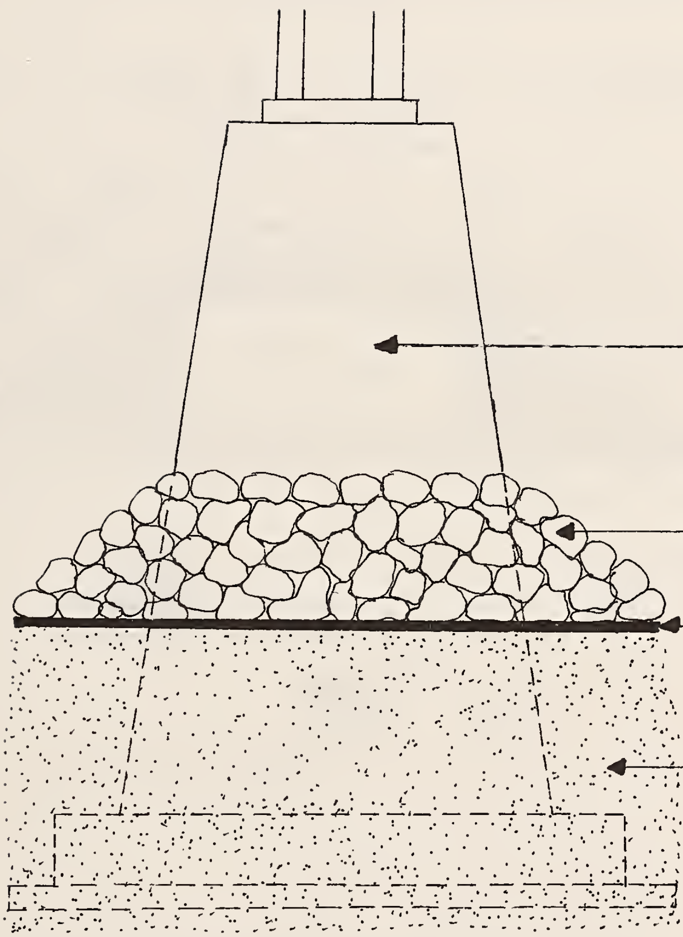


FIGURE 3-30. Scour Protection Around Bridge Pier [36]

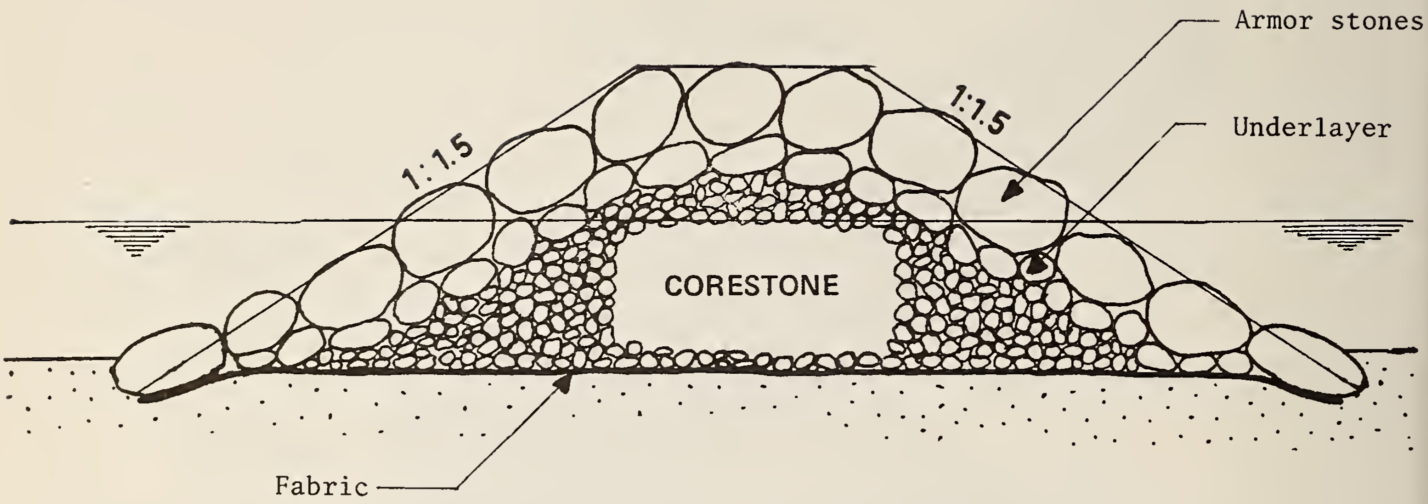


FIGURE 3-31. Rock Groin or Jetty [46]

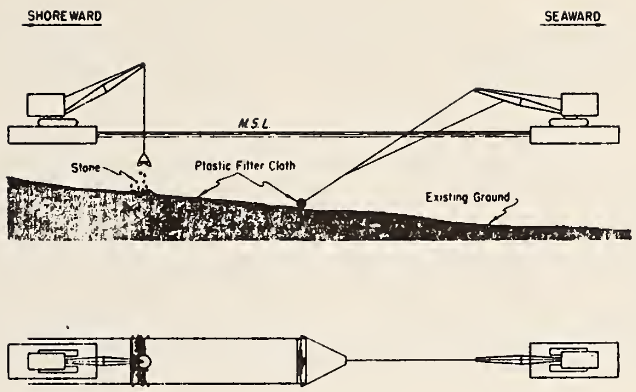


FIGURE 3-32. First Method of Placing and Securing Filter Fabrics Beneath Sea Level [47]

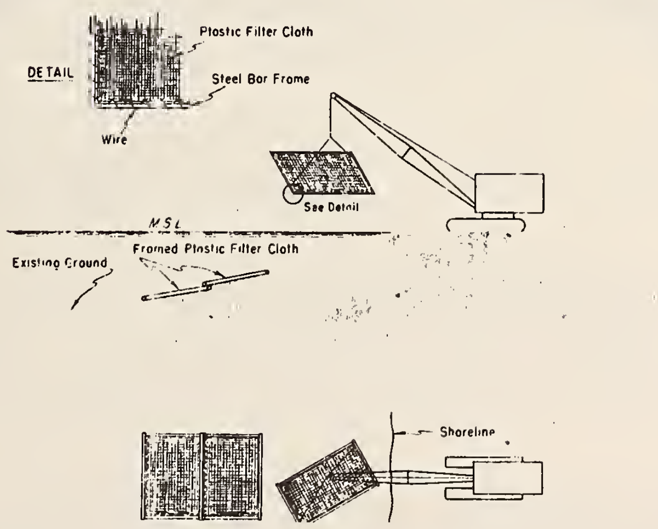


FIGURE 3-33. Second Method of Placing and Securing Filter Fabrics Beneath Sea Level [47]

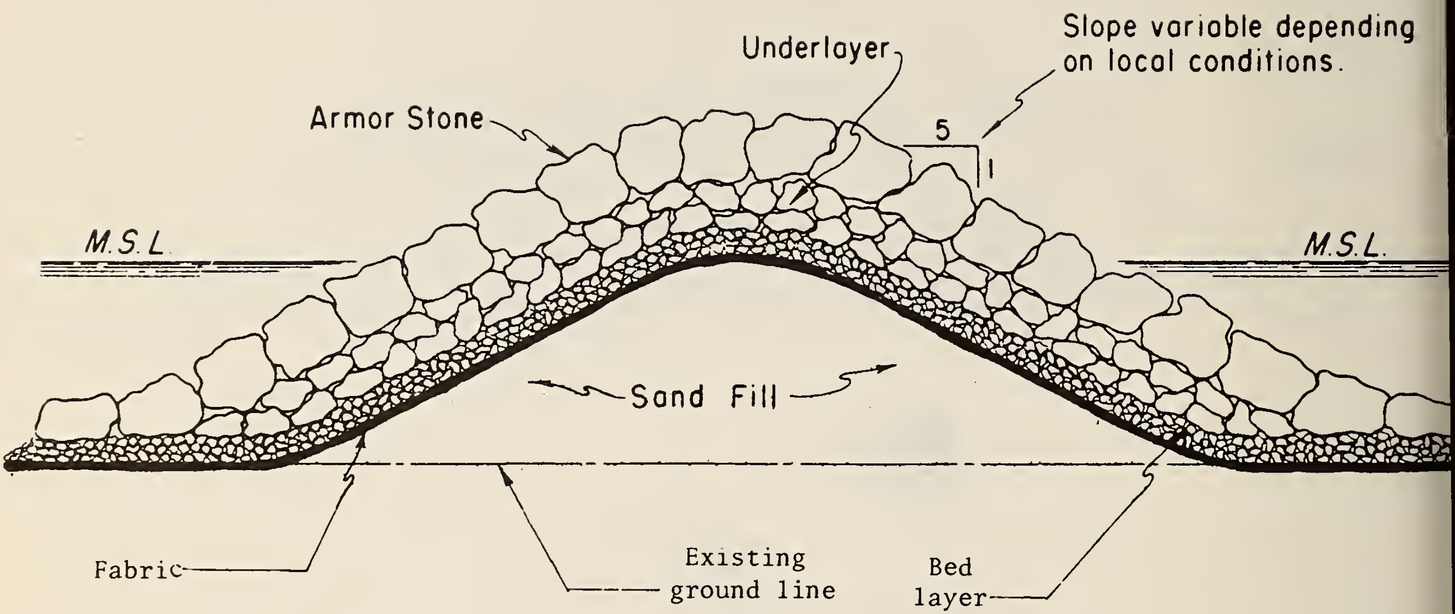


FIGURE 3-34. Fabric Used in Sand Core Jetty [46]

impermeable core prohibits transmittal of energy through the structure to the protected area [47].

(3) Possible Modes of Failure. Fabrics used for shoreline stabilization may fail for a number of reasons. The most likely modes of failure are listed below:

(a) The fabric permeability may be inadequate to allow water to escape freely. Normally, the water level behind an oceanfront revetment drops more slowly than the adjacent sea surface on an ebbing tide, thus creating a head differential. If the void area between stones is large, the soil will eventually move from the weighted area to the unweighted void area, thereby causing the cloth to "balloon" (Figure 3-35) [45,36].

(b) The fabric may clog or blind due to particle deposition, or biological growth. The fabric permeability would be reduced and the probability of "ballooning" would increase.

(c) Excessive piping may occur, resulting in eroded, unstable slopes.

(d) The fabric may deteriorate due to one or more of the following: chemical or biological action, thermal effects, abrasion due to friction between revetment material and fabric caused by wave action or puncturing or tearing during installation or service. In all cases, excessive soil loss may eventually occur, thus degrading the stability of the shoreline slope.

(4) Performance Experience. Barrett has reported several cases where woven fabrics have been used with success in coastal structures [47]. A few cases are summarized below.

(a) Woven monofilament fabrics have been used beneath interlocking block revetments (similar in design to Figure 3-26) in Florida since 1958. The combined length of the revetments is several miles long. As of 1966, there had been no failures, even though some of the structures had been subjected to as many as three hurricane attacks.

(b) A riprap revetment was constructed in Deerfield Beach, Florida in 1962 with rocks weighing from 227 kg to 2270kg (500 pounds to 2-1/2 tons) placed directly on a woven fabric. As of 1966, there had been no settlement of the revetment nor had any maintenance been required. In addition to several storms during the four years, the structure had also been subjected to attack from three hurricanes without experiencing any damage.

The Illinois Department of Transportation reported similar success with a riprap installation utilizing a woven fabric [48]. Minor construction prob-

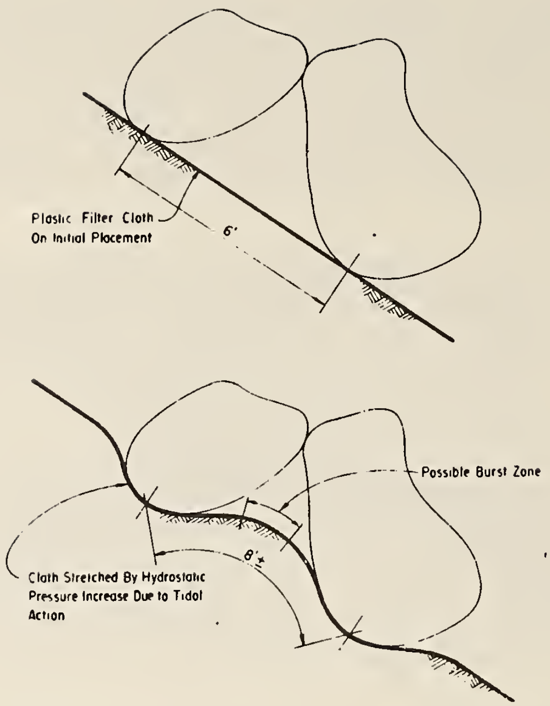


FIGURE 3-35. Ballooning Effect with Large Stones on Slope [45]

lems included the following:

(a) Since the fabric floated when placed into the stream, heavy stones were required to weight it down.

(b) The fabric tore if large rocks (weight/area not known) were dropped from a height of more than three feet.

These problems could be eliminated by good construction practices. After three years of service, no signs of erosion or settlement of the riprap structure was noted.

The Corps of Engineers (Memphis District) has noted problems in four of their 35 riverbank protection projects. In these four projects, ballooning of the fabric occurred over about ten percent of each revetment. These failures were not catastrophic, as the revetment did not collapse. Damage was repaired by slitting the bubble to relieve the pressure built up behind the fabric, then placing a granular filter in the affected area and finally covering with riprap [36].

(5) Criteria and Properties. To design embankment and shoreline stabilization structures, the criteria and properties listed in Table 3-14 should be known. In addition to the criteria and properties listed in Table 3-14, the following information should be known:

(a) Grain size distribution of the embankment material,

(b) Permeability of the embankment material,

(c) Anticipated water level fluctuations,

(d) Severity of wave action or currents,

(e) Temperature conditions,

(f) Chemical nature of water (particularly salinity), and

(g) Applied stresses (riprap loads, etc.).

3.3.4 Summary of Criteria and Properties

Recommended criteria and properties for erosion control applications are summarized in Table 3-15.

