PB87-155008

GEOCOMPOSITE DRAINS

Vol. I: Engineering Assessment and Preliminary Guidelines

Research, Development, and Technology
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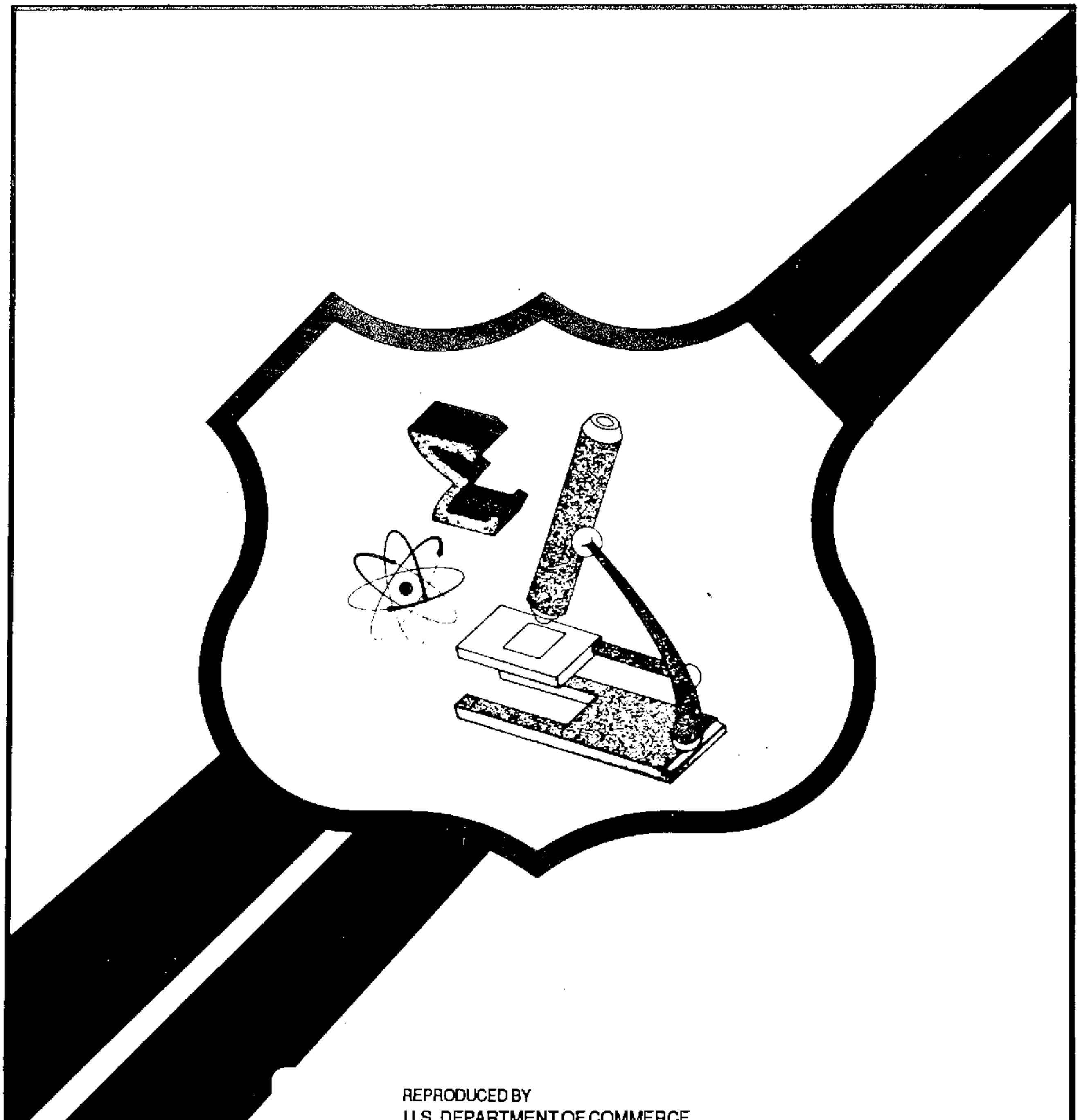
McLean, Virginia 22101-2296

U.S. Department of Transportation
Federal Highway Administration

Report No.
FHWA/RD-86/171

Final Report
October 1986



FOREWORD

This report presents the results of a comprehensive investigation of the use of geocomposite drains to collect and transport subsurface water. Design and construction guidelines for using geocomposite drains are presented along with detailed descriptions of available drains. This report will be of interest to bridge engineers, roadway design specialists, construction and geotechnical engineers concerned with drainage of water behind and adjacent to structures.

Sufficient copies of the report are being distributed by FHWA Bulletin to provide a minimum of two copies to each FHWA regional and division office, and three copies to each State highway agency. Direct distribution is being made to division offices.

Richard E. Hay, Director
Office of Engineering and Highway
Operations Research and Development

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/RD-86/171		PB87-155008/AS

4. Title and Subtitle
Geocomposite Drains
Vol. I, Engineering Assessment and Preliminary Guidelines

5. Report Date
October 1986

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Haley & Aldrich, Inc.
238 Main Street
Cambridge, Massachusetts 02142

10. Work Unit No. (TRAIS)
FCP 35P2-032

11. Contract or Grant No.
DTFH61-83-C-00101

12. Sponsoring Agency Name and Address
Office of Engineering and Highway Operations Research and Development
Federal Highway Administration
6300 Georgetown Pike, McLean, Virginia 22101-2296

13. Type of Report and Period Covered
Final Report
September 1983 - August 1986

14. Sponsoring Agency Code
CME-02~~1~~8
5

15. Supplementary Notes

FHWA Contract Manager (COTR): A. F. DiMillio (HNR-30)

16. Abstract

This volume presents a summary of relevant information available on geocomposite drain products, current research in testing of their critical properties, and design considerations including specifications. This volume is intended to provide the engineer with a summary of currently available technical information and comments on the design and use of geocomposite drains.

This volume is the fourth in a series. The others in the series are:

FHWA No.	Vol. No.	Title
RD-86/168	I	Prefabricated Vertical Drains: Engineering Guidelines
RD-86/169	II	Prefabricated Vertical Drains: Summary of Research Effort
RD-86/170	III	Prefabricated Vertical Drains: Laboratory Data Report.
RD-86/172	II	Geocomposite Drains: Laboratory Data Report

17. Key Words
Geocomposite drains, prefabricated drainage systems.

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Services, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	76	

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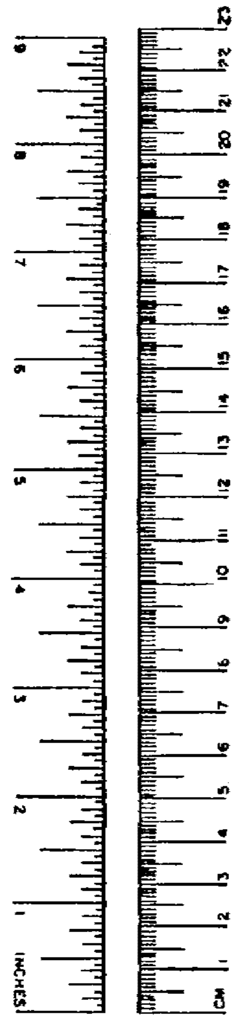
METRIC CONVERSION FACTORS

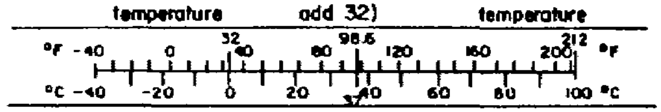
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



REPORT ON GEOCOMPOSITES

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Purpose

The use of prefabricated drainage systems (geocomposite drains) for geotechnical applications is increasing rapidly. New products and technology are being introduced to the commercial marketplace faster than design engineers can gain confidence in their knowledge of the products, appropriate uses and design criteria.

This volume has been prepared to provide a summary of relevant information available on geocomposite drain products, current research in the testing of their critical properties, and design considerations including specifications. This volume is intended to provide the engineer with a summary of currently available technical information and comments on the design and use of geocomposite drains.

Throughout the volume, "geocomposite drain" will be used to refer to synthetic sheet drains as compared to prefabricated vertical (PV) drains which are used in the consolidation of compressible soils. All of the currently available geocomposite drains include a geotextile and core; this volume assumes both components are part of the drain product. Future products may eliminate the geotextile, or involve other modifications to the geocomposite drain.

This volume has been prepared in accordance with the Task D Modification of Contract DTFH61-83-C-00101. The research tasks identified in the modification include:

D.1 Review Available Information

Perform a literature search to identify available products and obtain existing technical information from drain manufacturers. In particular, seek out and review research and development work which addresses geotechnical aspects of these products. Make contacts, either by phone or in person, with knowledgeable people. Visit a single installation under construction to observe field procedures.

D.2 Identify Critical Properties

Based on Task D.1, identify those properties and characteristics of a geocomposite which are important to the intended function of the drain and overall performance of the structure or facility. Develop an understanding of the significance of the properties, particularly those which have been overlooked to date.

D.3 Development of Testing Scope

Prepare a recommended program for field and/or laboratory testing which will be pertinent to the above items and which would be of most benefit to the FHWA in developing performance and acceptance criteria, with emphasis on realistic design applications.

D.4 Interim Report

Summarize Tasks D.1 through D.3 in a written technical report to be submitted to the FHWA for review and comment.

D.5 Testing

Evaluate the drain properties identified in Task D.2 using either existing standard laboratory tests, or test procedures developed by the drain manufacturers. The tests will focus on those properties which appear to have direct impact on the product performance, such as:

a. Compressibility, elasticity, and long-term creep.
b. Flow capacity as a function of compressibility.
c. Long-term permeability.
d. Long-term clogging potential.

D.6 Specification

Prepare a generic specification for typical highway applications based on the results of Task D.5 and the necessary installation requirements.

D.7 Final Report

Prepare a written summary report including appropriate revisions of the Task D.4 technical report and the results of Tasks D.5 and D.6.

Geocomposite Drain Components

Prefabricated drainage products, also referred to as in-plane drains or geocomposite drains, are specially fabricated subsurface drains typically constructed of a geotextile and a semi-rigid drainage core (see Figure 1). An optional drainage collector may also be included in the drain system. Although each of the components serves different functions in the drainage process, the major function of the system is to collect and transport subsurface water. To accomplish this objective, the geocomposite drain system must: (1) allow water to seep perpendicular to the plane of the geotextile into the flow volume of the core, (2) allow water to flow in the plane of the core (to the collector if provided), and (3) if required, collect the water flowing from the core and conduct it to some discharge point(s).

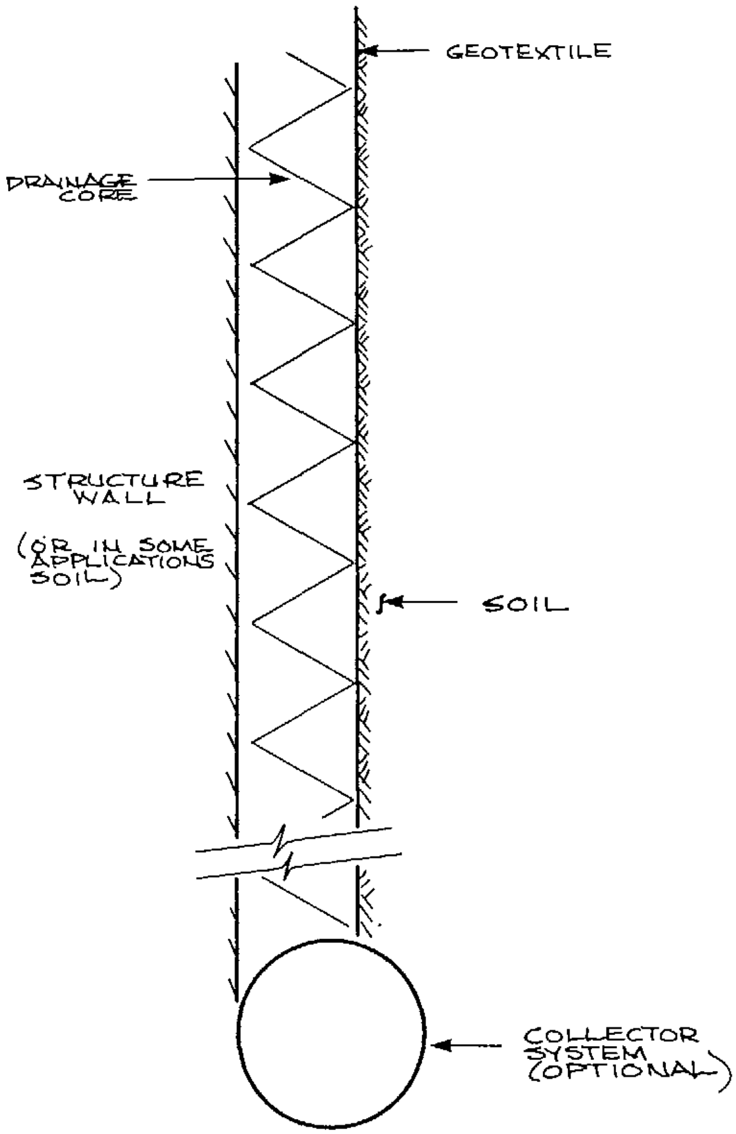


Figure 1 Components of a typical geocomposite drain.

Each component is discussed in the following sections. Although the components are discussed separately, these are components of a system and the overall design objective is a system for drainage. The system design requires consideration of the component properties, but the system characteristics determine whether or not the geocomposite drain will function satisfactorily (i.e., collect and transmit subsurface water adequately).

Geotextile:

The geotextile component serves two functions: (1) As a hydraulic filter between the soil and the open volume of the drainage core, and (2) to form the outer boundary of the core flow area (separation).

As with any filter in a geotechnical application, the functions of the geotextile in a geocomposite drain with respect to filtering are to permit the seepage of water with minimal head loss and to enable the creation of a natural filter in the neighboring soil to prevent piping. These objectives are themselves somewhat contradictory. The ability to permit seepage without substantial head loss (i.e., no clogging) is dependent on the interaction between soil particles carried by the seeping water and the geotextile. Excessive movement of fines may result in clogging of the geotextile. However, to create a natural filter in the neighboring soil requires some movement of the fines in the soil mass.

In a geocomposite drain application, the desired separation properties of the geotextile are adequate modulus and strength to prevent the geotextile from deflecting into the openings of the drainage core and reducing the available flow volume of the core.

The hydraulic and separation properties of the geotextiles are determined in large part by the raw materials and manufacturing process used for the geotextile. For example, heatbonded geotextiles (relatively high modulus and low permeability) have different properties than needle punched geotextiles (relatively low modulus and high permeability). The selection of a geotextile for geocomposite drain applications represents a trade-off of design objectives.

In addition to the desired hydraulic and separation properties, a geotextile used in a geocomposite drain application needs to possess other characteristics to perform satisfactorily during construction and throughout the design life of the structure. Bell, Hicks, et al. (1980) identified important criteria and properties for geotextiles to be used in drainage and separation applications that can be modified and applied to geocomposite drain design as follows:

CRITERION	INFLUENCING PROPERTIES	
Constructability	Thickness Weight Absorption Flexibility Tensile strength Puncture resistance Cutting resistance	Stability (temper. & wet/dry) Modulus Seam strength Tear strength
Durability	Clogging resistance Biological stability	Chemical resistance Wet & dry stability
Mechanical	Creep Tear strength Puncture resistance Burst strength	Tensile strength Fatigue Seam strength
Hydraulic	Thickness Piping resistance	Permeability Intrusion resistance

Numerous properties of the geotextile influence the drainage and separation functions. Many of the properties are desirable for both functions with the only difference being the priority of desirability. In some cases, the required functional criteria for the geotextile are apparently contradictory.

Christopher and Holtz (1984) in the geotextile engineering manual prepared for the FHWA present a comprehensive summary of geotextile design and selection criteria which is directly applicable to geocomposite drains. The major criteria considered for a geotextile drainage/filtration application include: 1) soil retention (piping resistance), 2) permeability, 3) clogging potential, 4) chemical composition requirements/considerations, and 5) constructability and survivability requirements. Selection of the proper geotextile for a geocomposite drain is therefore a function of the soil adjacent to the drain, the drainage core material and configuration, the installation and handling procedures, and the in-situ conditions (confining stress, groundwater and soil chemical properties, and hydraulic gradient).

The Drainage Core:

Water passing through the geotextile is intercepted by the drainage core. The water is transported through the open volume of the core, usually by gravity only, to a collector or system outlet. Although its major function is to transport the water to the collection system or outlet, the core also supports the geotextile during construction, and may also serve as a waterproofing barrier or thermal insulation depending on the particular product and application.

For clarity it is useful to distinguish the structural properties of the core from the hydraulic properties. The term "core" will be used to refer to the structure and the term "flow area" to refer to the cross-sectional area within the core structure available to conduct water.

The desired properties of the drainage core are: 1) adequate cross-sectional flow area for the transport of water; 2) compressive strength adequate to maintain flow area under the imposed seepage forces and horizontal soil pressures (resistance to short-term compression and long-term creep); and 3) resistance to physical and chemical degradation.

Since the major function of the drainage core is to transmit water which passes through the geotextile with as little head loss as possible, the hydraulic flow resistance properties of the core under confining stress can be important. The effect of confining stresses on the core cross-sectional area and the potential increase in the hydraulic resistance can be critical to the geocomposite drain design and performance (see Figure 2).

The deformation of the geotextile and drainage core, which can result in a reduction in cross-sectional area available to transport water, may increase with time under constant stress depending on the drain geometry and creep behavior of the component materials. The potential for significant creep effects is an important concern given that the geocomposite drain will in most applications be exposed to confining pressure throughout its service life.

The Collector:

The third component of some geocomposite drain systems is the drainage collector that collects the water from the drainage core and conducts it to a discharge point(s). Typically, the collector is a perforated or porous wall drainage pipe discharging to weep holes or other outlet point(s). The geotechnical concerns with the collector system are potential clogging and a satisfactory direct connection of the drainage core to the collector system. The design of the collector system involves considerations (pipe sizing, etc.) which are hydraulic more than geotechnical. Drainage collector design is not included in the scope of this research.