3.3.5 Summary of Tests and Test Conditions

Tests measuring erosion control properties are similar to those used to evaluate filtration properties (Section 3.1.5). Reversible and turbulent flow conditions would most nearly simulate field conditions for shoreline stabilization applications. Tests utilizing angular rocks and/or surcharge loads would be analogous to riprap installations. Silt fence and brush

TABLE 3-14. Design Criteria and Properties for Embankment and Shoreline Stabilization

CRITERIA	PROPERTIES
Permeability	Initial Permeability Clogging and Blinding Resistance
Filtration	Piping Resistance
Durability	Chemical Stability Biological Stability Thermal Stability Effect of Loading Condition on Residual Strength Abrasion Resistance
Constructability	Specific Gravity Weight and Size Flexibility Burst Strength Tensile Strength Puncture Resistance Tear Resistance

TABLE 3-15. Erosion Criteria and Properties Summary

CRITERIA	PROPERTIES
Permeability	Transverse Permeability Clogging and Blinding Resistance
Durability	Chemical Stability Biological Stability Thermal Stability Effect of Loading Condition on Residual Strength Abrasion Resistance Animal and Insect Resistance
Filtration	Piping Resistance
Constructability	Weight and Size Absorption (Wet Weight) Specific Gravity Flexibility Tensile Strength Burst and Puncture Resistance Impact Cutting Resistance Seam Strength Tear Strength

barrier installations are simulated in tests utilizing a slurry of soil and water.

3.4 FABRICS FOR REINFORCEMENT AND SEPARATION

3.4.1 Introduction

Fabrics have been used in a number of reinforcement and separation applications. Four general categories of these applications are listed below and are illustrated in Figure 3-36.

(1) Retaining structures,

(2) Embankment reinforcement,

(3) Fill foundation reinforcement, and

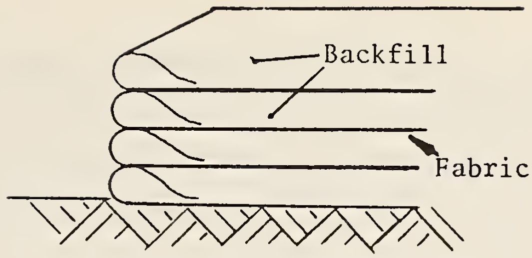
(4) Subgrade stabilization.

In retaining structures, the fabric is included in the backfill to provide tensile strength to the soil-fabric system. The fabric provides stability to the overall system in a manner analogous to that of the steel inclusions in the conventional Reinforced Earth construction. The fabric may be used to form the wall face as well as the reinforcing elements, or it may be used with other facing elements.

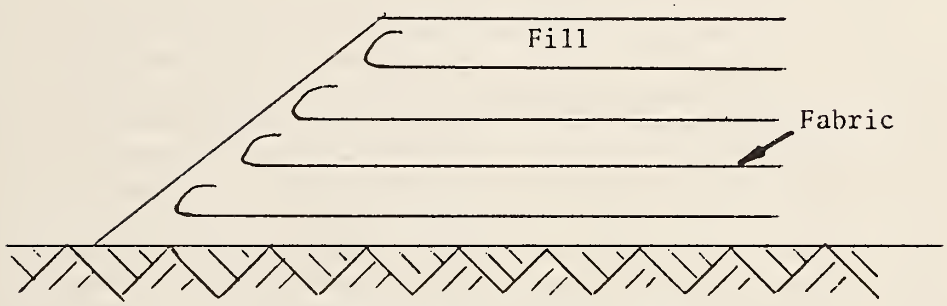
In the embankment reinforcement application, the fabric is used to provide a reinforced soil system similar to that of the retaining structures, except that facing elements are not used. In this case, the embankment face is sloped and stabilized with vegetation or by other means.

When used as a fill foundation reinforcement, one or more fabric layers are included in the embankment near or at the interface with the foundation soil. The fabric provides tensile strength to the bottom of the embankment and also may serve as a shear plane interrupter for potential circular-type failures. For embankments constructed of coarse material over soft, fine-grained foundations, the fabric will also serve as a separation layer. This will prevent the coarse material from penetrating into the foundation and the fine foundation material from working up and contaminating the embankment. This application will usually be limited to relatively low embankments over soft foundations. It has been used for permanent fills for foundations for structures, as storage yards, and as routes of transportation. It has also been used for temporary haul roads and construction working platforms.

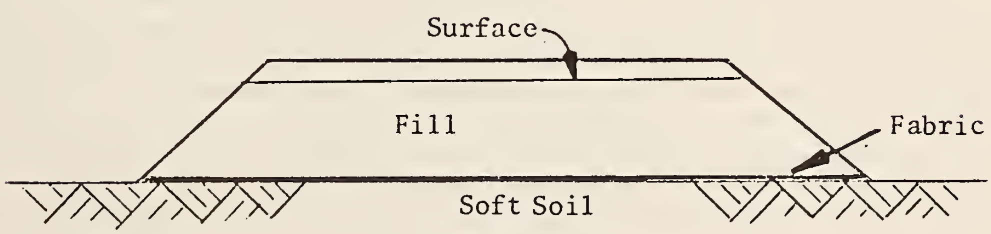
Subgrade stabilization refers to those applications where fabrics are placed between the base course or ballast layer and the subgrade of airports, parking areas, roadways or railroads. It may refer to applications with high class paved roadways or with secondary or temporary aggregate surface haul roads. As the roadway section becomes thick, the distinction between subgrade stabilization and fill foundation reinforcement tends to disappear. In these discussions, fill foundation reinforcement will refer to those cases where the fabric is to prevent a rupture failure from occurring under rela-



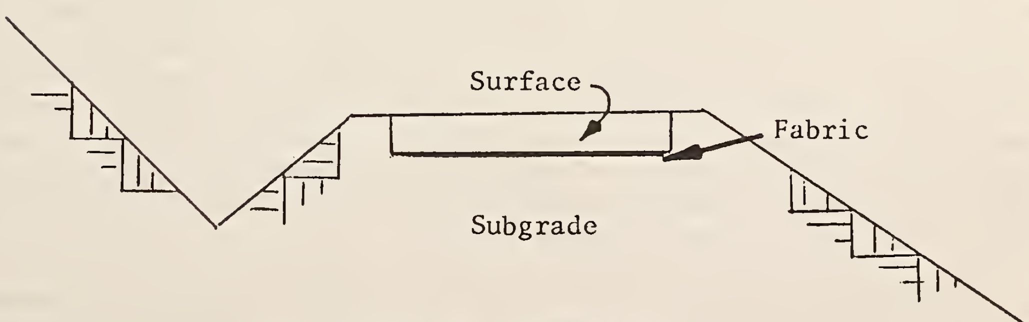
(a) Retaining Structures



(b) Embankment Reinforcement



(c) Fill on Soft Foundation



(d) Subgrade Stabilization

FIGURE 3-36. General Categories of Combined Reinforcement and/or Separation Applications tively few applications of load. The load may be simply the dead weight of the fill or may include an applied load. Subgrade stabilization will refer to those cases where the fabric is intended to prevent failure due to fatigue of the pavement or rutting due to the accumulated inelastic deformations occurring under a relatively large number of load applications. In subgrade stabilization, the fabric may function as either a reinforcing element or a separation layer, or both. As a reinforcing element, it would be intended to reduce deformation under live loads and as a separation layer, it would be intended to prevent penetration of the fine subgrade into a coarser base course either by pumping or intrusion.

All of the above applications are included under the general heading of reinforcement. It must be recognized, however, that the fabric may also be performing the separation function. In the case of the fabric reinforcing the backfill of retaining structures, the fabric is essentially serving only as a reinforcing element. As a fill foundation reinforcement, the reinforcing and separation functions may both be very important. In the case of a fabric for subgrade stabilization under a roadway pavement, where the main purpose of the fabric is to prevent contamination of the subgrade by pumping, it is almost a pure separation function and the reinforcing effect would be very small. The theories of soil reinforcement and separation by fabrics are discussed below. Even though they frequently act together, for convenience in this discussion, they are treated separately.

3.4.2 Reinforcement Theory

The modern concept of soil reinforcement by the inclusion of materials with high tensile strength in the soil mass was developed by Vidal [55] and his coworkers in the early 1960's. Since that time, there have been many studies of reinforced soil, including a number considering fabrics as the reinforcing elements. Retaining walls with fabric sheets for backfill reinforcement were studied by Holtz and Broms [56], and Stilley [57]. Antonini [58] and Al Hussaini [59] studied retaining walls with fabric strips for reinforcement elements. Bell, Greenway and Vischer [60] used finite element techniques to analyze the reinforcing effect of fabrics for fill foundation reinforcement. Lavansiri [61] investigated the reinforcing effect of fabrics in subgrade stabilization by finite element methods.

Yang [62] tested triaxial specimens with fabric reinforcement layers and McGown and Andrews [63] performed an extensive series of tests of the reinforcing effects of fabric inclusions in sands in plane strain. From these studies, it can be concluded that fabrics can be used to provide tensile reinforcement to soil masses. In such applications, the stresses are transferred from the soil to the reinforcing element by friction and/or adhesion between the fabric and the soil, the geometry and spacing of the reinforcing strips or layers, and the orientation of the reinforcement with respect to the direction of maximum shear.

There is no current practical general theory which will allow the analysis of fabric reinforced soil systems for all cases. Different techniques have been applied to different applications of fabric reinforcement. Reasonable theories exist for use with some applications, while only general guidelines are available for others. Because there is no general theory, the four categories of reinforcement applications are discussed separately below.

3.4.2.1 Theory of Fabric Reinforced Retaining Structures

Fabric reinforced structures are similar to the conventional reinforced earth structures which have been studied extensively over the past few years. Therefore, there is considerable literature pertaining to the analysis of this type of construction. There are currently several theories of the behavior of reinforced soil retaining structures. Three of the more popular theories are identified by Hausmann and Vagneron [64] as the rigid block, equivalent homogeneous soil, and failure wedge theories.

In the rigid block theory, the soil is analyzed along the lines of traditional rigid retaining wall analyses with respect to overturning and sliding. The reinforced soil block is so heavily reinforced that failure through the block is not possible.

In the equivalent homogneous soil theory, the soil reinforcement system is replaced by a homogeneous soil with properties such that it will behave as a composite material. In this method the angle of internal friction and/or the cohesion of the actual soil is increased to account for the effects of the reinforcing elements.

The failure wedge concept is the most popular theory and has been researched extensively. This theory, in the forms presented by Lee, et al. [65] and Schlosser and Nguyen [66], is widely used. The general method, as proposed by Lee, has been applied successfully to the design and construction of fabric reinforced walls by Bell, Stilley and Vandre [67]. Broms [68] also has discussed the failure wedge concept with respect to fabric retained walls. This method is based on conventional lateral earth pressure theory. A wedge of soil behind the wall is considered tied back to the stable soil by the tension in the reinforcing elements (Figure 3-37a). The requirements for strength and embedment length of the reinforcing ties can be readily calculated. If used as recommended by the above cited authors, this method is adequate to provide a reasonable design of fabric reinfroced earth walls.

Analysis by the failure wedge theory requires knowledge of the shearing resistance between the fabric and the soil and the tensile strength of the fabric. The selection of the appropriate fabric strength is a problem of considerable importance.

The deformations in a soil mass behind a retaining structure are essentially plane strain. Therefore, the tensile strength of the fabric should be the plane strain strength for that material. Also, failure of a structure is frequently defined in terms of some maximum deformation rather than complete collapse. Therefore, the strength of the fabric should be defined in terms of the stress in the fabric at the strain corresponding to the maximum allowable deformation of the structure, rather than the ultimate rupture strength of the fabric.

Many fabrics tend to creep under sustained loads [56]. This factor must be considered in selecting the allowable stress or strength for the fabric.

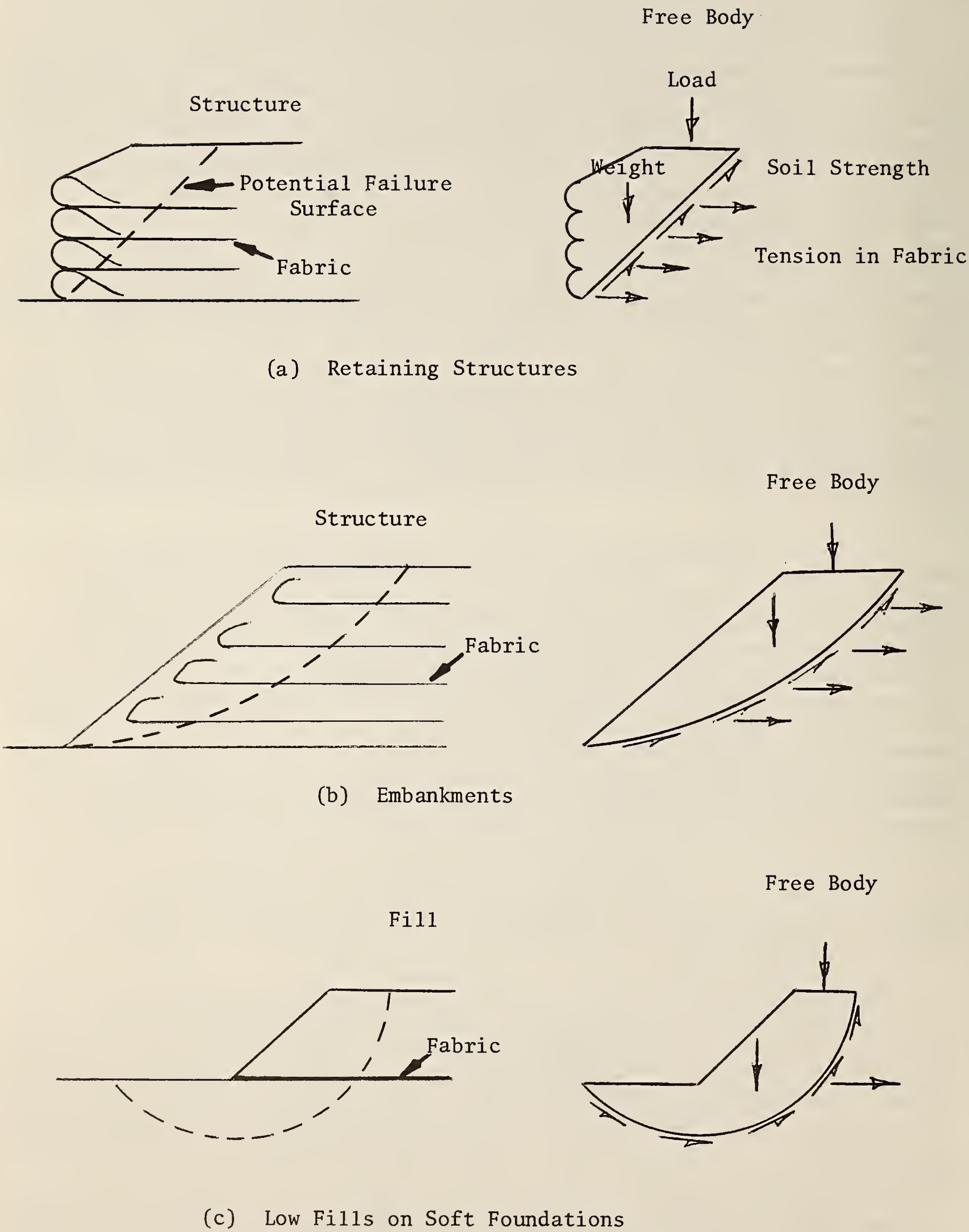


FIGURE 3-37. Failure Mass Concept of Fabric Reinforced Soils

If the sustained deadloads on the structure and the weight of the soil are large relative to the transient loads, static creep conditions would be used to determine the allowable stress in the fabric. If, on the other hand, the live loads are relatively large compared to the sustained deadloads, cyclic creep or fatigue testing would probably be required to determine the strength of the fabric to be used in the analysis.

3.4.2.2 Fabric Reinforced Embankment Theories

Embankment reinforcement is the inclusion of fabric layers in the body of an embankment to improve its stability. This differs from retaining structures in the absence of a wall face and a non-vertical slope. A method of analysis analogous to the sliding wedge method discussed above has been proposed by Christie and El Hadi [89]. This method assumes a discrete mass of soil sliding along some well-defined failure surface which is tied back to the stable portion of the embankment by tension in the reinforcing elements (Figure 3-37b). Christie and El Hadi assume a circular failure surface and their method is a modification of the method of slices commonly used in slope stability analyses. The method could easily be extended to include surfaces other than circular.

This method is very similar in concept to the sliding wedge method. They both assume a sliding mass of soil separated from a stable mass by a well-defined failure surface. The reinforcing elements provide tensile forces across this surface. Implicit in this model is the assumption that both the shearing resistance of the soil and the tensile strength of the reinforcing elements are fully developed. This requires that both the soil and the reinforcing elements are able to yield sufficiently to develop their strength. Unless the reinforcements have extremely high moduli or are prestressed, they will not develop their tension until the fabric has yielded significantly. On soft foundations, prestressing may occur naturally during construction by lateral spreading of the foundation. Materials with high moduli might have to have sufficient strength to provide stability without the full contribution of the soil's shearing resistance. On the other hand, reinforcing members with low moduli might actually require that the soil fail before the full contribution of the reinforcing element would come into play.

Behind the retaining structure, the soil is not capable of standing vertical or near vertical; therefore, it will always yield sufficiently to develop the tension in the reinforcing members. In a reinforced embankment, it might be necessary, however, to literally force the soil to fail during construction to mobilize the tension in the reinforcements to provide the post-construction factor of safety desired.

As in the reinforced retaining structures, the yielding in the reinforced embankment is essentially plane strain. The theory requires a knowledge of the shearing resistance between the reinforcing elements and the soil and the tensile strength of the fabric. The same considerations of strength determination for the fabric apply as discussed above. It is probable, however, that in most cases of this type, the deadloads will dominate and static creep will be a controlling parameter.

3.4.2.3 Fill Foundation Reinforcement

A fabric reinforcement applied at or near the interface between the embankment and the foundation material is generally restricted to relatively low fills on very soft foundations [69]. If the soils are such that the failure will be a general shear failure along a well-defined failure plane, the problem may be analyzed by a method analogous to that for the retaining structure and the reinforced embankment. Volman, Krekt, and Risseeuw presented a modified circular arc method to analyze this particular problem [70]. The general comments directed to the analysis in the preceding section apply to this method as well.

As indicated above, a relatively rational analysis can be made for the case of the general failure on a well-defined surface and where the fabric reinforcement is used to increase the factor of safety against rupture. However, if the purpose of the reinforcement is to prevent failure by long-term plastic deformations, by consolidation of the foundation soil, or to limit elastic deformations under transient loads, theories and methods of analysis are not well-developed. Elastic theory is sometimes used as an approximate method for analyzing problems of this type. However, in this instance, elastic theory does not seem viable. For the case of large plastic flows, it is clear the the soil materials would not be operating in their elastic ranges. For other cases where this condition might be reasonably satisfied, the strains would be very large for the types of situations of interest. Elastic theory is usually limited to conditions of small strain.

The only analytical tool available which might be applicable for these problems is the finite element method. Greenway [69] used this technique to analyze a low fill over muskeg in Alaska. The method may have some usefulness as a research tool; however, it does not appear to be a practical design method. Obtaining the appropriate parameters to describe the behavior of the materials is an extremely difficult task. Also, to handle the boundary conditions and the non-linear, time-dependent nature of the material properties, a very sophisticated finite element program and computers with very large capacities are required to solve the problem. Because of these difficulties with rational analysis, design is usually based on experience, trial and error, or simplified semi-rational models.

Efforts to apply rational analyses to fabrics in low embankments over soft foundations have almost invariably led to the conclusion that the fabric did not produce any benefit due to reinforcing effect [60,71,72]. However, in practice, it has been frequently observed that the use of fabrics does reduce the amount of fill material required to produce a stable embankment by one quarter to one third [60,73,74]. There are at least two possibilities for this inconsistency.

First, it may be that the function of the fabric is as a separator. The benefit may be that the fabric is preventing the fine-grained foundation material from entering the voids in the embankment material and thereby reducing its stability. The fabric may in fact not be providing the reinforcing effect, as indicated by the theory. The second possibility is that the fabric is indeed providing some reinforcement, however not in the form analyzed by the model. The models assume uniform soil layers. In reality, the actual foundation may be quite heterogeneous. In the field, without the fabric the failure may begin as a localized failure at some point of low foundation strength and then spread progressively to include larger volumes. This would result in having to place more fill material to displace the weak and failed soils. With the fabric present, adequate reinforcement to bridge small localized weak areas may be provided, so that the foundation soil behaves more or less as the homogeneous material assumed in the theory. If this is the case, the fabric is essentially forcing the natural material to behave as assumed in the theories. Therefore, the calculations without fabric show essentially the same behavior as the real situation with the fabric, and indicate no benefit, whereas the real benefit is derived from the fabric preventing local failures which the theory does not consider [75].

It is probable that for the foreseeable future, design of fabric reinforcement for low embankments on soft foundations will continue to be by trial and error, past experience, and test embankments. Such theories as are available, however, suggest that the general fabric properties which are important in this application are essentially the same as those discussed in previous reinforcement applications. One exception may be with respect to foundations over muskeg and highly organic materials which consolidate very rapidly. In these cases, the need for the reinforcement would only be until the foundation had consolidated to the point where its increased strength would support the fill loads. For highly permeable materials, this might be only a short time. In these instances, the problem of creep would not be as great as for soft materials of low permeability which would consolidate very slowly. In the latter case, the need for the reinforcement would persist for a long period of time and creep of the fabric would be an important consideration.

3.4.2.4 Roadway Subgrade Reinforcement with Fabrics

The geometry of the system in this application is very similar to that in the previous application of fill foundation reinforcement. The distinction between the two is that fill foundation reinforcement refers to the protection against failure due to excessive shear deformations under one or a very few loads, whereas in subgrade reinforcement, the failure is in the form of a rut developed by accumulating very small non-recoverable strains under many applications of load. In this situation, the stresses developed are much lower than those required to cause the general shear failure referred to in the previous section. In this application there are two main problems:

(1) To establish a theory of stress distribution which will allow calculations of the effect of the fabric on the stresses in the subgrade, and

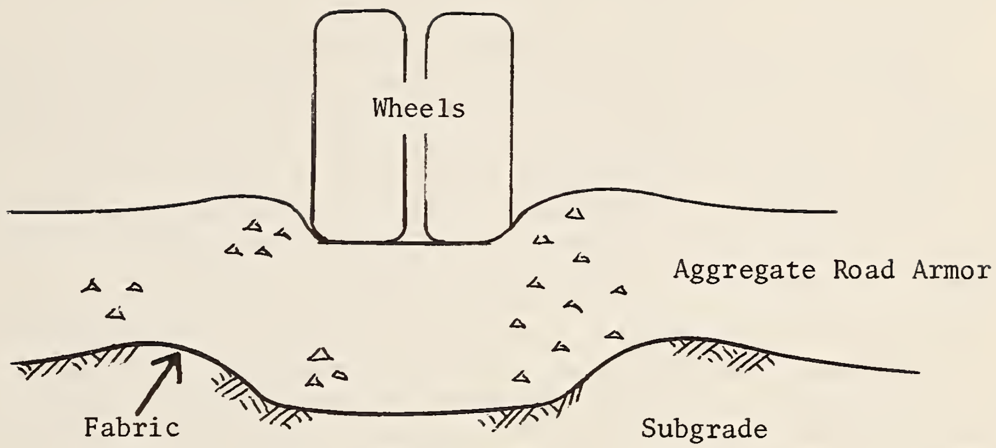
(2) To develop correlations between rut depth and the number and magnitude of stress applications.

There are some well-developed theories which allow the calculation of the required pavement thickness for given numbers of applications of loads for pavement systems without fabrics; however, proven design methods with fabric are not available.

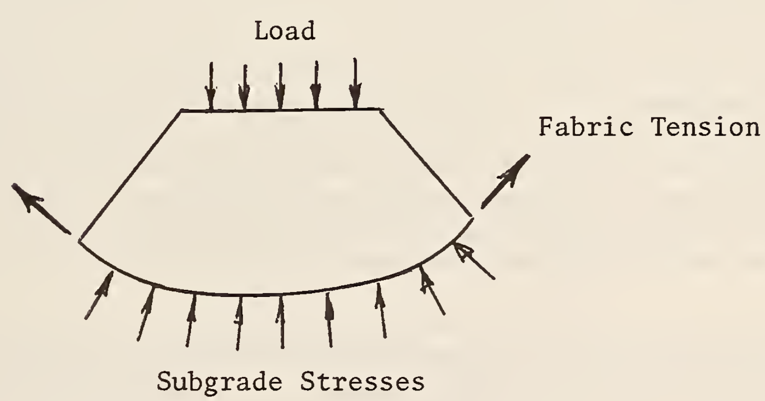
Several attempts to develop design procedures for subgrade reinforcement have been made. Barenburg, et al. [76] developed design procedures based on small scale laboratory tests. There are few actual data to judge the validity of this method when applied to field problems. Intrusion of the subgrade into the base course was not prevented in the tests without fabric. Therefore, there is some question with these tests as to whether the benefit attributed to the fabric was due to reinforcement or separation. Also, these tests were made with one fabric and therefore did not provide a general design procedure which could be applied to other fabrics, since the interpretations were empirical. Lavansiri [61] performed similar but somewhat larger scale laboratory tests. In these tests, intrusion was prevented by using a dense graded base course material. Also, several fabrics were tested. Results were in the same general form as those of Barenburg, but the actual magnitude of the influence of the fabric was somewhat different. These tests were limited in number and the scatter in results between tests with the same fabric was as large or larger than the scatter between tests with different fabrics; therefore, the effect of fabric type and strength is not clarified. Other investigators have tried to calculate the effects of fabric on the rut development in subgrade soils [71,77]. Again, there is no field confirmation of the results. Also, these methods all include assumptions about the stress-strain behavior of the soil, the shape of the fabric deformations, and the distribution of stresses which may be questioned.

At the present time, there does not appear to be a general theory which will calculate the effects of fabrics with specific properties on the rut development in pavements. The theories do, however, give some insight as to the factors which are important. Figure 3-38 illustrates the conditions at the subgrade base course interface after a rut due to traffic loads has begun to develop. The fabric has been stretched so that it is in tension and has been deformed so that the tensile stress has a vertical component to help resist the wheel load. As the wheel load is applied, the subgrade is compressed and the fabric is stretched, increasing the tension in the fabric. This tension will resist the application of the wheel load, reducing the stress increase on the subgrade. This reduces the induced strain in the subgrade and thereby presumably reduces the non-recoverable deformation and rut development. The fabric characteristics which would control tension in the fabric under any wheel load application and rut development would be the resilient modulus of the fabric and the residual tension in the fabric. The tension in the fabric for a given deformation would depend upon the modulus and creep or stress relaxation characteristics of the fabric for the environmental conditions in the pavement.

Even though this is not strictly a plane strain problem, the plane strain tensile test would probably be most appropriate for determining the appropriate fabric properties. Some data concerning fabric creep, both static and cyclic, are available [24]. Also, at least one investigator has attempted to evaluate the dynamic moduli of the fabrics [7]. These data are inadequate for design; however, they do show the importance of these factors and the difficulty of evaluating them with proper considerations for time, rate of loading and temperature conditions. It is clear that the stress strain characteristics of the fabric are so highly dependent upon initial stress level, rate of loading, temperature, and test morphology that analyses without consideration of these factors are essentially meaningless.



(a) Section Through Rutted Roadway



(b) Rut Section Free Body Indicating Major Forces

FIGURE 3-38. Fabric in a Rutted Roadway Section

3.4.2.5 Factors That Affect Reinforcement

From the above sections, it can be seen that the factors which will affect the performance of a fabric reinforcement are many and varied. For purposes of discussion, they may be categorized as fabric, soil, loading, failure mode and geometry, and environment. Each of these are discussed briefly below.

The fabric factors are discussed in previous sections; therefore, they are simply listed here. These factors are the fabric stress-strain characteristics, both static and dynamic, and the time-dependent creep deformation characteristics, both static and cyclic. Also important are the fabric friction and/or adhesion, both fabric-to-fabric and fabric-to-soil. These properties are essential to the theoretical analyses and design. Also, for any practical problem, it is necessary to have a knowledge of the properties required for satisfactory construction, durability and cost.