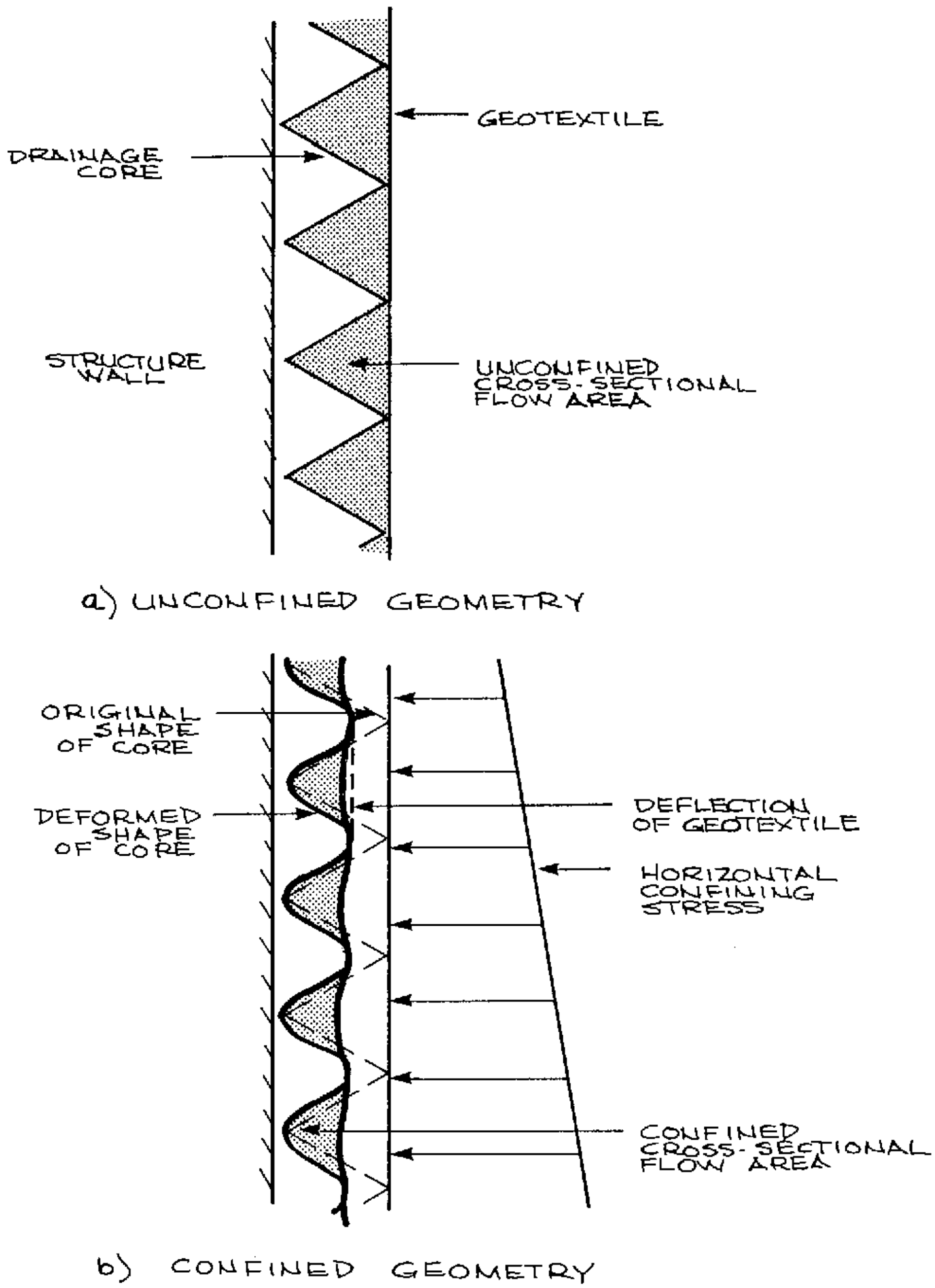


Figure 2 Idealized deformation of a geocomposite drain.

APPLICATIONS OF GEOCOMPOSITE DRAINS

Introduction

The purpose of a geocomposite drain is to collect subsurface water and to convey it to a discharge or collection point(s). This purpose is common to each of the applications discussed below regardless of the variations in other factors specific to a particular application and/or a specific site.

Parameters which may differ in geocomposite drain applications on transportation projects include the following:

- depth of embedment
- confining stress (direction, magnitude, duration, cyclic vs. constant)
- orientation (horizontal, vertical, sloped or irregular)
- confining material (soil, concrete, rock, other)
- drainage surface (one side or both sides)
- collector system
- design life (short-term during construction, life of the structure, etc.)
- exposure to extreme temperatures or other adverse environmental factors
- construction environment (controlled or not controlled, season of year, experience of installer, handling)
- conventional drainage alternatives (cost effectiveness)
- groundwater and soil chemical properties
- groundwater flow conditions
  - steady or intermittent
  - one direction or reversing
  - hydraulic gradient

The potential combinations of the above parameters are innumerable. Therefore, any specific application will involve consideration of different design variables. However, it is possible to discuss typical geocomposite drain applications and the general influence of the major design parameters.

To date geocomposite drain applications have typically been vertical drains behind structures, in cut slopes, and along pavement edges. However, the variety of applications is increasing as manufacturers and designers gain experience with geocomposite drain products. The major applications for transportation (highway) projects are listed in Table 1. Significant considerations for each application are also included in Table 1.

Table 1 Summary of geocomposite drain applications.

Type of Application	Orientation of Drainage Plane	Drainage Surface	Significant Considerations
Adjacent to Retaining Walls	Vertical	One Side	• Resistance to clogging • Compressibility & creep effects on hydraulic properties
Bench Cut Slope Stabilization	Vertical	Two Sides	• Resistance to clogging • Temperature effects
Pavement Edge Drain	Vertical	Two Sides	• Resistance to clogging • Effect of cyclic loading • Temperature effects
Underslab Drain	Horizontal	One Side	• Resistance to clogging • Compressibility & creep effects on hydraulic properties
Backfill Drain	Sloped	One or Two Sides	• Resistance to clogging • Compressibility & creep effects on hydraulic properties

Applications

Since the design variables are numerous and in some cases difficult to quantify, it is convenient to discuss the variables qualitatively with regard to their contribution to the risk of poor structure or project performance. Each variable will influence the risk to different degrees. Depending on the specific application, the influence of any one design variable may or may not be significant. Potential effects of the design variables on risk are presented in Table 2.

Table 2 Effects of major design variables on risk.

Design Variable	"Low"	"High"
Depth of Embedment	Shallow (<10 ft)	Deep (>20 ft)
Design Life	Short (<5 yrs.)	Long (50 to 75 yrs.)
Construction Environment	Controlled Good weather Experienced labor Careful handling	No control Poor weather Inexperienced labor Rough handling
Confining Material	Granular select Backfill (<5 percent fines)	Silt, clay or gap graded fine granular soil
Structure Design	Include limited hydrostatic pressures	No consideration of hydrostatic pressures
Chemical Environment	Non-aggressive	Aggressive

Although the geocomposite drain products have all been developed for the same basic purpose, it is apparent that the manufacturers have, in some cases, tailored their product to a particular application. Not all products are suitable for a given application.

Critical Properties

The properties that are critical to the satisfactory performance of a geocomposite drain depend on the application and on the subsurface soil and groundwater conditions. The most common applications are considered here including pavement edge drains, and drains behind retaining walls and in slopes.

The major function of a geocomposite drain is to collect subsurface water and discharge it into a collection point. In order to accomplish this objective the drain must permit water to seep from the adjacent soil through the geotextile into the core, and then to flow within the core to the collection point. Ideally, this process is achieved with a minimal head loss throughout the design life of the structure.

Critical properties are listed below by application and discussed in the following sections:

Application	Critical Properties
Pavement Edge Drain	High in-plane flow capacity at a low gradient Resistance to relatively high, cyclic stresses Resistance to freezing effects and chemicals (road salt, petroleum, etc.) Hydraulic properties of the geotextile
Retaining Wall Drain	Moderate in-plane flow capacity at high gradients High compressive strength and resistance to creep Hydraulic properties of the geotextile
Slope Drain	Low in-plane flow capacity at moderate gradients Moderate compressive strength and resistance to creep Hydraulic properties of the geotextile

Although the listing of critical properties requires using relative terms, it is obvious that there are four consistent critical properties: 1) compressive strength, 2) creep characteristics, 3) in-plane flow capacity, and 4) hydraulic properties of the geotextile. These properties are very closely related to each other in geocomposite drains. The properties are discussed individually below, but in fact they are interrelated to the extent that they must be considered collectively for any application.

Compressive strength is required to withstand the stresses imposed on the drain by the adjacent soil and any other source. In-situ stresses include lateral earth pressures as well as transient loads due to vehicular traffic or construction traffic. In many cases the stresses are constant but can be cyclic or repeating in other applications such as pavement edge drains. "Quick" compression tests discussed later in this report can be used to get an index of the geocomposite drain compressive strength.

Closely associated with the compressive strength is the ability of the geocomposite drain to resist the imposed stresses without detrimental deformation with time. Creep, deflection of the drain under constant stress over time, is a major consideration when evaluating a geocomposite drain application and/or drain product. The capacity of materials (soil, concrete, steel, etc.) to creep is a well documented phenomenon. Various theories have been proposed to predict the capacity of polymers to creep; however, the current understanding of polymer creep is limited such that creep of geocomposite drains can not be accurately predicted using theoretical methods. Therefore, designers are now forced to utilize creep test results and a considerable amount of engineering judgement when considering creep tendency.

The in-plane flow capacity of the geocomposite drains is an obvious critical property. A typical design objective is that the capacity of the drain be greater than the seepage from the adjacent soil throughout the design life of the application. Intuitively, in-plane flow capacity is a function of the drain geometry and materials, the magnitude and duration of the applied stresses, and the influence of the adjacent soil. These factors are discussed later in this report along with methods of measuring flow capacity within the plane of the drain.

Hydraulic transmissivity and in-plane flow rate are two means of expressing the flow within the plane of the drain. Hydraulic transmissivity is the product of the effective coefficient of permeability and the drain thickness for laminar flow. In-plane flow rate is the volume rate of flow per unit width. Hydraulic transmissivity is the slope of the plot of in-plane flow rate versus gradient. For laminar flow the slope is constant regardless of the gradient. For turbulent flow the slope (hydraulic transmissivity) typically decreases as the gradient increases.

The hydraulic properties of the geotextile include filtering and clogging. Filtering characteristics are a function of the adjacent soil, the opening size distribution in the geotextile, and the flow conditions. Clogging of the geotextile is a function of the adjacent soil and the hydraulic conditions (steady state vs. intermittent flow, etc.) that exist with a given application. Design guidance with respect to geotextile filtering and clogging is provided by Christopher and Holtz (1984), and will not be repeated in this volume.

AVAILABLE GEOCOMPOSITE DRAIN PRODUCTS

Introduction

At present, there are at least sixteen geocomposite drain products available in the United States and that number has increased steadily in recent years. Several new products were introduced during the course of this one-year study. This proliferation has lead to a confusing variety of drain designs from which the engineer must choose when specifying a geocomposite drain system. There are also several products in foreign markets which are not currently available in the U.S.

Summary of Products

The following section is a brief overview of the major products that are currently known to be available in the U.S. It may not be all-inclusive, since new products are being introduced continually, but an effort has been made to include all of the known products at the time of this report.

The following summary lists the products, and their manufacturer/distributors.

Product Name	Manufacturer/Distributor
Amerdrain™ 360	American Wick Drain Corp.
Eljen® Drainage System	Eljen Corp.
Enkadrain® 9010	BASF Corporation
Enkadrain® 9120	" "
GEOFAB	Merchantile Development, Inc.
GEOTECH™ Drainage Board	GeoTech Systems Corp.
HITEK™ Cordrain™	Burcan Manufacturing, Inc.
HITEK™ Stripdrain™	" " "
Hydraway™	Monsanto Co.
Miradrain™ 4000	Mirafi, Inc.
Miradrain™ 6000	" "
Nudrain™ A	Spencer Lemaire Industries Ltd.
Nudrain™ B	" " " "
Permadrain®	N.W. Fabrics Company

Stripdrain 75	Armco, Inc.
Stripdrain 150	" "
Tensar^{R} DN-1	The Tensar Corp.

In order to obtain information on the configuration and materials used for the products, a questionnaire was sent to each of the manufacturers/distributors requesting information on their products. A tabulated summary of the information regarding the manufacturer/distributor and the responses obtained are included in Tables 3 and 4. Photographs of the available geocomposite products are provided in Figure 3. Brief summaries of the available products follow:

Amerdrain^{TM} 360:

Amerdrain^{TM} 360 is a fairly thin (5/16 in) geocomposite with a channelized core which was formerly of polypropylene, but which is now formed of high density polyethylene. A nonwoven, spun-bonded polypropylene filter fabric (DuPont Typar 3341) is bonded to one side although other types of fabrics are available. The channelized core appears to be highly directional in its flow properties. Relatively unobstructed flow can occur along the longitudinal channels, but the intermittent cross channels may restrict flow perpendicular to the longitudinal channels. Like most of the geocomposites, flow perpendicular to the plane of the core is not allowed. The product is available in 48 in by 96 in panels which may be nailed or glued in place when used in vertical orientation behind walls.

Eljen^{R} Drainage System:

The Eljen^{R} Drainage System consists of a waffle-shaped core of high impact polystyrene that is 5/8 in thick, and covered on both sides by a nonwoven, heatbonded Terram fabric which is 85 percent polypropylene. Other types of fabrics are available for use as well. The fabric is not bonded to the core, and the drainage system includes an integral drainage pipe inside the fabric sleeve. This product is available in panels of variable height and widths of 5, 10, and 25 ft.

Enkadrain^{R}:

The Enkadrain^{R} products have a core design which is unique among geocomposite drains. It consists of wire-like fibers of Nylon-6 polymer which have been stamped into an approximate waffle shape and allowed to cool into a relatively stiff nonwoven mat. The 9010 product is the thinner of the two, 0.4 in thick and weighing 13.7 oz/sq yd, while the 9120 is 0.8 in thick and weighs 23.6 oz/sq yd. The filter fabric for both drains is Stabilenka Type 100, a nonwoven polyester fabric that is bonded to one side of the Nylon-6 core. Both of these products are available in rolls 38.2 in wide and 99 ft long.

Table 3 Manufacturers/distributors of geocomposite drain products.

Product Name	Manufacturer / Distributor
Amerdrain™ 360	American Wick Drain Corp. 301 Warehouse Drive Matthews, North Carolina 28105. (800) 438-9281
Eljen® Drainage System	Eljen Corporation 15 Westwood Road Storrs, Connecticut 06268. (203) 429-9486
Enkadrain® 9120 9010	BASF Corporation Enka, North Carolina 28728 (704) 667-7110
GEOTECH™ Drainage Bd.	GeoTech Systems Corp. 100 Powers Court Sterling, Virginia 22170. (703) 450-2366
HITEK™ Cordrain™ Stripdrain™	Burcan Manufacturing, Inc. 111 Industrial Drive, Suite 19 Whitby, Ontario, Canada L1N 5Z9. (416) 668-3131
Hydraway™	Monsanto Engineered Products Div. 800 N. Lindbergh Boulevard St. Louis, Missouri 63167. (800) 325-4330
Miradrain™ 4000 6000	Mirafi®, Inc. P.O. Box 240967 Charlotte, North Carolina 28224. (800) 438-1855
Nudrain™ A,B	Nilex Geotechnical Products, Inc. P.O. Box 4063 Edmonton, Alberta, Canada T6E 4S8. (403) 463-9535
Permadrain®	NW Fabrics Company P.O. Box 77 Devon, Pennsylvania 19333. (215) 647-6477
Stripdrain 75,150	ARMCO Inc. Construction Products Div. 1001 Grove Street Middletown, Ohio 45042. (513) 425-5088
Tensar® DN1	The Tensar Corporation 1210 Citizens Parkway Morrow, Georgia 30260. (800) 845-4453

Table 4 Summary of geocomposite manufacturer's questionnaire response and product literature.

Product	General Data Rolls/Sheets	Approx. Size (ft)	Overall Thickness (in)	Weight oz/yd^2
Amerdrain™ 360	Sheets	4 X 8	0.31	24
Eljen® Drainage System	Rolls	1 to 25 X 25 to 5	0.63	29
Enkadrain® 9010	Rolls	3 X 99	0.46	10 to 14
Enkadrain® 9120	Rolls	3 X 99	0.86	19 to 24
GEOTECH™ Drainage Board	Sheets	4 X 4	2 to 24	45 (2"t)
HITEK™ 8	Rolls	0.3 to 3.7 X 164	0.34	10
HITEK™ Cordrain™	Rolls	0.3 to 3.7 X 164	0.82	18.7
HITEK™ Stripdrain™	Rolls	0.3 to 3.5 X 164	1.60	33
Hydraway™	Rolls	3 X 200 1 X 400 1.5 X 400	1.0	50
Miradrain™ 4000	Sheets	4 X 8	0.75	26
Miradrain™ 6000	Sheets	4 X 8	0.377	26
Nudrain™ A	Rolls	1 & 1.5 X 49	1.60	35.4
Nudrain™ B	Rolls	0.5 X 49	0.40	17.7
Permadrain®	Rolls	3.3 to 9.6 X 24	0.75	36
Stripdrain 75	Rolls	0.7 to 3.7 X 180	0.75	28.8
Stripdrain 150	Rolls	0.5 to 3.5 X 80	1.50	43.2
Tensar® DN1	Rolls	5.6 X 100	0.25	30.2

Table 4 Summary of geocomposite manufacturer's questionnaire response and product literature (continued).

	Geotextile Data			
Product	Material*	Fabrication**	Trade Name	Other Options
Amerdrain™ 360	PP	NW, SB	Typar 3341	Yes
Eljen® Drainage System	PP	NW, HB	Terram	Yes
Enkadrain® 9010	PE	NW	Stabilenka	Yes (3)
Enkadrain® 9120	PE	NW	Stabilenka	Yes (3)
GEOTECH™ Drainage Board	Can laminate any geotextile			
HITEK™ 8	PP	NW	Typar 3401	Yes
HITEK™ Cordrain™	PP	NW	Typar 3401	Yes
HITEK™ Stripdrain™	PP	NW	Typar 3401	Yes
Hydraway™	PP	NW,NP,HS	--	No
Miradrain™ 4000	PP	NW, NP	Mirafi 140N	Yes (2)
Miradrain™ 6000	PP	NW, NP	Mirafi 140N	Yes (2)
Nudrain™ A	PP	NW	Typar	--
Nudrain™ B	PP	NW	Typar	--
Permadrain®	PE	NW, NP	Polytex	Yes (6)
Stripdrain 75	PE	NW	Trevira	No
Stripdrain 150	PE	NW	Trevira	No
Tensar® DN1	PP	NW	Typar	Yes

* Legend:
- PE Polyester
- PP Polypropylene

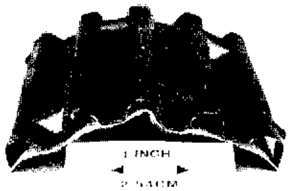
** Legend:
- HB Heat bonded
- HS Heat set
- NP Needle punched
- NW Nonwoven

Table 4 Summary of geocomposite manufacturer's questionnaire response and product literature (continued).

	Core Data		
Product	Type	Material*	Compressive Strength (psi)
Amerdrain^{TM} 360	Channels	HDPE	28
Eljen^{R} Drainage System	Waffle	HIPS	30
Enkadrain^{R} 9010	Fibers	Nylon 6	7
Enkadrain^{R} 9120	Fibers	Nylon 6	16
GEOTECH^{TM} Drainage Board	Beads	EP	6
HITEK^{TM} 8	Waffle	HDPE	70
HITEK^{TM} Cordrain^{TM}	Waffle	HDPE	40
HITEK^{TM} Stripdrain^{TM}	Waffle	HDPE	20
Hydraway^{TM}	Columns	LDPE	60
Miradrain^{TM} 4000	Waffle	HIPS	30
Miradrain^{TM} 6000	Dimpled Sheet	HIPS	75
Nudrain^{TM} A	Waffle	ABS	40
Nudrain^{TM} B	Waffle	PP	15
Permadrain^{R}	Waffle	HDPE	28
Stripdrain 75	Waffle	HDPE	35
Stripdrain 150	Waffle	HDPE	20
Tensar^{R} DN1	Grid	LDPE	--

* Legend:

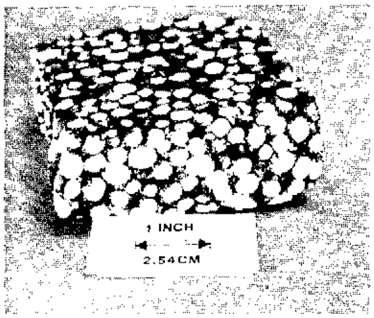
ABS Acrylonitrile-Butadiene-Styrene
EP Expanded Polystyrene
HDPE High Density Polyethylene
HIPS High Impact Polystyrene
LDPE Low Density Polyethylene
PP Polypropylene



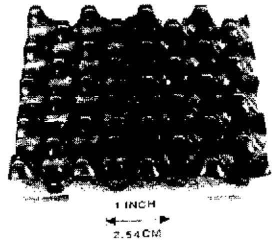
a. Amerdrain™ 360

b. Eljen® Drainage System

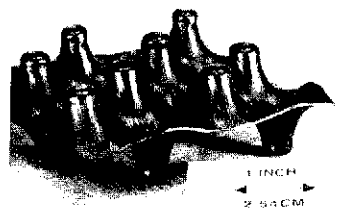
c. Enkadrain® 9120



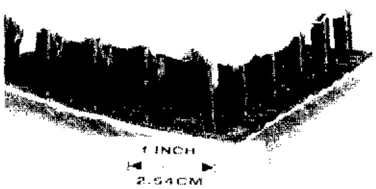
d. GEOTECH® Drainage Board



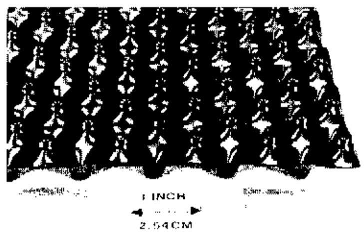
e. HITEK™ Cordrain™



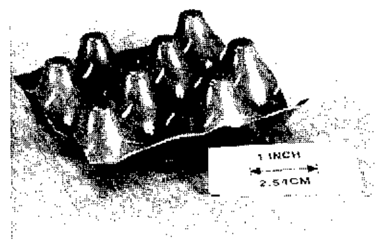
f. HITEK™ Stripdrain™



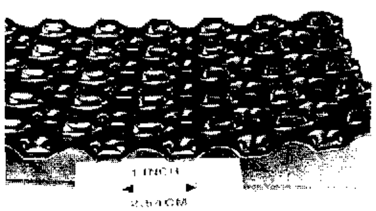
g. Hydraway™



h. Miradrain™ 4000

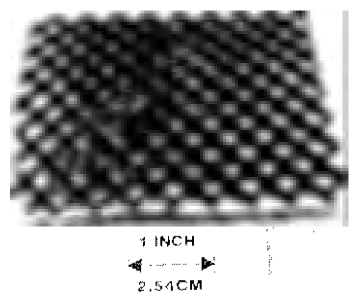


i. Nudrain™ A



j. Permadrain®

k. Stripdrain 75



l. Tensar® DN1

Figure 3 Photographs of available geocomposite drain products.