The fabric reinforcement problems considered are in reality soil-fabric system problems. The performance of the system will be influenced as much and in some cases more by the nature of the soil than the fabric. Also, the nature of the soil may dictate the load and failure mode, and consequently the method of analysis. The main soil properties of importance are the stress-strain (strength) and consolidation characteristics. The strength characteristics of the soil in connection with other factors will determine whether failure is by general shear failure along a well-defined failure surface, general plastic deformation, or by elastic deformation. Relatively stiff soils will tend to fail along well-defined failure surfaces and the methods of analysis described above in Sections 3.4.2.1-3.4.2.3 are likely to be applicable. Very soft soils will tend to flow plastically and these theories will not be appropriate.

The loading is also a very important factor. Very heavy sustained loads will tend to cause failure due to shear or plastic flow under the application of one or very few loads. Lighter loadings will tend to cause only elastic deformations and relatively small inelastic strains. For large sustained loads, the creep of the fabric may be the dominant factor. On the other hand, for small sustained loads but relatively large repetitive loads, fatigue or accumulated small inelastic strains could be critical.

How failure is defined and the geometry of the loading system are also important factors. The failure mode is frequently dictated by the nature of the structure and the use requirements. Some structures can only tolerate very small strains. In this case, the purpose of the reinforcement would be to limit elastic deformation. Others can tolerate very large strains and the purpose of reinforcement would be to prevent total rupture and collapse. Also, the geometry of the system can control whether or not the strains are likely to be plain strain or multiaxial.

The structure and the reinforcing fabric must function properly within their environment. This can vary considerably from site to site and region to region. Environmental factors which might influence the relevant fabric properties include moisture and temperature. Any testing program should properly account for these factors.

3.4.3 Separation Theories

Some of the earliest uses of fabrics in Civil Engineering were with respect to separation under roadways. This has been one of the major applications, and large quantities of fabric materials have been used for this purpose over the years. Even so, the theories of separation are not well developed and methods of analysis are not readily available. Separation as used here is the process of physically separating two materials and preventing their mixing. The purpose is usually to prevent a fine-grained material from entering a coarse-grained material and reducing the stability or permeability of the coarse-grained material. The classic example is the separation of the fine subgrade from the granular base course material under a roadway. For purposes of discussion, separation will be divided into two modes. The prevention of particles moving due to the action of water is similar to the prevention of piping in the filter function, except that in separation, it is in connection with a flow of water induced by the sudden application of an external load. Usually, this load will be a wheel load from some mode of transportation. This process of erosion of the subgrade and transportation of the soil particles by a water flow induced by a rapidly applied wheel load is frequently referred to as "pumping". The second phemomenon considered here will be that of intrusion of the fine subgrade into a coarser granular material by plastic flow due to the application of external forces. This would normally only occur with very soft soils with very high water contents and is a shear failure of the fine material which causes it to be squeezed into the voids in the granular material.

3.4.3.1 Theory of Subgrade Pumping

When stresses are applied to a base course material with water present at the base course subgrade interface, and when the subgrade is a fine-grained soil, pumping may occur. The high stresses cause the granular material at the interface to deform the soft soil and cause it to form a slurry with the water. The excess pressures cause the slurry to squirt up into the base course. The fine suspended soil particles are deposited in the base course and tend to fill its voids, decreasing its permeability and reducing its shearing resistance. For pumping to develop requires high stresses at the interface, free water, pumpable subgrade and a base course open enough to allow the entry of the fine material.

There have been a number of studies of pumping and the general factors are well established, but quantitative evaluations are not possible [79,80]. The actual magnitude of the stresses necessary to initiate pumping are not well defined. Also, it is not possible to clearly define a pumpable soil. It is true that fine-grained soils are the ones which tend to pump. However, it is not always possible to define the degree of susceptibility for a specific fine-grained material. Very fine soils which tend to disperse in water are probably the most susceptible; however, this tendency cannot always be reliably determined. Open graded base courses are clearly susceptible to damage by pumping, but at least one study has indicated that pumping will cause fine-grained soil to migrate further into a well graded base course than for a relatively open-graded base material [80]. However, visual observations have shown that on railroads the subgrade may pump upwards through 45 cm (18 inches) or more of open graded ballast rock. It has long been accepted that the layer of the pavement structure adjacent to the subgrade should satisfy the Terzaghi filter criteria to prevent pumping. There are few definitive studies, however, that establish the validity of these criteria for this purpose.

The purpose of fabric to prevent pumping is to replace the graded granular filter layer at the bottom of the base course. In this case, because of the mechanical action and surging effect of the water below the fabric, the natural soil filter developed in connection with fabrics around drains may not be developed. If this is true, the fabric pores have to be of such size that they will prevent the migration of the fines in the soil water slurry themselves. In considering the typical values of fabric pore diameters and the size of very fine clay-like subgrades, this would lead to the conclusions that fabrics could not prevent pumping of clay subgrades. A laboratory study by the British Railroad Association [81], which is the only pumping study of this type known to the authors, supports this conclusion. For the very fine subgrade soil tested and the conditions of these tests, there was no fabric which completely prevented fines from migrating through the fabric during the application of the pumping loads.

There are, however, numerous installations of fabrics under roadway base courses and railway ballast layers which indicate that many of the fabrics on the market today do effectively prevent pumping of subgrades. However, there are no studies known where the success of the fabric has actually been documented when all of the conditions necessary for pumping were available and the subgrade consisted of a very fine clay-like soil. There are many reports of successes, but none include the measurements of soil properties and performance necessary to prove that fabrics will prevent this occurrence. It may be, however, that the fabrics are effective in these situations and that the fabric layer may prevent the pumping of particles significantly smaller than the pores within the fabric itself. There are several possibilities why this could be:

(1) The fabric might simply provide enough resistance to flow that significant quantities could not pass through the fabric in the very short period of time that the wheel load is applied.

(2) The fabric might cause the build-up of a filter cake layer on the fabric which would prevent a migration of fines.

(3) The presence of the fabric might tend to prevent the formation of the soil-water slurry necessary to transport the soil fines.

The theories of pumping and fabric influences on the phenomenon are not well developed. They do not even show clearly the fabric properties which are important to prevent pumping. All that can be said is that some fabric pore chracteristics of size, shape, tortuosity and distribution are in some way necessary to prevent pumping. There is probably some effective fabric pore size which can be related to some characteristic soil grain size; however, the relationship between these sizes is not clear. Also, it is not clear how the nature of the fabric structure might interact with the actual pore sizes of the fabric to control the effective size of a given fabric with respect to pumping.

3.4.3.2 Theory of Separation with Respect to Intrusion

There is no known theory which attempts to analyze this problem. It is obviously a plastic shear-flow phenomenon. The coarse particles are punched into the soft subgrade and the subgrade material is squeezed up into the voids in the aggregate layer. The relationships between soil strength, aggregate grain size and gradation, and loading are not known. There are no known methods of predicting the amount of intrusion into a base course which can be expected for a given set of conditions.

Numerous installations with fabric separation layers between base courses and subbases have shown that in most situations the fabrics are capable of preventing this type of contamination.

In this application, the fabric physically prevents the penetration of the coarse material into the subgrade and the fine materials from flowing up into the voids of the base course. To do this, the fabric must have some maximum pore size. However, this pore size is considerably larger than would be necessary to prevent pumping, because the soil must flow under the relatively short period of a traffic load and as a plastic solid rather than suspended in a liquid. The fabric must have a high enough strength so that the aggregate particles will not puncture the fabric and the pressure of the subgrade will not cause the fabric to fail by burst across the voids in the aggregate. It is reported that membranes under these conditions fail not by puncture, but rather by burst [82,83]. This is a point which has not been clearly documented for the actual case of subgrade separation. Granular materials have very low tensile strength, therefore, under the center of the wheel load, the base course tends to spread and the voids open, allowing easier access for the soft subgrade. When a fabric is present, it may provide some tensile reinforcement to the bottom of the base course layer to prevent this phenomenon.

The lower zones of base course which have been contaminated with fines either by pumping or intrusion have reduced effectiveness with respect to load bearing capacity. Some design methods have proposed that the base course thickness should be increased by some amount to allow for this reduced effectiveness when fabrics are not used [76,84]. These same methods suggest that when fabrics are used, this difference can be considered in the economic analysis. The problem is that there is no basis for predicting the thickness of the contaminated layer for a given set of conditions.

While quantitative estimates cannot be made, it is clear that the fabrics will tend to prevent the intrusion or pumping of subgrades and that the fabric properties which are important are pore characteristics, friction, strength, puncture resistance, abrasion resistance and burst strength.

3.4.3.3 Factors That Affect Separation

The theories relative to separation are not well developed or quantitative. They do point out the general factors which influence the performance of a fabric separator. These factors can be categorized as fabric, soil, loading, and environmental factors. They are discussed below.

Fabric factors, which include pore characteristics, permeability, strength, abrasion resistance, penetration resistance, burst strength, friction, and creep and fatigue were discussed previously and therefore are not discussed here.

The soil and drainage conditions which are important are grain size, soil plasticity, soil strength, and availability of water. The soil grain size, plasticity, and availability of water, along with loading conditions will determine whether or not the soil-water slurry necessary for pumping develops. Coarse-grained soils will not pump, and it is possible that the fine-grained soils with high cohesion will also not be as susceptible to pumping as those with somewhat less cohesion. The availability of water, of course, is necessary to the pumping phenomenon. For fine-grained soils which are wet and soft, but where there is insufficient free water to cause pumping, the dominant process will be intrusion. Other things being equal, the soils with the lower shear strengths will be more prone to intrusion than stiffer soils.

Loading is important in that, for both pumping and intrusion, high stresses at the subgrade - base course interface are necessary. Also, the rate of loading and the number of load applications during the life of the project will be very important in controlling the amount of pumping or intrusion which will occur. The main environmental factor, other than the presence of water, will probably be temperature. Temperature has significant influence on the stress-strain characteristics of the fabrics. At low temperatures the fabric modulus tends to be higher than at high temperatures. Under these conditions, the fabrics will be more prone to puncture, will probably have lower fatigue resistance and will be more likely to fail under the application of cyclic loads. This temperature effect, of course, may only extend down to approximately 0°C. Below freezing, the ground itself will freeze and be much stronger and the strains and consequently the stresses induced in the fabrics will be greatly reduced.

3.4.4 Applications

The several applications listed in Section 3.4.1 are discussed below. The purpose of each application is stated, then the construction procedures are described and discussed with respect to how they would influence the required fabric properties. Possible failure modes for each application are then discussed to further elaborate the fabric properties required. A brief indication of the type and numbers of installations of each application is given along with a brief evaluation of their general performance. Finally, the criteria and properties required for the fabric in each application, as indicated by all of the discussion, are summarized.

3.4.4.1 Fabric Reinforced Retaining Structures

These structures have been described previously. Their purpose is to provide support for soil backfills and possible surcharge loads on nearly vertical faces. The purpose of the fabric in this case is to provide tensile strength to the soil mass to allow it to stand steeper than its angle of repose and to resist the shearing forces due to the surcharge loadings. The wall may have facings of concrete, steel, timber or other material or in some cases, the fabric itself may form the wall facing.

Detailed descriptions of construction procedures of fabric-retained walls are presented in papers by Bell, et al. [67] and Steward, et al. [84]. A brief discussion of the general construction methods are provided below.

The first step in construction is to prepare the site by excavating to provide foundations which will provide a satisfactory support for the structure. If a wall with facings other than fabric is to be used, it may be necessary to construct a special foundation for the facing itself. Minimum scrapping and excavation is required to provide contact between the fabric and reasonably firm subsoil and to allow for the length of fabric embedment required. Large stones and sharp objects are removed. The next step is to place an appropriate facing element to support the first lift of the wall. This may be either the permanent facing element or a temporary element, serving merely as a form which will be removed as construction proceeds.

Next the fabric is laid directly on the prepared foundation. If the facing elements are permanent, the fabric will be attached to the facing element. If the facing element is a temporary form, sufficient lengths of fabric to provide the facing and overlap are draped over the top of the form.

Suitable backfill is placed over the fabric behind the form to the height of the first wall lift. During this operation, care should be exercised to prevent cutting or puncturing the fabric either by dropping backfill, driving construction equipment directly on the fabric, or driving construction equipment over lifts of backfill material too thin to protect the fabric. The care necessary depends greatly upon the fabric used, the nature of the backfill material, and the type of construction equipment used.

When the backfill has been placed and compacted, the facing element for the next lift is set in place, a new sheet of fabric placed on top of the first fill lift and the backfill operation continued. For fabric faced walls, the excess fabric is folded back over the first lift, the temporary facing element is removed and reset on top of the first lift to support the second. A new sheet of fabric is placed again with overlap over the form and the filling operation continued. These steps are repeated until the desired height of the wall has been obtained. The main considerations with respect to the fabric during construction are that the fabric not be severely punctured, cut or torn by the construction operation, and that construction joints be strong enough to withstand the fabric stresses. Also, if the fabric is particularly flammable or subject to deterioration under ultraviolet exposure, these factors should be known so that the fabric can be adequately protected during storage, transportation, and construction. Other factors of less importance are fabric weight and adsorption. These would be imporant in planning a job so that the fabric could be easily handled by the crew available. Also, highly absorptive fabrics would, if exposed to rainfall, become very heavy and could cause construction difficulties.

Fabric retained walls could fail either during or after construction for a variety of reasons. A few of the more common of these related to the fabrics themselves are discussed below. The most obvious type of failure would be due to the rupture of the fabric reinforcing elements due to excessive stresses in the fabric. If this occurred during or shortly after construction it would probably result from an error in design or in estimating the loads which would be imposed on the structure. The long-term effects, however, should be considered for many cases and the durability of the fabric with respect to its ability to retain its strength upon exposure to the appropriate environmental factors would also be important. This might involve deterioration of the fabric due to chemical or biological activities. It is also possible that some fabrics might be strain-softening and that long-term creep could reduce the tensile strength and cause future rupture.

It is also possible that the walls incorporating the fabric as a facing element could fail due to failure of the fabric in the face. This is unlikely during construction or in the short term immediately after construction, because the stresses in the facing are much lower than those in the reinforcing member. However, the faces may be subject to exposure to ultraviolet light, vandalism, fire and other factors which the buried reinforcing portion is not. Long-term face failures are probably more likely than long-term embedded reinforcing component failures.

Another failure mode would be failure of the embedded reinforcing elements by pullout due to slipping at the interface between the fabric and the soil, rather than actual rupture of the fabric itself. Resistance to this type of failure is provided by the friction and/or adhesion between the fabric and soil. Therefore, it is necessary that this factor also be evaluated.

Walls may fail, in that they would no longer be able to perform their intended function, even though there was not an actual collapse due to pullout or rupture, if the reinforcing elements were to elongate excessively. This characteristic would be controlled by the stress-strain characteristics of the fabric and creep. If the dead loads constitute the major loading on the fabric, steady-state creep would dominate, but if live loads are more significant, cyclic creep would be most important.

Other types of failure unrelated to the fabric itself are also possible. Facing elements in walls which incorporate materials other than the fabric itself could fail. A more likely type of failure would be a soil failure outside of the reinforced soil mass. It would be possible that the foundation would be incapable of supporting the weight of the wall and a deep bearing failure could occur. Or the whole soil, fabric, reinforced system could fail by sliding along its base. A general slope stability failure with the failure mass including the wall, foundation and part of the hill above the wall is also a possibility that should be analyzed.

The preceding considerations of possible failure modes show that the satisfactory performance of the fabric depends also on those properties indicated by the basic theories and upon satisfactory durability characteristics so that the properties of the fabrics will not deteriorate excessively over the design life of the structure.

Only a few fabric reinforced retaining walls have ever been built.

Several investigators have performed laboratory model tests of fabric retained walls and four studies of actual walls or model walls of this type were reported at the 1977 Paris Conference on Fabrics in Geotechniques [25,27,56,86]. It is understood that other walls of this type have been constructed in Europe; however, documentation of these walls is not available [87]. In general, the experience with fabric retained walls has been satisfactory. The current state of knowledge allows us to rationally design and construct fabric retained walls which will perform satisfactorily at least for several years. It is anticipated that future use of fabric as reinforcement for this type of structure will become fairly common. It is believed that the greatest use will be for fabric as the embedded reinforcement element used in connection with concrete, steel, timber, or other facing elements.

From the above discussions it is apparent that for satisfactory and economical performance, fabric retained earth walls must satisfy criteria with respect to mechanical performance, constructability, durability and economy. These criteria and the associated properties for this type of structure are listed in Table 3-16. The properties are discussed above in their appropriate place and these discussions are not repeated here. The tests necessary to evaluate these properties are discussed in a later section.

3.4.4.2 Fabric Reinforced Embankments

The fabric reinforced embankment has been described previously. The purpose is to increase the stability of the embankment over that of an unreinforced embankment and/or to allow construction of the embankment with steeper side slopes.

Construction of reinforced embankments would require very little variation from conventional construction methods. Foundations would be prepared in the usual manner and a sheet of fabric would be placed on the foundation soil. The fabric might be continuous across the full base of the embankment or might only be placed on each side in the zone of maximum shear. Soil would be compacted over the fabric in the usual manner. The only precautions might be to use some care to see that the fabric was not torn or punctured by the constructure operation. This was discussed in the section on Fabric Retained Structures.

It would usually be necessary to join the fabric sheets to give the covering necessary. Such joints could usually be given the desired strength by providing an adequate overlap of the two fabric sections. It is also possible that the fabric joints could be sewn or they could be bonded either by welding or gluing. It may be necessary to hold the fabric down to prevent wind from disturbing it until the soil can be placed on the fabric. This could be accomplished by using pins or weighting the fabric with piles of soil or rocks. Where wind is a problem, it is sometimes desirable to staple overlapped joints. In this case, the stapling is merely to hold the joints together to prevent wind disturbance and is not to add tensile strength. The strength would still be provided by friction between the two fabric segments. Other general construction considerations would be as discussed in the previous section on Fabric Retained Structures.

TABLE 3-16. Criteria and Properties for Fabric Reinforcement in Retaining Structures

CRITERIA	PROPERTIES*
Constructability	Strength Ultraviolet Light Stability Flammability Thickness Weight Absorption Puncture Resistance Cutting Resistance
Durability	Ultraviolet Light Stability Chemical Resistance Wetting and Drying Stability Biological Resistance
Mechanical	Tensile Strength Modulus - Static Friction/Adhesion Fatigue Creep - Static Creep - Dynamic Seam Strength
Hydraulic	Initial Permeability

*All may not be important for every application.

Embankment failures involving fabric would be either rupture of the fabrice by excessive tensile stresses, excessive deformations due to stretching of the fabric, or pullout of the fabric segments allowing the embankment to fail either by spreading or rotation. These modes of failure are all very similar to those discussed relative to the fabric retained structures.

As in all of the structures, it would be necessary to analyze the overall stability of the structure and its foundation. It would be possible for a foundation failure to occur which did not involve a fabric failure.

There is no significant performance experience record documenting fabric reinforced embankments. There have been theoretical considerations [88,89] of such structures, but no known cases of actual structures being built.

Except for factors relating to the durability of the fabrics when used as a facing element, the criteria and properties relating to fabric reinforced embankments are the same as those for fabric reinforced structures, presented in Table 3-16.

3.4.4.3 Reinforced Low Embankments on Soft Foundations

The use of fabrics in the base of low embankments has been described previously. The purpose of the fabric in this application is to facilitate construction, add tensile strength to the bottom of the fill and/or reinforce the foundation, and to provide a separation layer to prevent the fine grained foundation material from contaminating the embankment and reducing its stability.

The first step in construction is to prepare the subgrade surface by removing large, sharp objects and major irregularities. It is usually desirable to do this with a minimum disturbance to the natural vegetation root mat as possible. Then the fabric is rolled out over the prepared foundation. If to provide the fabric width required, it is necessary to join fabric sections, the seam can be made by overlapping, welding, sewing, or bonding, as discussed previously. The fill material is then placed over the fabric by end dumping from trucks and spreading by dozer or other appropriate equipment. The trucks should dump rock some distance back from the end of the fill and it should be pushed forward onto the fabric by dozer. If heavy trucks back up to the very end of the fill, then dump directly on the fabric, it is highly probable that the fabric will be overstressed. This will either cause damage to the fabric, failure of the foundation, or require using a very heavy fabric to withstand construction stresses greater than design stresses. This may be uneconomical. Construction is usually simple and requires only minimum special consideration to prevent damage to the fabric during construction. The questions of handling and protection during construction are similar to those discussed in the preceding two applications.

Low embankments over soft foundations can fail in a variety of ways. There are several modes of failure which do not involve the fabric significantly. These include consolidation of the foundation, a general foundation shear failure, and excessive elastic deformations of the system. As discussed in the theory section, presence of the fabrics will have very little influence on these problems except that it may help to mobilize strength of soft foundations by accelerating consolidation.

The failures which would involve the fabric are a spreading failure of the embankment or a bearing failure of the foundation with the failure plane passing through the embankment itself. These failures could involve either an actual tensile rupture of the fabric, excessive deformations of the fabric and/or slipping of the embankment material on the fabric surface. If the dead load of the embankment is a considerable portion of the total loads on the structure, the creep characteristics of the fabric may be important in controlling the deformations under load. However, in many instances, with low embankments designed to support transportation routes, the live loads tend to dominate. In these cases, the deformations may be the result of cyclic creep.

In this application, in addition to reinforcement, one of the functions of the fabric is to separate the embankment material and the foundation soil. Therefore, failure could involve excessive movement of the fine subgrade material through the fabric or through local failures in the fabric due to puncture by the embankment material or burst of the fabric over voids in the embankment. A few local failures of this type might not seriously impair the reinforcing function, but could seriously reduce the ability to perform the separation function.

There are many examples of successful applications of fabric for this purpose. When appropriate fabrics are used for the specific site condition, such embankments have been successfully used for highways, secondary roads, industrial sites, storage yards, and many other purposes. These experiences include applications all over the world and involving many agencies, including the U.S. Forest Service, several highway departments, and the U.S. Corps of Engineers, to name only a few.

The criteria and fabric properties required for satisfactory use as a reinforcement for low fills over soft foundations are presented in Table 3-17. These factors were all discussed previously and the discussions are not repeated here.

3.4.4.4 Fabrics for Subgrade Stabilization

As discussed previously, the purpose of the fabric in subgrade stabilization is to prevent the development of ruts due to the gradual accumulation of small inelastic deformations under repeated loadings. This is opposed to the shear failure due to plastic deformation under a few applications of load as discussed in the reinforcement of fills over soft foundations. Ruts in the pavement can develop either from the accumulated strains in the subgrade or from accumulated irreversible strains in the base course material itself. A situation may be aggravated by the contamination of the base course by the subgrade material either from pumping or intrusion. Therefore, the functions of the fabric in subgrade stabilization are to reinforce and/or to provide separation.

Construction is essentially as described for low embankments on soft foundations. A couple of differences do, however, occur. One is that in this application the subgrade may be quite firm. This will allow use of different equipment and somewhat different procedures. The general considerations of protecting the fabric during construction, however, are essentially unchanged. If the subgrade is firm, it may change the requirements, however, for the

TABLE 3-17. Criteria and Properties for Fabric Reinforcement of Low Embankments on Soft Foundations

CRITERIA	PROPERTIES*
Constructability	Strength Failure Elongation Tear Resistance Ultraviolet Light Stability Flammability Thickness Weight Absorption Puncture Resistance Burst Strength
Durability	Chemical Resistance Biological Resistance
Mechanical	Tensile Strength Modulus - Static Friction/Adhesion Fatigue Creep - Static Creep - Dynamic Seam Strength Failure Elongation
Hydraulic	Initial Permeability Pore Characteristics

*All may not be important for every application

failure elongation of the fabric because in this case the fabric will not be subjected to large strains. If the application is one of separation to prevent contamination of an asphalt stabilized base course, temperature stability of the fabric might be important if a hot mix were being used.

In the subgrade stabilization application, failure would occur either by the development of excessive ruts in the roadway surface or cracking of a pavement due to excessive repeated deformation. Failure will rarely be due to actual tensile rupture of the fabric. It will be due to excessive deformations of the fabric, slipping of the base course at the fabric contact, or failure of the fabric to provide separation, and therefore contamination of the base by the subgrade material.

Failure by fatigue cracking of a pavement due to excessive elastic deformations will probably be controlled by the base and subgrade materials exclusive of the fabric. It is improbable that any of the currently existing fabrics have a high enough initial modulus to significantly reduce the elastic deformations of a pavement system under traffic loads.

If the subgrade is quite firm, rutting could develop by spreading of the base course material due either to slipping of the base on the fabric or movement of the base with the extension of the fabric as the load is applied, resulting in lateral deformations which would not be recovered when the load was removed. This type of failure has been postulated, but it involves a complex relationship between the loads, base course, fabric modulus, the modulus of the subgrade, and the friction and/or adhesion between the fabric and the base in the subgrade. While such failure appears possible, it has not been documented. It has however, been suggested by some test results [98].

A more common problem is the development of ruts in the subgrade surface and the resulting rutting of the roadway surface. As the rut develops, the fabric is deformed so that it is placed in tension in such a manner that this tensile stress in the fabric resists further rutting of the subgrade. The ability of the fabric to resist further rutting in this configuration depends upon its static modulus, dynamic modulus, and creep or relaxation tendencies. Since the largest stresses in the fabric are due to the transient wheel loads, the creep must be considered in terms of a cyclic creep in addition to static creep.

The other possible failure mode is that the fabric should not satisfy its separation function. It could fail in this mode either by having pores too large which would let excessive fine material pass through the fabric, or by the bursting of the fabric due to very high pressure from the soft saturated subgrades, which would then allow contamination of the base course.

In addition to the durability considerations discussed with respect to the other applications, abrasion could be a significant factor in this application. This would be true especially if the fabric were placed with granular material both above and below it. In this situation, the stresses from the heavy wheel loads could cause the aggregate particles to abrade the fabric and create holes which would contribute to the pumping or intrusion of fine material into the base course.

Subgrade stabilization is one of the earliest and most often used applications of fabrics. Fabrics have been shown to be effective for airports, both low class and high class highway pavements, railroads, access roads, storage yards, etc. As discussed earlier, the theories are not well developed, and design is usually by rule of thumb or trial and error. Several studies however, have been undertaken and are being conducted, which should provide better methods of design in the future. There is little doubt that fabrics have a considerable future application in this use.

The criteria and properties required for subgrade stabilization are tabulated in Table 3-18.

3.4.5 Summary of Criteria and Properties

All of the criteria and fabric properties necessary for reinforcements and separation, as discussed in the preceding sections, are combined and tabulated in Table 3-19.

3.4.6 Tests and Test Conditions

To be able to select appropriate fabrics for separation installations, it is necessary to have a knowledge of the values for all of the properties in Table 3-19. This requires that acceptable test apparatus and test methods be available for use with geotechnical fabrics for each of those properties. A compilation of many of the standard tests available and the tests evaluated with respect to simplicity and adequacy was prepared by Cogne [96]. The results indicate that acceptable test methods are available for most of the general property tests such as weight, thickness, adsorption, durability, etc. Tests for the hydraulic properties are discussed in other sections of this chapter. Therefore, the following discussion is limited to the mechanical tests of strength, abrasion resistance, puncture resistance, burst strength, etc.

3.4.6.1 Tensile Strength Tests

There is almost universal agreement that the standard strip tensile and grab tensile tests do not adequately model the strains in service and therefore are not adequate for civil engineering testing of fabrics. A wide variety of special, non-standard tests have been devised for use with these materials. Some are biaxial tests and others are attempts to more closely approximate the plane strain conditions encountered in many reinforcing applications. Many biaxial tests are probably not suitable for tensile testing of fabrics because, as explained in previous sections and in Chapter 2, the strain in most reinforcing applications is plane strain and the anisotropic character of many fabrics confuses the interpretation of biaxial tests.