GEOFAB:

GEOFAB consists of a 0.75 in thick waffle shaped core of high impact polystyrene covered by a nonwoven polypropylene filter fabric. The geocomposite material weighs 24 oz/sq yd, and is available in sheets 5 ft by 10 ft.

GEOTECH™:

GEOTECH™ Insulated Drainage Panel is a product which can serve both as a drainage and insulation material. This is due to the expanded polystyrene bead core. The approximately 0.25 in diameter polystyrene beads in the core are glued together by a bitumen binder into large blocks which are then sliced into panels that are 4 ft square and from 1 to 24 in thick. A geotextile is then laminated to the panel to form the geocomposite. Both the thickness of the panels, and the type of geotextile may be specified by the user. The resulting product weighs 45 oz/sq yd for a 2 in thickness.

HITEK™ Cordrain™:

Manufactured by the Canadian firm of Burcan Manufacturing, HITEK™ Cordrain™ has a 0.82 in thick waffle-shaped core of high density polyethylene, which is available with geotextile either bonded to one side or wrapped around both sides and unbonded. The standard filter fabric used is Typar 3401, a spun bonded polypropylene geotextile. Other types of filter fabric may be specified by the user. HITEK™ Cordrain™ is available in rolls from 4 to 44 in wide by 164 ft long, and weighs 18.7 oz/sq yd.

HITEK™ Stripdrain™:

HITEK™ Stripdrain™ has a 1.6 in thick waffle shaped core of high density polyethylene, wrapped on both sides by Typar 3401 polypropylene fabric which is not bonded to the core. This product is available in rolls from 4 to 42 in wide and 164 ft long, and weighs 33 oz/sq yd. Other types of geotextile are available upon request.

Hydraway™:

Monsanto's Hydraway™ Drain consists of a 1 in thick core of 0.25 in diameter hollow cylinders of linear low density polyethylene protruding from a permeable base and wrapped on both sides by Amoco 4545, a nonwoven, needled, heatset fabric of polypropylene which is firmly bonded to the core. Intended primarily for use as a pavement edge drain, the material is machine-installable with standard trenching equipment, and comes in rolls of 12 and 18 in wide by 400 ft long, as well as 36 in wide and 200 ft long. The wider material is suitable for use as a sheet geocomposite drain.

Miradrain™ 4000:

Miradrain™ 4000 consists of a lightweight waffle-shaped core of high impact polystyrene 0.75 in thick. It is covered on one or both sides (at the user's option) with Mirafi 140N geotextile, a nonwoven needle-punched fabric of polypropylene, which is bonded to the core. The total weight of the product is 26.1 oz/sq yd, and flow channels occur on both sides of the core. It is available in 4 ft by 8 ft sheets.

Miradrain™ 6000:

Miradrain™ 6000 has a thinner polystyrene core that is flat on one side, with small (approximately 0.25 in dia.) dimples protruding from the other side to supply flow area. The product is 0.38 in thick and weighs 26.1 oz/sq yd. It is covered on the dimpled side by Mirafi 140N which is bonded to the core.

Nudrain™ A and B:

Two very different products called Nudrain™ A and Nudrain™ B are distributed by Nilex Geotechnical Products, Incorporated. Nudrain™ A has a thick (1.5 in) waffle-shaped core of ABS polymer (Acrylonitrile-Butadiene-Styrene). The core is covered on both sides by DuPont Typar fabric, a nonwoven polypropylene geotextile which is not bonded to the core. Nudrain™ A weighs 35.4 oz/sq yd and is available in rolls 49 ft long and in two widths, 10 and 20 in. It is intended primarily for use as a pavement edge drain.

Nudrain™ B has a thinner (0.35 in) core of polypropylene in a waffle shape, covered also by DuPont Typar fabric which is bonded to one side of the core. This product weighs 17.7 oz/sq yd, and is available in rolls 59 in wide and 41 ft long.

Permadrain®:

Permadrain® has a 0.75 in thick waffle-shaped core made of high density polyethylene. The core is covered by a Polytex needle-punched, nonwoven polyester geotextile, which is manufactured in six different weights, and bonded to the core on one side. The geocomposite material weighs approximately 36 oz/sq yd, and is available in rolls 39 to 115 in wide.

Stripdrain 75 and 150:

Distributed by Armco Construction Products Division, the two Stripdrain products each have yellow waffle-shaped cores made of high density polyethylene. Stripdrain 75 has a 0.75 in thick core with Hoechst TREVIRA S61170 fabric bonded to one side. This fabric is a 70 mil nonwoven polyester geotextile. Stripdrain 75 weighs 28.8 oz/sq yd, and is available in rolls in several widths from 8 in to 44 in and up to 180 ft long.

Stripdrain 150 has a 1.5 in thick core wrapped all around with Hoechst TREVIRA, and glued at the overlapped seam. It weighs 43.2 oz/sq yd, and is available in rolls of 5 to 40 in wide and up to 80 ft long.

Tensar^R:

A recent product to the market, Tensar's prototype drain is composed basically of Tensar^R DN1 geogrid material with a geotextile laminated to the face. DN1 is an open grid-like structure made of low density polyethylene, weighing approximately 23 oz/sq yd and 0.25 in thick. The DN1 grids are spaced approximately 0.37 in apart. The fabric that will ultimately be used has not yet been determined.

The polymer used to fabricate the geotextile and the drainage core is a major factor in the physical properties of the geocomposite drain. Common polymer types were studied and a summary of their important characteristics was prepared (see Appendix A).

It is possible with many of the geocomposites to special order the geotextile or to purchase the core without a geotextile. These options give the designer considerable flexibility in the area of geotextile design and application. With the flexibility to design the geotextile, the designer can be more selective in matching the properties of the geotextile to the specific field conditions. It is also possible to attach the geotextile in the field with some of the products.

As part of the product information survey, cost information was obtained for the various products. Because the cost for the products is so highly dependent on the quantity required and geographic location of a specific project, prices for each product are not reported here. However, the information obtained for the cost of materials only is summarized as follows:

	Geocomposite Drain Product Cost ($/sq ft)
Range	0.55 to 1.55
Mean	1.10

The range in cost is attributed mainly to the variations in product characteristics (weight, thickness, geotextile on one side or wrapped around both, etc.).

LABORATORY AND FIELD TESTING

Introduction

The drain manufacturers were requested to provide any available field and laboratory test results applicable to geocomposite drains. Test results were received from most of the manufacturers. The scope of the test results provided varied considerably, but was limited to one manufacturer's product (i.e., no comparative testing with other products) and to laboratory tests (i.e., no field testing) with one exception.

It should be realized that due to the competitiveness of the relatively new geocomposite drain market, it is probable that the manufacturers have performed more extensive tests on their own product and comparative tests with other products; however, they either are not able or willing to release that information at this time.

Laboratory Testing by Others

Laboratory testing of geocomposite drain products has concentrated on testing of systems (geotextiles and drainage cores) and on the hydraulic transmissivity (i.e., flow within the plane of the drainage core) of the system in a confined state. No information has been found on any laboratory testing of geocomposite drain products specifically to evaluate the flow perpendicular to the geotextile or in the plane of the geotextile itself. It appears that the manufacturers are relying on previous research and laboratory testing of the geotextiles.

Extensive laboratory tests on geocomposite drain systems have been performed by or under contract with The Tensar Corporation, Mirafi Inc., and Monsanto Company. H&A has met with these parties to discuss their test methods and results.

The testing by Tensar and Mirafi has concentrated primarily on measuring the hydraulic properties of their geocomposite drain products under confining stress. Figures 4 through 8 are conceptual presentations of some of the test results obtained by these other researchers. The test results can be summarized as follows:

- The available geocomposite drain products have considerably different stress-strain relationships when tested in compression (see Figure 4). At compressive stresses within the working stress range for typical geocomposite drain applications the percent strain ranged from less than 10 percent to more than 50 percent.

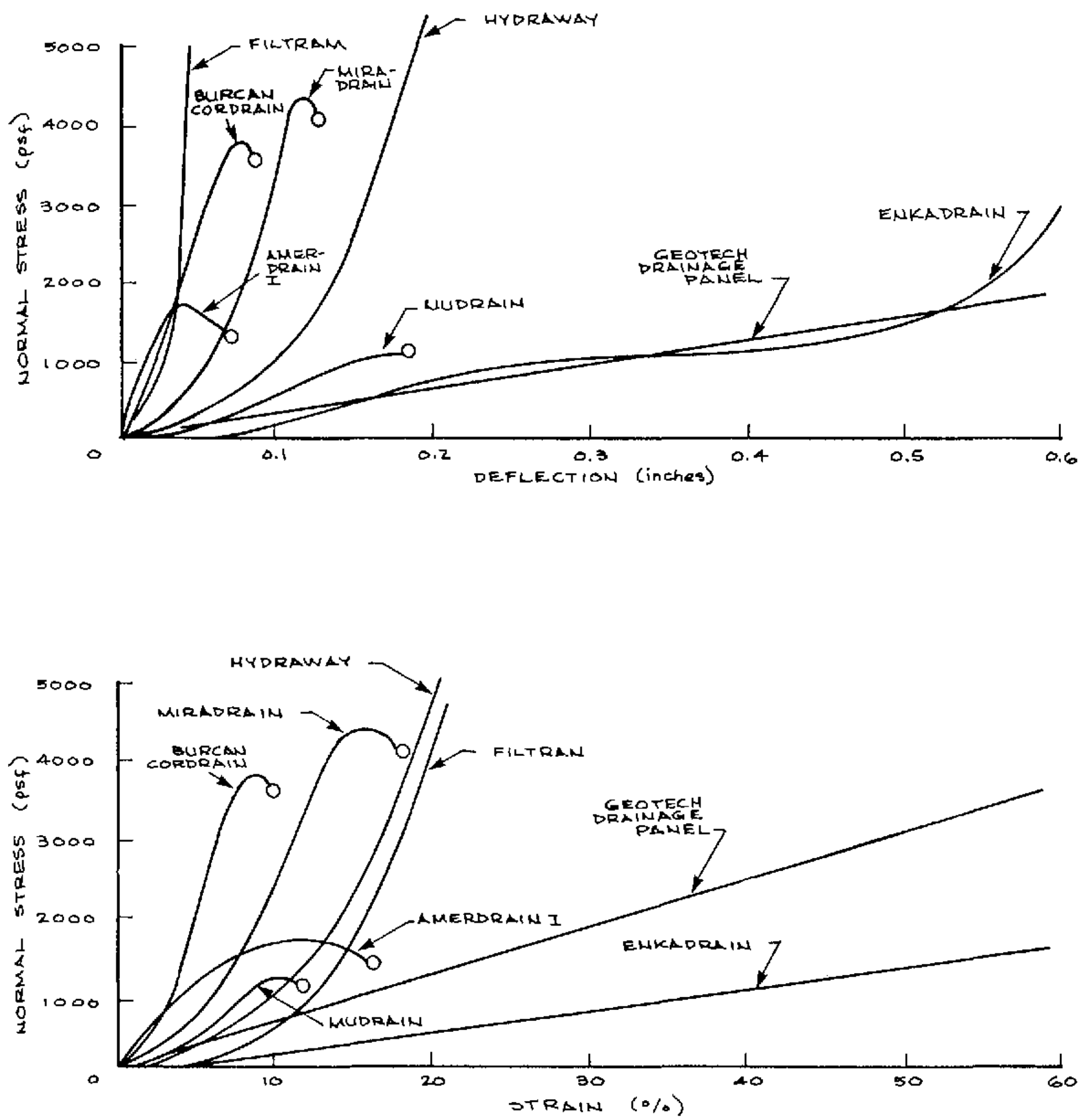


Figure 4 Compressibility behavior of geocomposite drain products (Luciani, 1985).

- Hydraulic transmissivity (the volume flow rate in the plane of the core per unit width) decreases with increasing confining stress (see Figure 5). The magnitude of the decrease is influenced in part by the compressibility of the system (drainage core and geotextile) as well as the material in contact with the geocomposite drain (i.e., manner in which the confining stress is applied).

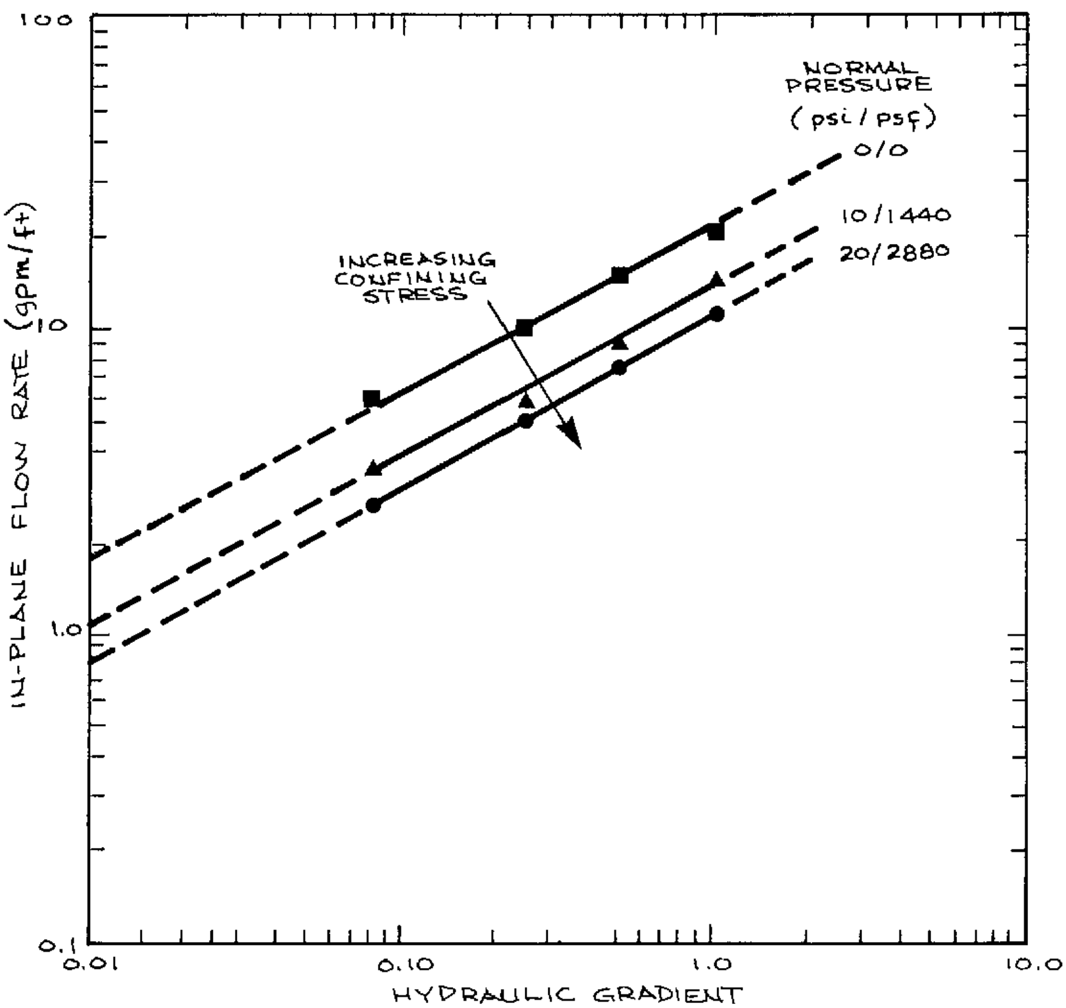


Figure 5 General effect of confining stress on in-plane flow (Luciani, 1985).

- The test results indicate that flow through geocomposite drain products may be either laminar or turbulent. With turbulent flow (see Figure 6) the hydraulic transmissivity will decrease with increasing gradient (i.e., flow is a non-linear function of hydraulic gradient). This is a significant departure from the usual geotechnical assumptions of laminar flow and the applicability of Darcy's law (flow is a linear function of the hydraulic gradient).

- Penetration of the geotextiles and the confining media into the core flow area tend to reduce the hydraulic transmissivity of the confined geocomposite drain. The reduction is typically greater with needle punched geotextiles than heatbonded geotextiles (see Figure 7).

- The effect of the confining media (rigid plate, sand, clay, or flexible membrane) was measurable and as expected any material that would tend to penetrate into the core openings reduced the hydraulic transmissivity (see Figure 8). The effect was a hydraulic transmissivity reduction ranging from 20 to 50 percent which is considerably more than the observed reduction due to the difference between needle punched and heatbonded material (see Figure 7).

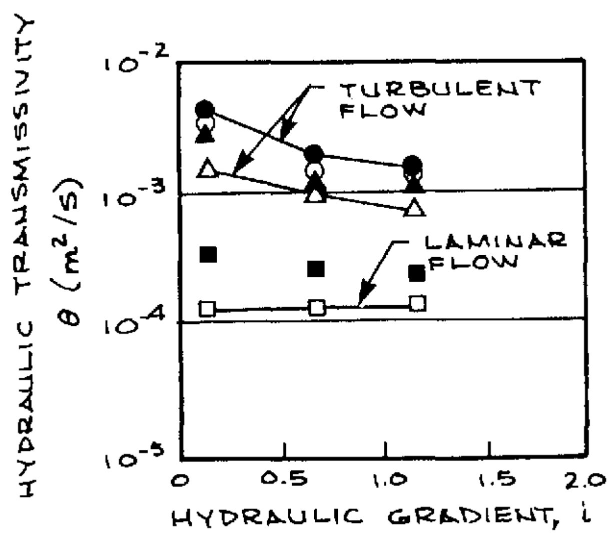


Figure 6 Examples of turbulent and laminar in-plane flow (Williams, et al., 1984).

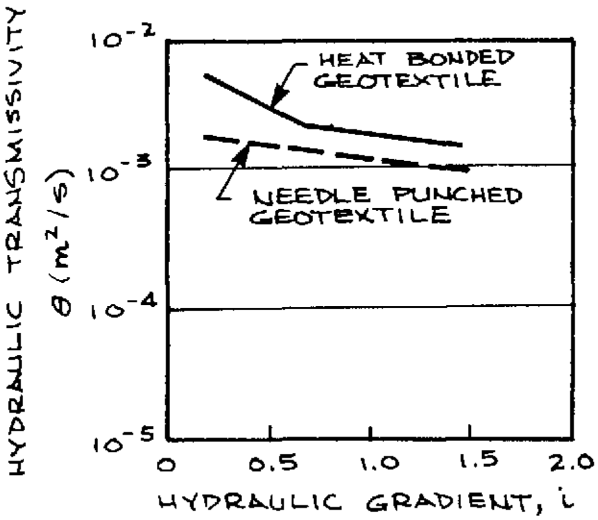
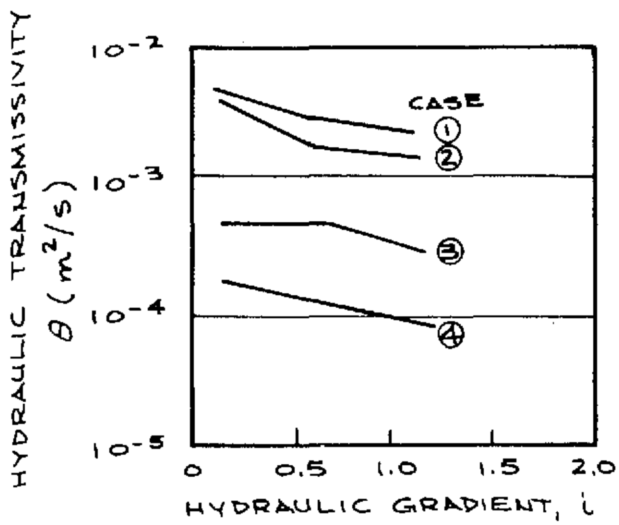


Figure 7 Example of the effect of the geotextile on in-plane flow (Williams, et al., 1984).