Several investigators have studies the plane strain test and compared it with other types of tensile tests. Sissons [90] used the strip tensile test with special spreaders on the fabric to prevent lateral strain to approximate the plane strain condition. Paute and Segouin [91] used a cylindrical test where the specimen consisted of a sleeve which was expanded to failure

TABLE 3-18. Criteria and Properties for Fabrics for Subgrade Stabilization

CRITERIA	PROPERTY*
Constructability	Strength Failure Elongation Tear Resistance Ultraviolet Light Stability Flammability Thickness Flexibility Weight Absorption Puncture Resistance Cutting Resistance Burst Strength
Durability	Chemical Resistance Biological Resistance Abrasion Resistance
Mechanical	Tensile Strength Modulus - Dynamic Friction/Adhesion Creep - Dynamic Creep - Static Seam Strength Fatigue Failure Elongation Burst Strength
Hydraulic	Initial Permeability Thickness Pore Characteristics Capillary Potential

*All may not be important for every application

TABLE 3-19. Summary of Criteria and Properties for Fabrics for the Reinforcement/Separation Function

CRITERIA	PROPERTIES*
Constructability	Strength Ultraviolet Light Stability Flammability Thickness Weight Absorption Puncture Resistance Cutting Resistance Failure Elongation Tear Resistance Wetting and Drying Resistance Burst Strength
Durability	Chemical Resistance Biological Resistance Abrasion Resistance Wetting and Drying Resistance
Mechanical	Tensile Strength Modulus - Static Friction/Adhesion Fatigue Creep - Static Creep - Dynamic Seam Strength Failure Elongation Modulus - Dynamic Burst Strength
Hydraulic	Initial Permeability Thickness Pore Characteristics Capillary Potential

*All may not be important for every application

by a pressure acting on the inside of the sleeve. Raumann [78] used what she termed a trough test. This tested a rectangular specimen fixed on all four edges and failed by applying a pressure on one surface. In the center of the specimen, the strain was almost pure plane strain. Raumann also compared the results of this test with simple strip tensile tests of various length-to-width ratios. She found that as the width to length of the specimen approached four to one for specimens sufficiently large to reduce edge effects, the ultimate strength of the strip tensile test approached that of the plane strain test. Agreement for strain was not as good as for rupture stress. There may also be more significant differences when static and cyclic creep are considered. It does appear, however, that it may be possible to use a modified simple strip tensile test of appropriate specimen size and shape to yield results adequate for practical design purposes. This would be advantageous because the true plane strain tests are more complex.

There are, of course, many other problems in tensile strength testing besides the geometry of the test specimen. Some important factors are the moisture conditioning of the specimen before testing, temperature of tests, rate of loading, details of clamping the specimen in the machine, and other factors. Most of these factors have been discussed elsewhere in this report.

3.4.6.2 Burst, Penetration, and Puncture Tests

In this report, burst refers to the failure of a fabric held at its edges, due to a uniform pressure applied normal to the fabric. For a circular specimen, tensile stresses develop more or less uniformly in all directions in the plane of the fabric. Penetration refers to failure caused by a pointed object, which first penetrates the fabric by either spreading or breaking a few fibers, and then enlarges the hole by tearing. Puncture is made by a more or less blunt object applying a high stress over a relatively small area. Failure is due to tensile failure of the fibers. Unlike the burst test the stresses are not uniform over the entire surface of the fabric.

Burst may be important with respect to several separation applications. Standard burst tests are probably reasonably adequate for evaluating this resistance if they are modified to reflect appropriate test conditions of specimen size, temperature, rate of loading, etc.

Penetration may be significant in the separation functions. It would indicate the resistance to the enlargement of punctures by rocks.

In practice, puncture of the fabric is most likely be due to the action of aggregate particles under the application of wheel loads. It is at this time not clear whether puncture is a real problem with respect to reinforcement or separation applications. The failure may actually be one of burst, abrasion, or cutting. Some additional investigation needs to be made to determine whether this is an important factor. If it is, some special test may need to be developed to adequately determine the resistance to puncture by aggregate particles over subgrade. Ruddock [92] and Loudiere [93] and Raymond [94] have made preliminary investigations of this subject, but more work is needed.

3.4.6.3 Abrasion Tests

Fabric abrasion in reinforcement-separation applications may only be a problem when a fabric is placed under conditions with very heavy loads and where the fabric is placed between aggregate layers. The standard abrasion tests, such as the Taber test which is frequently used, do not model this type of abrasion and there is little reason to believe that there would be significant correlation between these tests and field performance. Raymond [94] in his work with railroad ballasts has developed a test where a fabric placed between two aggregate layers is subjected to repetitive loads. This test may serve as a basis for a suitable abrasion test for this application of fabrics.

3.4.6.4 Cutting Tests

This type of damage to the fabric is different from burst, puncture or abrasion, in that is results from the actual cutting of the fabric fibers between two hard objects usually by impact. This type of damage would essentially be limited to construction operations. Some knowledge of this problem would make it possible to plan construction procedures to limit the damage. There is only one known investigation of this property [94]. In addition to developing tests, some studies are needed to indicate to what degree this is really a problem. The mechanism is relatively simple and it should not be difficult to devise a suitable test.

3.4.7 Current Design Standards

Most design standards and specifications in use today with respect to fabric reinforcement-separation are empirical and are not based upon theory or carefully controlled field testing. For the most part, those specifications are written to assure that any fabric which is used will be equal to or better than some fabric which has been observed to perform satisfactorily on some other job. In many cases, the fabric which was used as the basis was stronger or more resistant to the factors in question than was necessary. Therefore, specifications based on the performance of this type of fabric are often overconservative and unduly restrictive. However, even though they may be somewhat overconservative, most projects being built by current specifications seem to be at least adequate.

CHAPTER 3.0 REFERENCES

1. Marks, B. Dan, The Behavior of Aggregate and Fabric Filters in Subdrainage Applications, Department of Civil Engineering, University of Tennessee, February 1975.

2. McGown, A., The Properties and Uses of Permeable Fabric Membranes," Residential Workshop on Materials and Methods for Low Cost Road, Rail, and Reclamation Works, Leura, Australia, September 1976.

3. Sweetland, D.B., The Performance of Nonwoven Fabrics as Drainage Screens in Subdrains, Master of Science Thesis, University of Strathclyde, Glasgow, Scotland, 1977.

4. Hoogendoorn, A.D. and Van Der Meulen, J., "Preliminary Investigations on Clogging of Fabrics," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 177-182.

5. Ogink, H.J.M., "Investigations on the Hydraulic Characteristics of Synthetic Fibers," Delft Hydraulics Laboratory, Publication No. 146, Delft, Holland, May 1975.

6. McKeand, E., "The Behavior of Nonwoven Fabric Filters in Subdrainage Applications," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 171-176.

7. ________________, "Subsurface Drainage with Mirafi 140 Fabric," PM8, Celanese Fibers Marketing Company, Charlotte, NC, 1975.

8. Seemal, R.N., "Plastic Filter Fabrics Challenging the Conventional Granular Filter," Civil Engineering, ASCE, March 1976, pp. 57-59.

9. McGuffey, Verne C., "Filter Fabrics for Highway Construction," Highway Focus, Vol. 10, No. 2, Federal Highway Administration, May 1978.

10. Mascunana, Indalecio, "An Evaluation of PRF-140 Industrial Fabric as Filter-Cloth for Underdrains," Illinois Department of Transportation, Springfield, April 1975.

11. List, H.J., "Woven and Nonwoven Fabric Filters in Waterway Engineering Tests and Dimensioning," (German), Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 339-345.

12. Roth, H., "Filter Fabric for Improving Frost Susceptible Soils," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 23-28.

13. Calhoun, C.C., "Development of Design Criteria and Acceptance Specifications for Plastic Filter Cloths," Technical Report S-72-7, U.S. Department of Commerce, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi, 1972.

14. Rollin, A.L. and Masounave, H., "Study of Hydraulic Behavior of Nonwoven Fabrics," (French) Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Vol. II, April 1977, pp. 201-208.

15. ________________, "Textiles - Yarns, Fabrics, and General Tests Methods," Annual Standards, Part 32, American Society for Testing and Materials, Philadelphia, PA, 1977.

16. Broughton, R.S. and Gibson, W., "The Field Evaluation of Drain Tube Filter Materials," Department of Agricultural Engineering, McGill University, Quebec, Canada, October 1977.

17. Bell, A.L. and Snaith, M.S., "Preliminary Report on Embankment Stabilization Using Woven Fabrics," Joint QUB/LIRA Project, Department of Civil Engineering, Queen's University, Belfast, 1977.

18. Bourdillon, M., "Utilization of Nonwoven Fabrics for Drainage," (French), Rapport No. 54, Ministere De L'Equipment, Laboratory Des Ponts et Chaussees, June 1976, pp. 1-40, (Translation by International Paper Co., Corporate Research Center, Sterling Forest, NY).

19. ________________, "Laboratory Test Reports, Poly-Filter X and Filter X," Soil Testing Services, Inc., Northbrook, IL, July 5, 1967.

20. Patronsky, R.J., "Subsurface Drainage -- Filter Fabric Testing," U.S. Department of Agriculture, May 10, 1977.

21. Benz, L.C., Doering, E.J., Reichman, G.A., and Follet, R.F., "Evaluation of Some Subsurface Drainage Envelopes," Third National Drainage Symposium Proceedings, American Society of Agricultural Engineers.

22. Carabetta, D.G., "Synthetic Filter Cloth, Summary of Tests and Guide Specifications," Report No. 45-04-01, British Columbia Department of Highways and Public Works, Victoria, British Columbia, July 1976.

23. Hoffman, Gary L. and Malasheskis, Gerald, "A Laboratory Evaluation of Pertinent Materials and Design Characteristics of Penndot's Underdrain System," Bureau of Materials, Testing and Research, Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, December 1977.

24. Lockett, L., "Standard Method of Tests for Filter Cloth," State of Alabama Highway Department, Montgomery, 1977.

25. Ball, John, "Design Parameters for Longitudinal Filter Cloth Lined Subsurface Pavement Drainage Systems," Quarterly Report for the Period January 1, 1978 to March 31, 1978, Submitted to the Alabama State Highway Department, March 31, 1978, Univ. of Alabama, Tuscaloosa.

26. Ruddock, E.C., "Tests on Woven and Nonwoven Fabrics for Pore Size and Damage by Aggregate," Proceedings, International Conference on the Use of Fabrics on Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 317-322.

27. ________________, "Filter Fabric Soil Retention Test," (Interim Procedure), New York State Department of Transportation Soil Mechanics Bureau, Albany, 1977.

28. Dohmen, Willy, "Report on the Use of Polyfelt TS 400 in the Construction of the Federal Autobahn A 44 Between Dusseldorf and Aachen," Chemie Linz Ag, Linz, Austria, 1976.

29. ________________, "Falling-Head Water Permeability of Filter Fabrics Determination of Permeability Coefficient and Flow Rate at a Given Change in Water Head," CFMC-FFET-2, Celanese Fibers Marketing Company, Charlotte, NC, May, 1977.

30. ________________, "Determination of Filter Fabric Piping Performance," CFMC-FFET-101, Celanese Fibers Marketing Company, Charlotte, NC, June 1975.

31. ________________, "Determination of Average Pore Size and Equivalent Opening Size of Filter Fabrics," CFMC-FFET-1, Celanese Fibers Marketing Company, Charlotte, NC, June 1976.

32. ________________, "Recommended Specifications for Filter Fabrics Used in Subsurface Drainage Structures," Celanese Fibers Marketing Company, Charlotte, NC.

33. Loudiere, D., "The Use of Synthetic Fabrics in Earth Dams," (French), Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chausseees, Paris, Vol. II, April 1977, pp. 291-324.

34. Resseeuw, P. and Van Der Elzen, L.W.A., "Construction on Compressible Saturated Subsoils with the Use of Nonwoven Strips as Vertical Drains," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 265-272.

35. Marks, B.D. and Rosen, W.J., "Preliminary Report on the Implementation and Evaluation of Mirafi 140 in Temporary Erosion Control," Marks-Rosen Inc., Knoxville, Tennessee, February 1975.

36. Dallaire, G., "Filter Fabrics Can Cut Costs of River-Bank and Shoreline Protection Structures," Civil Engineering, ASCE, New York, March 1977, pp. 74-79.

37. ________________, "Erosion and Siltation Control with Mirafi 140 Fabric," PM7 Celanese Fibers Marketing Company, Charlotte, NC, 1975.

38. Darby, L.M., "Erosion Control During Construction," Highway Focus, Vol. 7, No. 1, Federal Highway Administration, 1975, pp. 4-15.

39. Darby, L.M., "Silt Fences and Brush Barriers," Highway Focus, Vol. 7, No. 1, 1975, Federal Highway Administration, pp. 86-90.

40. Rosen, W.J. and Marks, B.D., "Investigation of Filtration Characteristics of a Nonwoven Fabric Filter," Transportation Research Record, No. 532, National Research Council, Washington, D.C., 1975.

41. ________________, "Dredged Material Research," Notes, News, Review, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksberg, Miss, Vol. D77-10, October 1977.

42. ________________, "Hold/Gro-Erosion Control Fabric," Gulf States Paper Corporation, Tuscaloosa, AL.

43. Steward, J.E., Williamson, R. and Mohney, J., "Guidelines for Use of Fabrics in Construction and Maintenance of Low-Volume Roads," FHWA TS-78-205, U.S. Department of Agriculture, U.S. Forest Service, Portland, Oregon, 1977.

44. ________________, "Use of Mirafi 140 Fabric for Embankment and Shoreline Stabilization," PM12 Celanese Fibers Marketing Company, Charlotte, NC, 1977.

45. Dunham, J.W. and Barrett, R.J., "Woven Plastic Cloth Filters for Stone Seawalls," Journal of the Waterways Harbors and Coastal Engineering Division, ASCE, February 1976.

46. ________________, Filter Handbook, Carthage Mills - Erosion Control Division, Cincinnati, OH.

47. Barrett, Robert J., "Use of Plastic Filter in Coastal Structures," International Conference on Coastal Engineering, Tokyo, Japan, September 1966.