CASE	UPPER BOUNDARY	LOWER BOUNDARY
①	STEEL PLATE	STEEL PLATE
②	CLAY / HEAT BONDED GEOTEXTILE	STEEL PLATE
③	CLAY/ HEAT BONDED GEOTEXTILE	HEAT BONDED GEOTEXTILE / CLAY
④	CLAY / GEOMEMBRANE	GEOMEMBRANE / CLAY

Figure 8 Effect of the media in contact with the geocomposite drain (Williams, et al., 1984).

- The possible effects of creep varied considerably depending on the geocomposite drain product. For the more rigid core materials creep effects were apparently insignificant over the test stress ranges. For the more compressible cores creep effects were readily apparent. Many of the geocomposite drains exhibited substantial creep effects in various test apparatus.

- The hydraulic transmissivity is a function of the temperature of the system and the water. Therefore, testing for any application should consider the effect of anticipated ambient temperatures.

<u>Field Testing by Others</u>

As part of Phase I of this research, selected highway departments and other agencies, as well as manufacturers, were contacted to identify locations where field testing of geocomposite drain products has been performed and to obtain the results of the testing. In general, the field testing that has been performed has been almost exclusively qualitative - are the geocomposite drain products functioning satisfactorily or not? H&A is aware of three organizations, PennDOT, Monsanto and the U.S. Forest Service, that are conducting long-term field testing of geocomposite drain products.

PennDOT is researching the effectiveness, both in performance and cost, of using geocomposite drain pavement edge drains (Monsanto Drainage Mat) for both new and retrofit construction. Based on price bids, PennDOT has concluded that the installed cost of the geocomposite edge drain is currently approximately 60 percent of the installed cost of their standard coarse aggregate edge drain (geotextile filter with crushed stone and drainage pipe). PennDOT is currently monitoring a test section with both drain types to evaluate their comparative performance. No quantitative performance results are available at this time, but the geocomposite edge drains appear to be functioning satisfactorily.

Monsanto has performed comparative laboratory and field testing with their Hydraway product. In general the data indicate that the Hydraway product can transmit more water than a standard Illinois pavement edge drain section (concrete sand with a drain pipe).

The U.S. Forest Service is interested in the application of geocomposite drain products in remote areas where the use of coarse aggregate is costly due to the required hauling. In California the Forest Service has undertaken a laboratory and field testing program to determine the effectiveness of the geocomposite drain products. The emphasis of its program has been in field installations where piezometers have been installed behind and in front of several retaining walls with geocomposite drains to obtain daily maximum/minimum groundwater readings. The Forest Service has not published any of the results, but indicated during an H&A visit to their facility that the initial results show that the piezometric surface was consistently and substantially lowered by the geocomposite drain products. The Forest Service intends to expand its field monitoring to include tipping bucket rain gages to measure outflow from the geocomposite drain installations.

H&A Testing of Geocomposite Drains

During the preparation of the proposal for the Task D modification contract, H&A was provided with a general description of the laboratory testing program that FHWA envisioned for Task D. In the proposal, the anticipated objectives of Task D.5 were stated to be: "Evaluate the drain properties identified in Task D.2 using either existing standard laboratory tests, or test procedures developed by the drain manufacturers. The tests will focus on those properties which appear to have a direct impact on the product performance, such as:

a. Compressibility, elasticity, and long-term creep.
b. Flow capacity as a function of compressibility.
c. Long-term permeability.
d. Long-term clogging potential."

The overall objective of the Phase II laboratory testing was to investigate important properties for the evaluation of geocomposite drain products. Previous research, including the FHWA study of geotextile engineering (Christopher and Holtz, 1984), has summarized the state-of-the-art understanding of the critical properties of the geotextiles. Therefore, it was decided that the H&A laboratory testing of geocomposite drains should concentrate on the properties of the drainage core and the geocomposite drain system.

Based on the summary information provided above and discussions with others who have tested geocomposite drain products, the following Phase II test program was proposed.

Compressibility and Elasticity:

Each of the available geocomposite drain products (11 at the time the Phase II scope was developed) was to be tested in a universal compression machine to evaluate short-term, stress-strain properties including:

- Stress vs. deflection
- Stress vs. strain
- Ultimate crushing strength
- Variation in stress-strain characteristics with different samples of the same geocomposite drain product

Long-Term Creep:

A minimum of six of the geocomposite drain products were to be confined under plane strain conditions in an apparatus similar to that shown in Figure 9 to evaluate creep potential. The samples were to be confined by pressures ranging from 0 to 5,000 psf (typical of the range for most geocomposite drain applications) for a minimum time of one week per stress increment or until the creep had stabilized, whichever was less. Samples for creep evaluation were to be selected based on their performance in the short-term compressibility and elasticity tests described above.

Flow Capacity as a Function of Compressibility:

A minimum of six of the geocomposite drain products were to be confined under plane strain conditions in an apparatus similar to that shown in Figure 10 to evaluate flow capacity (hydraulic transmissivity) as a function of confining stress. The apparatus and general test procedure was to be that of the proposed

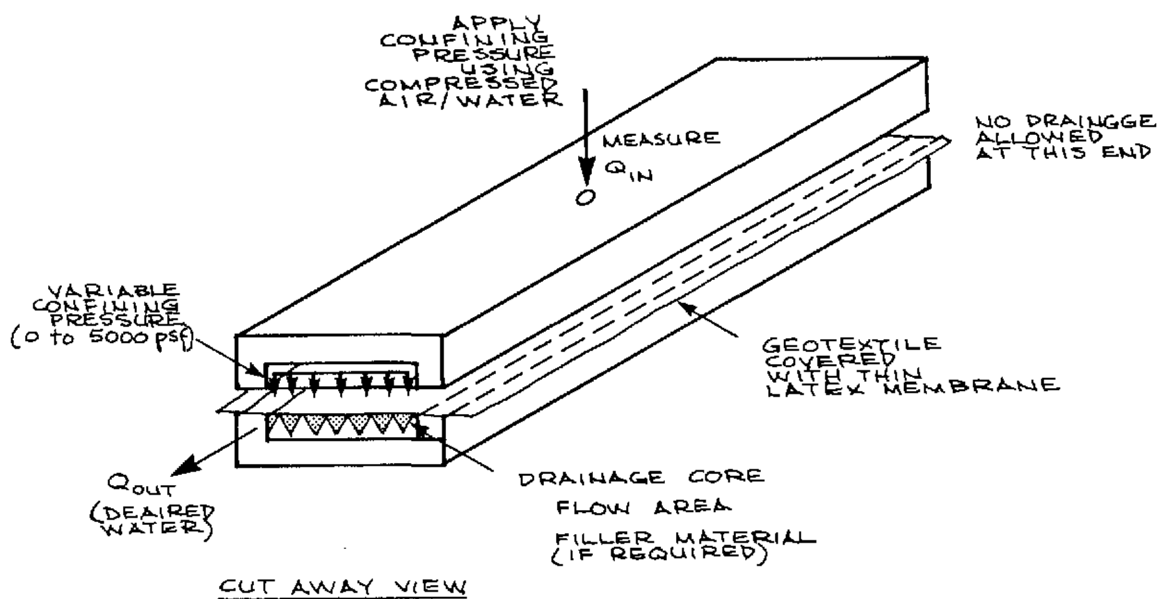


Figure 9 Proposed apparatus to measure compressibility and long term creep of geocomposite drains.

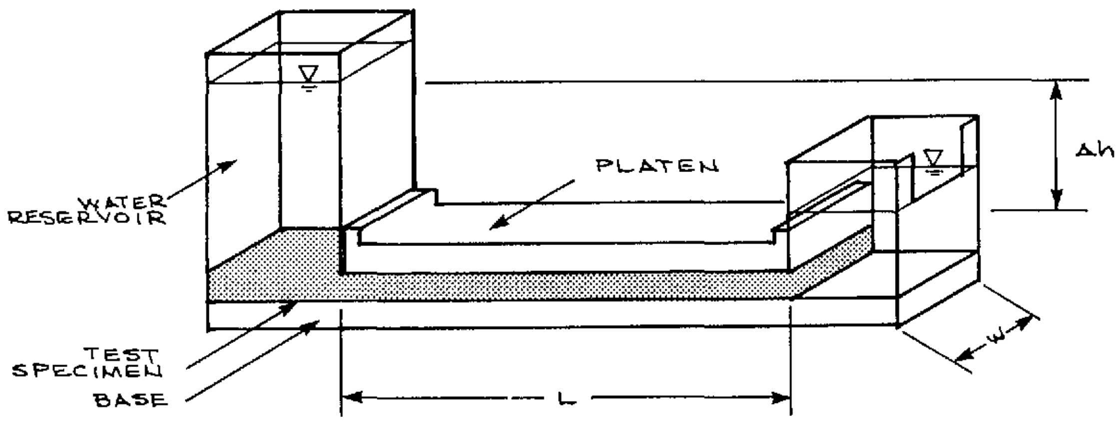


Figure 10   Proposed constant head in-plane flow testing device.

ASTM Standard Test Method for Testing Constant Head Hydraulic Transmissivity (In-plane Flow) of Geotextiles and Geotextile Related Products. If appropriate, minor modifications were to be made in the proposed test procedure which is currently being developed by the ASTM committee.

Long-Term Permeability:

The available technical literature and information obtained from manufacturers and researchers was to be summarized for ready reference. No actual laboratory testing was to be performed since the results would only apply to a specific geotextile/soil combination and current practice is documented by previous FHWA research.