48. Masucnana, Indalecio, "An Evaluation of Woven Polypropylene Filter for Riprap," Illinois Department of Transportation, Springfield, April 1978.

49. ________________, "Erosion Control Fabric Evaluation," Technical Report, Brunswick Corporation, Skokie, Illinois, May 1975.

50. ________________, "Test to Determine Fabric Filters Erosion/Sediment Control Efficiency," Celanese Fibers Marketing Company, Charlotte, NC.

51. Fayoux, D., "Hydrodynamic Filtration of Soils by Fabrics," (French) Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 329-332.

52. Marlar, Bobby D., "Investigation of Mechanisms Related to Nonwoven Fabric Filtration," Master of Science Thesis, University of Tennessee at Knoxville, Tennessee, 1975.

53. Basvary, A.K. and Korgemagi, P., "The Geotechnical Use of Filter Fabrics in Highway Construction," Report EM-13, Ontario Ministry of Transportation and Communications, Toronto, January 1978.

54. Eiland, E. and Lockett, L., "Use of Filter Fabric in French and Trench Subsurface Drains on I-65 in Chilton County, Alabama," presented at the 1976 Annual Meeting of the American Association of State Highway and Transportation Officials at Birmingham, Alabama, November 1976.

55. Vidal, H., "La Terre Armee," (French) Annales de l'Institut technique du Batiment or des Travaux Publics, Paris, July-August, 1966, pp. 888-938.

56. Holtz, R.D. and Broms, B.B., "Walls Reinforced by Fabrics," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 113-117.

57. Stilley, A.N., "A Model Study of Fabric Reinforced Earth Walls," Master of Science Thesis, Oregon State University, Corvallis, Oregon, 1974.

58. Antonini, M., "Metal vs Fabric Earth Reinforcement in Dry Sands - A Comparative Statistical Analysis," Master of Science Thesis, Department of Civil Engineering, Louisiana State University, 1978.

59. Al Hussaini, M.M., "Field Experiment of Fabric Reinforced Earth Wall," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 119-122.

60. Bell, J.R., Greenway, D.R. and Vischer, W., "Constructon and Analysis of a Fabric Reinforced Low Embankment on Muskeg," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 71-76.

61. Lavansiri, Direk, "Evaluation of Fabric Reinforcement of the Roadway Structure," Doctor of Philosophy Thesis, Oregon State University, Corvallis, Oregon June 1977.

62. Yang, Z., "Strength and Deformation Characteristics of Reinforced Sand," Doctoral Dissertation, University of California, Berkeley California, 1972.

63. McGown, A., and Andrawes, K.Z., "The Influence of Non-woven Fabric Inclusions on the Stress Strain Behavior of a Soil Mass," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole National Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 161-166.

64. Hausmann, M.R. and Bagneron, J.M., "Analysis of Soil-Fabric Interaction," Proceedings, International Conference on the Use of Fabrics in Geotechnis, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977., pp. pp. 139-144.

65. Lee, K.L., Adams, B.D. and Vagneron, J.M., "Reinforced Earth Retaining Walls," Journal of the Soil Mechanics and Foundation Division, ASCE, October 1973, pp. 745-764.

66. Schlosser, F. and Nguyen, T.L., "Recent Results in French Research in Reinforced Earth," Journal of the Construction Division, ASCE, September 1974.

67. Bell, J.R., Stilley, A.N. and Vandre, B., "Fabric Retained Earth Walls," Proceedings, 13th Annual Engineering Geology and Soils Engineering Symposium, Moscow, Idaho, 1975.

68. Broms, B.B., "Design of Fabric Reinforced Retaining Structures," Paper presented at ASCE Annual Meeting, Pittsburgh, PA, April 1978.

69. Greenway, D.R., "Fabric Reinforcement of Low Embankments on Soft Foundations," Master of Science Thesis, Oregon State University, Corvallis, Oregon, June 1976.

70. Volman, W., Krekt, L., and Risseeus, P., "Reinforcement with Fabrics, a New Technique to Improve the Stability of Embankments on Weak Subsoils," (French), Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 55-60.

71. Nieuwenhuis, J.D., "Membranes and the Bearing Capacity of Road Bases," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 3-8.

72. Maagdenberg, A.C., "Fabrics Below Sand Embankments over Weak Soils, Their Technical Specifications and Their Application in a Test Area," Proceedings, International Conference on the Uses of Fabrics in Geotechnics, Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 77-82.

73. Vischer, W., "Use of Synthetic Fabrics on Muskeg Subgrade in Road Construction," U.S. Department of Agriculture, U.S. Forest Service, Region 10, Juneau, AK, November 1975.

74. Kelsay, H.S., "Investigation of a Non-woven Fabric as a Reinforcement for Gravel Paved Roads," Master of Science Thesis, Oregon State University, Corvallis, Oregon 1975.

75. Greenway, D.R. and Bell, J.R., "The Role of Fabric in Low Embankments On Muskeg," Proceedings, 17th Muskeg Research Conference, Saskatoon, Saskatchewan, Canada, October 1977.

76. Barenberg, E.J., Dowland, J.H. and Hales, J.H., "Recommended Design Procedures for Soil-Fabric-Aggregate Systems with Miarafi 140 Fabric," Department of Civil Engineering, University of Illinois, Urbana-Champaign, IL, August 1975.

77. Kelsay, H.S., "Investigation of a Non-woven Fabric as a Reinforcement for Gravel Paved Roads," Master of Science Thesis, Oregon State University, Corvallis, Oregon, 1975.

78. Raumann, G., Personal Communication, Monsanto Textiles Co., Research Triangle Park, NC, 1978.

79. Yoder, E.J., "Pumping of Highway and Airfield Pavements," Proceedings, Highway Research Board, Vol. 36, 1957.

80. Havers, J.A. and Yoder, E.J., "A Study of Interactions of Selected Combinations of Subgrade and Base Course Subjected to Repeated Loading," Proceedings, Highway Research Board, Vol. 36, pp. 443-478, 1957.

81. Ayres, D., Personal Communications, British Railways Board, London, England, 1978.

82. Giroud, J.P., Personal Communication, Universitaire de Technologie de Grenoble, Grenoble, France, 1978.

83. MacKinnon, K., Personal Communication, Terrafix Erosion Control Products, Inc., Rexdale, Ontario, Canada, 1978.

84. Steward, J.F., Williamson, R. and Mohney, F., "Guidelines for Use of Fabrics in Construction and Maintenance of Low-Volume Roads," U.S. Department of Agriculture, U.S. Forest Service, Portland, Oregon, 1977.

85. Holtz, R.D., "Studies of Reinforced Earth Using Woven Plastic Material," Report Order No. 20505, Swedish Geotechnical Institute, Stockholm, 1973.

86. Puig, J., Blivet, J.C. and Pasquet, P., "Earth Fill Reinforced with Synthetic Fabric," (French) Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 85-90.

87. Parks, R.M., Personal Communication, Monsanto Textiles Co., St. Louis, Missouri, 1978.

88. Bell, A.L. and Snaith, M.S., "Preliminary Report on Embankment Stabilization Using Woven Fabrics," Joint QJB/LIRA Project, Department of Civil Engineering, Queen's University of Belfast, 1977.

89. Christies, I.F. and El Hadi, K.M., "Some Aspects of the Design of Earth Dams Reinforced with Fabrics," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I., April 1977, pp. 99-104.

90. Sissons, C.R., "Strength Testing of Fabrics for Use in Civil Engineering," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 287-292.

91. Paute, J.L. and Segouin, M., "Determination of Strength and Deformability Characteristics of Fabrics by Dilatation of a Cylindrical Sleeve," (French) Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 293-298.

92. Ruddock, E.C., "Tests on Woven and Non-woven Fabrics for Pore Size and Damage by Aggregate," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 317-322.

93. Loudiere, D., "The Use of Synthetic Fabrics in Earth Dams," (French) Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 219-233.

94. Raymond, G.P., Personal Communication, Queen's University, Kingston, Ontario, Canada, 1978.

95. Bell, J.R. and Steward, J.E., "Construction and Observations of Fabric Retained Soil Walls," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 123-128.

96. Cogne, Jean-Jacque, "Evaluation of Fabric Test Methods," Transportation Engineering Report 78-5, Department of Civil Engineering, Oregon State University, September 1978.

97. Kern, F., "An Earth Dam With a Vertical Downstream Face Constructed Using Fabrics," Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. I, April 1977, pp. 123-128.

98. Webster, S.L. and Watkins, J.E., "Investigation of Construction Techniques for Tactical Bridge Approach Roads Across Soft Ground," Technical Report, S-77-1, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., 1977.

99. Paute, J.L. and Chene, G., "Pore Diameter Distribution of Non-Woven Fabrics and Comments on the Clogging Phenomenon," (French) Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 195-199.

100. Auriault, J.L., Cordary, D., Giroud, J.P. and Gourc, J.P., "Theoretical Study of the Importance of Fabric Drains in Earthfill Consolidation," (French), Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 273-278.

101. Bourdillon, M., Didier, G. and Gielly, J., "Utilization of Non-woven Fabrics in Drainage," (French) Proceedings, International Conference on the Use of Fabrics in Geotechnics, Ecole Nationale Des Ponts et Chaussees, Paris, Vol. II, April 1977, pp. 279-284.

4.0 EVALUATION PHASE I

This chapter briefly summarizes the more significant findings of Phase I of this study. Much of the information presented in this chapter is a summary of the work presented in Chapters 2 and 3 of this report.

4.1 SOIL-FABRIC INTERACTION THEORIES

To understand what properties are important for various applications, one must understand how fabrics function in each application. The following comments appear appropriate.

4.1.1 Reinforcement

The theories for reinforcement appear to be good for rupture type failures (walls, embankments) as discussed in Chapter 3. However, theories used to predict the behavior of fabrics for deformation or rutting type failures (e.g. subgrade stabilization) are poor. Finite element techniques or layered elastic theory both underestimate the observed benefits in the field. Semi-empirical approaches using bearing capacity concepts seem to work a little better.

4.1.2 Separation

Theories to estimate the fabric response in separation applications are inadequate. At present, there is no adequately documented method of analysis which can be used to show benefits of fabrics for these types of applications.

4.1.3 Filtration

The clogging phenomenon is still not completely understood. It seems impractical to perform soil-fabric permeability/clogging tests every time one wants to use fabrics as a filter. The simpler alternative is to develop relations between soil and fabric characteristics which would preclude any possibility of clogging.

4.1.4 Erosion Control

In these applications, the filtration function normally predominates. The previous comments are also applicable here. In addition, the effect of the surging water action on filtration and piping is not well understood.

4.1.5 Summary

Despite the lack of adequate theories, the mechanisms in most cases are well enough understood to define important use criteria and properties. The exceptions, if any, include subgrade stabilization (separation) and filtration where surging flow conditions exist.

4.2 USE CRITERIA AND PROPERTIES

Based on the review of the literature, interviews with users and producers of fabrics, and the theories available, use criteria and fabric properties applicable for drainage, erosion control and reinforcement including separation applications were identified. Important criteria for all applications are more or less the same and include:

(1) Constructability. The fabric must have certain minimum properties to insure that it can be constructed without damage.

(2) System Durability. The fabric must possess certain properties to insure that it will not deteriorate over time or that it cannot provide its intended function over time.

(3) Mechanical. Particularly for reinforcement and separation applications, the fabric must possess certain strength, deformation and/or frictional characteristics.

(4) Hydraulic. For drainage and erosion control applications, in particular, the fabric must possess certain permeability and/or filtration properties to ensure satisfactory performance.

Tables 4-1 through 4-4 summarize for the above criteria, the important properties needed to insure satisfactory performance for drainage, erosion control, reinforcement and separation applications.

4.3 TEST METHODS

Once important properties were identified, it was necessary to make an assessment of whether or not existing test methods could be used to evaluate these properties. As a part of this project, all available test methods were collected and summarized. For each important property, the available methods were rated in terms of:

(1) Simplicity. Whether or not the test is simple or complex to perform.

(2) Representation of Field Conditions. Whether or not the test represents what happens to the fabric in-situ, and

(3) Adequacy. Whether or not the test is considered adequate or inadequate for measuring the given property.

Based on this evaluation and information presented in Chapter 3, the needs for Phase II of this study were developed and were categorized in one or more of the following groups:

(1) Additional Testing Needed to Identify What Properties are Important. In this case, the project team feels that there is a lack of understanding of the soil-fabric behavior to clearly define what property

TABLE 4-1. Important Criteria and Properties - Reinforcement Applications

CRITERIA	PROPERTY*
Constructability	Strength Temperature Stability Ultraviolet Light Stability Wetting and Drying Stability Flammability Thickness Absorption Puncture Resistance Tear Resistance Cutting Resistance Modulus
Durability	Ultraviolet Light Stability Temperature Stability Chemical Resistance Wetting and Drying Stability Biological Resistance
Mechanical	Tensile Strength Modulus - Static Modulus - Dynamic Friction/Adhesion Fatigue Creep - Static Creep - Dynamic Seam Strength
Hydraulic	Thickness Permeability

*All may not be important for every application

TABLE 4-2. Important Criteria and Properties - Separation Applications

CRITERIA	PROPERTY*
Constructability	Strength Temperature Stability UV Light Stability Wet and Dry Stability Flammability Thickness Weight Absorption Puncture Resistance Cutting Resistance Modulus Flexibility Tear Resistance
Durability	Temperature Stability Chemical Resistance Wet and Dry Stability Biological Resistance Abrasion Resistance
Mechanical	Tensile Strength Fatigue Seam Strength Burst Strenghh Puncture Resistance Tear Strength Creep Friction/Adhesion
Hydraulic	Thickness Permeability Siphoning Capacity Pumping Resistance Intrusion Resistance

*All may not be important for every application

TABLE 4-3. Important Criteria and Properties - Drainage Applications

CRITERIA	PROPERTIES*
Constructability	Thickness
	Weight
	Absorption (Wet Weight)
	Flexibility
	Tensile Strength
	Puncture Resistance
	Cutting Resistance
	Seam Strength
	Flammability
	Tear Strength
	UV Stability
Durability	Chemical Stability
	Biological Stability
	Thermal Stability
	Clogging Resistance
Hydraulic	Thickness
	Permeability
	Piping Resistance

*All may not be important in every application

TABLE 4-4. Important Criteria and Properties - Erosion Control Applications

CRITERIA	PROPERTIES*
Constructability	Thickness Weight Absorption (Wet Weight) Specific Gravity Flexibility Tensile Strength Puncture Resistance Cutting Resistance Seam Strength UV Stability Tear Strength Flammability
Permeability	Permeability Particle Clogging Resistance
Durability	Chemical Stability Biological Stability Thermal Stability Abrasion Resistance Animal, Vegetable, and Insect Resistance Clogging Resistance
Hydraulic	Permeability Piping Resistance

*All may not be important in every application should be evaluated.

(2) New Test Methods and Procedure Should be Developed. In this case, the properties needed for design are clear; however, existing methods for evaluating these properties do not exist.

(3) Existing Test Methods Need to be Modified. In this case, the properties needed for design are clear. The existing methods are not quite adequate and may have to be modified.

In the following sections, the important properties are summarized and the types of test needed (based on Phase I) are briefly outlined.

4.3.1 Reinforcement

Table 4-5 summarizes the important properties needed to design and construct a fabric installation, as well as the type of additional testing or evaluation needed in Phase II. For example, tensile strength, friction and creep are all important design properties for which additional tests need to be developed. To construct, it is important to know strength, weight, absorption and ultraviolet light stability. For these properties, existing tests appear adequate. It still is not clear whether impact cutting or flammability is important, so additional evaluation and perhaps the development of a needed test is necessary.

In terms of long-term performance, additional evaluation appears necessary for chemical stability and wet-dry effects. Modification of existing tests or development of new tests appears appropriate. Modifications of existing methods also appear necessary to evaluate temperature stability.

4.3.2 Subgrade Stabilization (Separation)

Table 4-6 summarizes those properties considered important and tests needed for this broad application, based on Phase I findings. Considerably more properties have been identified, partly because of the lack of a clear theory to explain the benefit of fabrics in this use. As shown, much evaluation is still needed and several new tests or modifications to existing tests are required. It will certainly not be possible to modify existing or develop new test methods for all of these properties; hence the test plan which follows concentrates on the more important properties.

4.3.3 Drainage

In this report, drainage applications are divided into two broad functions: one where the fabric serves predominantly as a filter and the other where the fabric itself serves as a drain. Because the former has been used most widely, efforts in Phase II will be concerned primarily with fabrics used in filtration applications. Table 4-7 summarizes those properties considered important for these applications and indicates where additional work is needed.

TABLE 4-5. Evaluation of Properties and Additional Testing Needed for Reinforcement Applications

DESIGN	CONSTRUCTION	DURABILITY
Friction (2)	Strength (2)	Ultraviolet Light Stability
Tensile Strength (2)	Weight	Temperature Stability (3)
Creep (2): Static Cyclic	Absorption	Wet-Dry (1,2)
	Ultraviolet Light Stability	Chemical Stability (1-3)
	Cutting Resistance (1,2)	
	Flammability (1)	Biological Stability

(1) Additional Evaluation is Needed

(2) New Tests Need to be Developed

(3) Existing Tests Need to be Modified

TABLE 4-6. Evaluation of Properties and Additional Testing for Subgrade Stabilization Applications*

DESIGN	CONSTRUCTION	DURABILITY
Tensile Strength (2) (creep, fatigue, etc.)	Puncture Resistance	Abrasion Resistance (1,2)
Friction/Adhesion (2)	Strength (2)	Temperature Stability (3)
Dynamic Modulus (1,2)	Weight	Chemical Stability (3)
Burst Strength (1-3)	Absorption	Biological Stability
Pumping Resistance (2)	Ultraviolet Light Stability	
Permeability (1-3)	Cutting Resistance (1,2)	
Capillary Potential (1,2)	Flammability	
Isotropy (2)	Flexibility (1-3)	
	Seam Strength (2)	
	Tear Strength	
	Elongation	

*This table considers all categories of applications from light to heavy. Some cases would be almost pure separation and in some cases reinforcement would dominate. Therefore, all of the factors listed might not apply to any one application.

(1) Additional Evaluation is Needed

(2) New Tests Need to be Developed

(3) Existing Tests Need to be Modified

TABLE 4-7. Evaluation of Properties and Additional Testing Needed for Filtration Applications

DESIGN	CONSTRUCTION	DURABILITY
Fabric Permeability (1-3)	Strength (2)	Clogging Resistance (1,2)
Pore Size Distribution (1,2)	Weight	Wet-Dry (1,2)
	Absorption	Chemical Stability
	Ultraviolet Light Stability	
	Flexibility	
	Cutting Resistance (1,2)	
	Flammability	

(1) Additional Evaluation is Needed

(2) New Tests Need to be Developed

(3) Existing Tests Need to be Modified

4.3.4 Erosion Control

Tables 4-8 and 4-9 summarize those properties considered important for erosion control applications and indicate where additional evaluation and testing is required.

4.3.5 Summary

Table 4-10 summarizes the tests considered necessary for improved evaluation of construction fabrics, as indicated in Tables 4-5 through 4-9.

4.3.6 Size of Sample

Considerable care must be given in the selection of the sizes of specimens to be used in the test program depending whether the purpose is to measure average properties or maximum and/or minimum properties. Table 4-11 summarizes our present thinking on the size of specimen to be evaluated for certain specific tests. Additional work is needed to define each particular test planned in the Phase II program.

4.3.7 Evaluation Criteria

All tests should be evaluated in terms of the following criteria:

(1) Simplicity. Whether or not the test is easy to perform.

(2) Repeatibility. The ability of the test to yield consistent results.

(3) Time Requirements. The test method should be quick.

(4) Performance. The test should relate to fabric performance in-situ.

(5) Expense. The test should be relatively inexpensive.

(6) Accuracy. The test should be reasonably accurate.

4.4 FIELD PERFORMANCE

To develop standards or specifications for fabrics for drainage, erosion control and reinforcement separation applications, information documenting how fabrics perform in the field is needed. At present, there is a considerable lack of information showing how fabric installations perform. Further, much of the reported work has been of an experimental nature (not routine); therefore, cost data for these installations are not always reliable.

Considerable additional work is needed beyond the scope of this project to document how fabrics perform in the field and how their properties change over time. Examples of the types of data needed for two of the broad classes of installations are summarized in Tables 4-12 and 4-13.

TABLE 4-8. Evaluation of Properties and Additional Testing Needed for Embankment Protection

DESIGN	CONSTRUCTION	DURABILITY
Permeability (1,2)	Weight	Clogging Resistance (1,2)
Pore Size Distribution (1,2)	Specific Gravity	Wet-Dry Cycles (1,2)
Burst Strength (1,2)	Flammability	Ultraviolet Light Stability
	Tensile Strength (2)	Abrasion Resistance (1,2)
	Cutting Resistance (1-3)	Chemical Stability
		Biological Stability

(1) Additional Evaluation is Needed

(2) New Tests Need to be Developed

(3) Existing Tests Need to be Modified

TABLE 4-9. Evaluation of Properties and Additional Testing Needed for Silt Fence, Brush Barrier and Silt Curtain Applications

DESIGN	CONSTRUCTION	DURABILITY
Permeability (1,2)	Weight	Clogging Resistance (1,2)
Pore Size Distribution (1,2)	Flexibility	Wet-Dry Cycles (1,2)
Tensile Strength (2)	Tensile Strength (3)	Ultraviolet Light Stability (3)
Puncture Resistance	Flammability	Chemical Stability
Tear Resistance (3)		

(1) Additional Evaluation is Needed

(2) New Tests Need to be Developed

(3) Existing Tests Need to be Modified

TABLE 4-10. Summary of Types of Tests Needed for Phase II

CATEGORY	TEST
Mechanical	Stress-Strain
	Creep
	Fatigue
	Friction
	Tear Resistance
	Cutting Resistance
Hydraulic	Pore Size Distribution
	Fabric Permeability
Durability	Wet-Dry
	Temperature Stability
	Ultraviolet Light Stability
	Chemical Resistance
	Abrasion Resistance

TABLE 4-11. Tentative Recommendations for Specimen Sizes

SPECIMEN SIZE	TESTS
Large	Stress-Strain Characteristics Permeability Clogging
Small	Abrasion Resistance Puncture Resistance Piping

TABLE 4-12. Example of Types of Data Needed for Field Observations - Subgrade Stabilization

ITEM	PROPERTY	OBSERVATION
Fabric	Abrasion Resistance	Fraying of Surface Broken Fibers
	Tearing Resistance	Nature of Tears Postulate Apparent Causes
	Puncture Resistance	Nature of Tears Postulate Apparent Causes
Pavement	Surface Deformation	Rut Depth Pavement Thickness Maintenance Measure of Traffic Type of Traffic
	Subgrade Deformation	Cause of Failure Measure of Subgrade Support Shape and Depth of Rut
	Contamination of Rock	Soil Segregation in Fabric Vicinity
	Rot	Structural Disintegration of Fabric
		Lateral Movement of Gravel on Fabric

TABLE 4-13. Types of Data Needed for Field Observations - Drainage

FACTOR	OBSERVATION
Piping	Is the water being removed clear?
Clogging or Blinding	Are particles trapped within the fabric? Is there a soil "crust" on the fabric surface?
Filter Cake	Can a filter cake be seen? If so, how deep is it? Photograph if possible.
Chemical or Biological Contamination	Is there any mildew or not? Has the fabric disintegrated?
Tearing or Puncture Resistance	Are there any tears or punctures? If so, describe and postulate probable cause.
External Loads	Are there any static loads besides soil weight? Has there been any vibratory or dynamic loading during the installation's history?
Flow	Has there been any known flow reversal?
Soil	What type of soil is being filtered? What compaction methods were employed?

Sketch of photograph of installation.
Indicate direction of flow.

4.5 STANDARDS FOR SELECTION

It is difficult to set standards (or specifications) for selection of fabrics without some performance information. Table 4-14 summarizes what appear to be the fabric types currently most likely to be practical for the various applications. Note that various types of fabrics are recommended for each function. To insure satisfactory service in any specific application, the properties listed earlier would have to be evaluated. Actual values for these properties (strength, permeability, etc.) are not given at this time. Hopefully this can be accomplished, in part, in Phase II of this contract.

TABLE 4-14. Likely Practical Fabrics for Various Applications

USE	FABRIC
Drain Filter	Lightweight Bonded and Lightweight Needled Nonwoven and Slit film and Monofilament Woven
Separation: Light Duty	Lightweight Bonded and Lightweight Needled and Nonwoven and Slit Film Woven
Separation: Heavy Duty	Mediumweight Bonded and Mediumweight Needled Nonwoven and Slit Film Woven
Reinforcement: Light Duty	Monofilament and Slit Film Woven and Heavy Needled Nonwoven
Reinforcement: Heavy Duty	Multifilament Woven
Erosion Control: Light Duty	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film and Monofilament Woven
Erosion Control: Medium Duty	Slit Film and Monofilament Woven and Mediumweight Bonded and Mediumweight Needled Nonwoven
Erosion Control: Heavy Duty	Very Heavyweight Needled Nonwoven, Heavyweight Woven, and Special Heavyweight Combination Woven-Nonwoven Fabrics
Silt Fences	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film Woven
Drainage	Heavyweight Needled Nonwoven

5.0 CONCLUSIONS AND RECOMMENDED RESEARCH

This chapter briefly summarizes the most significant conclusions reached in this Phase I study and makes recommendations to the sponsor, the Federal Highway Administration, U.S. Department of Transportation, as to future research work (Phase II) under this contract, and possible future contracts.

5.1 CONCLUSIONS

The conclusions reached in this study are based upon:

(1) Review of available published and unpublished literature.

(2) Information gained from interviews with numerous users and producers of fabrics, and

(3) Limited analytical and laboratory studies.

The conclusions should be considered as interim only, which may be modified at the conclusion of the Phase II portion of the study.

Based on the findings of Phase I, the following conclusions are drawn:

(1) Several important uses of fabrics have been identified. For each use, the fabric serves a particular function (e.g. filter, drain, separator, reinforcement or armor). The primary and secondary functions for each use are discussed.

(2) Important use criteria for fabrics per function have been identified in Chapter 3. Fabric properties associated with the indicated criteria are enumerated. At present, the investigators feel that the most important properties have been clearly identified. A few are still not clear and need additional study.

(3) Many test methods are available to measure the identified properties. These methods have been reviewed and evaluated. At the present time, it appears that:

   (a) General tests and most durability tests are suitable or require only slight modification.

   (b) Considerable work is needed to further develop the needed tests to measure hydraulic and mechanical properties.

   (c) The size of the fabric specimen may have a significant effect on the property measured.

(4) Performance information for fabrics used in drainage, erosion control and reinforcement applications are extremely limited. Without controlled field experiments relating laboratory properties to observed performance, the task of putting acceptable numbers to fabric proper-

ties (standards or specifications) will be nearly impossible. Though there is considerable evidence that fabrics work in all of these applications, there is information in the literature on only three to four projects which documents how fabric properties change with time and how the fabric installations perform over time.

5.2 RECOMMENDED RESEARCH

Three areas of needed research are recommended for Phase II of this investigation, as follows:

(1) Existing Test Methods Need to be Modified. In this case, the fabric properties needed for design are clear. The existing test methods are not quite adequate and may have to be modified. The properties which fall into this category were identified in Chapter 4, and include principally durability tests.

(2) New Test Methods and Procedures Should be Developed. In this case, the properties for design are clear; however, existing methods for evaluating these properties do not exist. Those properties which fall into this category have also been identified in Chapter 4.

(3) Additional Testing is Needed to Identify What Properties Are Important. In this case, the project team still feels that there is a lack of understanding of the soil-fabric behavior to clearly define what property should be evaluated. Chapter 4 identifies those situations which fall into this category.

In addition to the work needed to develop test methods (Phase II), there appears to be other work needed before realistic standards or specifications can be developed. This work includes:

(1) Identification of fabric variability, and

(2) Development of controlled test sections to relate laboratory properties to field performance.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1980 627-894/2505

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.