Long-Term Clogging Potential:

Available information was to be summarized. No actual laboratory testing was to be performed since no "standard" test exists, and the results of any testing would only apply to a specific geotextile/soil combination.

All of the proposed testing was performed on geocomposite drain systems or on the drainage core alone. Testing was focused on the system or core for three reasons: 1) There is a need for comprehensive comparative test results on geocomposite drain systems; 2) Design engineers interested in a specific project will most likely test systems; and 3) There are a multitude of geotextiles that might be used in a geocomposite drain and therefore, any geotextile-dependent testing (i.e., permeability and clogging testing) would pertain only to the soil/geotextile selected for testing.

The program of laboratory testing of selected geocomposite drains was developed to better define which types of tests provide the most useful design information, and which tests might reveal the differences among the various products while having application to all of them.

Four different types of tests were performed: compression tests, core creep tests, system creep tests, and in-plane flow tests. Not all of the available geocomposite drains were subjected to each type of test, although some products were subjected to all four types. A description of each type of test, and an evaluation of each test based upon the results of the testing program follow. A complete record of all data, along with summaries and/or graphs of the results of all tests performed during the testing program is available in the accompanying data summary report.

Compression Tests:

Compression tests were performed as a part of this research because the test is a simple and useful procedure which is performed on a wide variety of engineering materials, and the equipment for performing the test is readily-available in most testing laboratories. The testing procedure is generally familiar to all civil engineers, and many geocomposite drain manufacturers have performed this test on their product and published test results in promotional literature. In addition, it was suspected that moisture and temperature conditions during testing might have a significant effect on the results that are obtained from these tests. For this reason, tests were run on samples that had been subjected to a range of climatic conditions to determine what effect these conditions would have on the results.

Under contract to Haley & Aldrich, thirty-one compression tests were performed by the geotechnical engineering laboratory at The Massachusetts Institute of Technology, Cambridge, MA. The products were tested to failure in static compression by loading them between flat metal plates perpendicular to the plane of their cores in a standard compression machine at a strain rate of approximately 10 percent/minute. These tests were run on 4.25 in by 4.25 in samples of twelve geocomposite products which had been prepared in one of four different ways. All of the twelve products were tested once while in dry condition and at room temperature, and once while dry and frozen to at least -18° Celsius. Certain products were also tested while wet after having been soaked for at least 24 hours, and while wet and confined in a brass box to prevent lateral displacement.

The results of the compression tests performed on dry samples (see Figure 11) indicate that the stress-strain characteristics tend to fall into three general categories: those with a yield stress within the range of working stresses for geocomposite drain applications, those exhibiting a yield stress above the range of working stresses, and those which displayed no distinct yield point at all, but rather yielded continuously with increase in stress. The indication of failure, if any, in this last group is very difficult to detect. A yielding criterion for these products will probably have to be based on a specified strain level. Since most of the other products reached yield stresses at strains from 10 to 20 percent, it seems reasonable to use the stress at 10 percent strain as the "yield stress" for any product that does not exhibit yielding when strained beyond 20 percent.

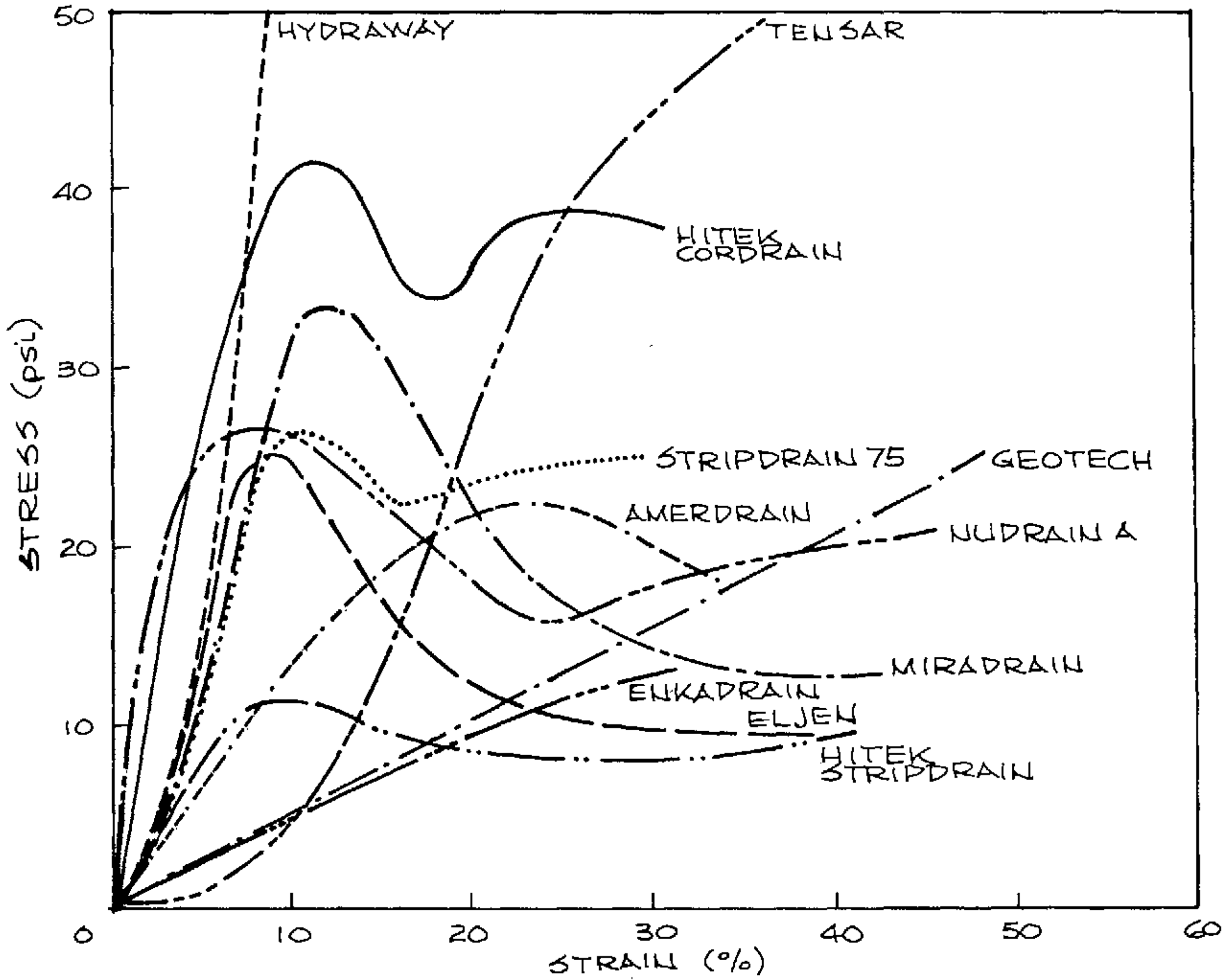
The differences among the tests on the same product that were performed under different climatic conditions were not found to be significant enough to warrant special concern regarding moisture or low temperature effects. As a rule, all of the tests on the same product displayed a similar yielding behavior regardless of the sample preparation.

The compression test was found to be a good classification or index test to differentiate among products, but it has limited applicability for determining design parameters due to the significant differences between the testing configuration and service conditions. In particular, the flat plates used to apply the load during the compression test tend to induce stress concentrations in the core of most of the products that will not be present in service.

Factors that can adversely affect the results of compression tests include small sample size, eccentricity of loading, and the presence of secondary yield phenomena due to the geometry of the geocomposite core.

Small sample size was discovered to be a problem for several of the products that were tested in this study. Due to the large cuspations (i.e., waffle shapes) present on some of the thicker products, the 4.25 in square samples included only a limited number of nodes. Nodes that are on the edges and corners of the samples were unable to support a representative share of the load, since they rely on the next node for a portion of their support. Therefore, larger samples are required in order to reliably test these products in compression.

Eccentricity of loading may become an issue for the testing of products whose core geometry makes their compressive strength highly direction dependent. Tests on products such as Monsanto's Hydraway, which has a core composed of small columns which tended to fail by column buckling, may be prone to such problems.



NOTE:
ALL SAMPLES (4.25" x 4.25") TESTED DRY AND AT ROOM TEMPERATURE.

Figure 11 Compression test results for various geocomposite drain samples.

Also, several of the products displayed a secondary yielding phenomenon when the tips of their cuspations buckled into a shape that was stable enough to support additional load, but which would not represent a favorable flow geometry.

The major conclusion reached from these observations is that all data on test conditions must be known and that care should be exercised whenever compression test results are evaluated for use in design of geocomposite drain systems.

Core Creep Tests:

All of the geocomposite products obtained for this study have cores formed of thermoplastic polymers. Such polymer materials are viscoelastic (elastic compression during relatively rapid increasing stress; creep under constant stress), and display marked creep behavior under constant stress. As a result of creep strain, the available flow area in the core, and possibly the effectiveness of the drain, can be reduced with time under constant stress conditions. To determine the potential for creep deformation of the polymer cores, constant stress creep tests, similar to those performed by Luciani (1985), were performed by loading samples of the geocomposite cores between two rigid metal plates and measuring the resulting deflection under constant stress.

The core creep tests were performed by placing 4.25 in by 4.25 in square samples of the geocomposite drains in a close fitting metal box with rigid plates on all sides of the sample to achieve a plane strain condition. A stress was applied to the top of the sample by means of a lever arm soil consolidometer. Assuming that the plate was rigid, the applied load results in a uniform displacement of the rigid plate with a non-uniform stress transferred to the sample. The resulting displacement was measured as time progressed using a dial gauge. After sufficient data were recorded (up to three days elapsed time), the applied load was increased and the process repeated.

Results of the core creep tests indicate that all of the polymer cores creep under stress to some extent with time. The magnitude depends on the nominal stress level and duration of load, as can be seen in Figure 12. Upward curvature of the strain-time curves indicates impending creep failure (see Miradrain™ 4000 sample in Figure 12). In general, the higher the applied stress, the greater the creep rate and the shorter time to failure. There will theoretically be some threshold stress below which "failure" due to creep will not occur (i.e., creep will stop before excessive deformation), but at present, it is not possible to determine the threshold from the available test results. This is due to the relatively short time available in the laboratory during this research for testing. Significantly longer times and specifically creep tests of longer duration at lower stresses would be required.

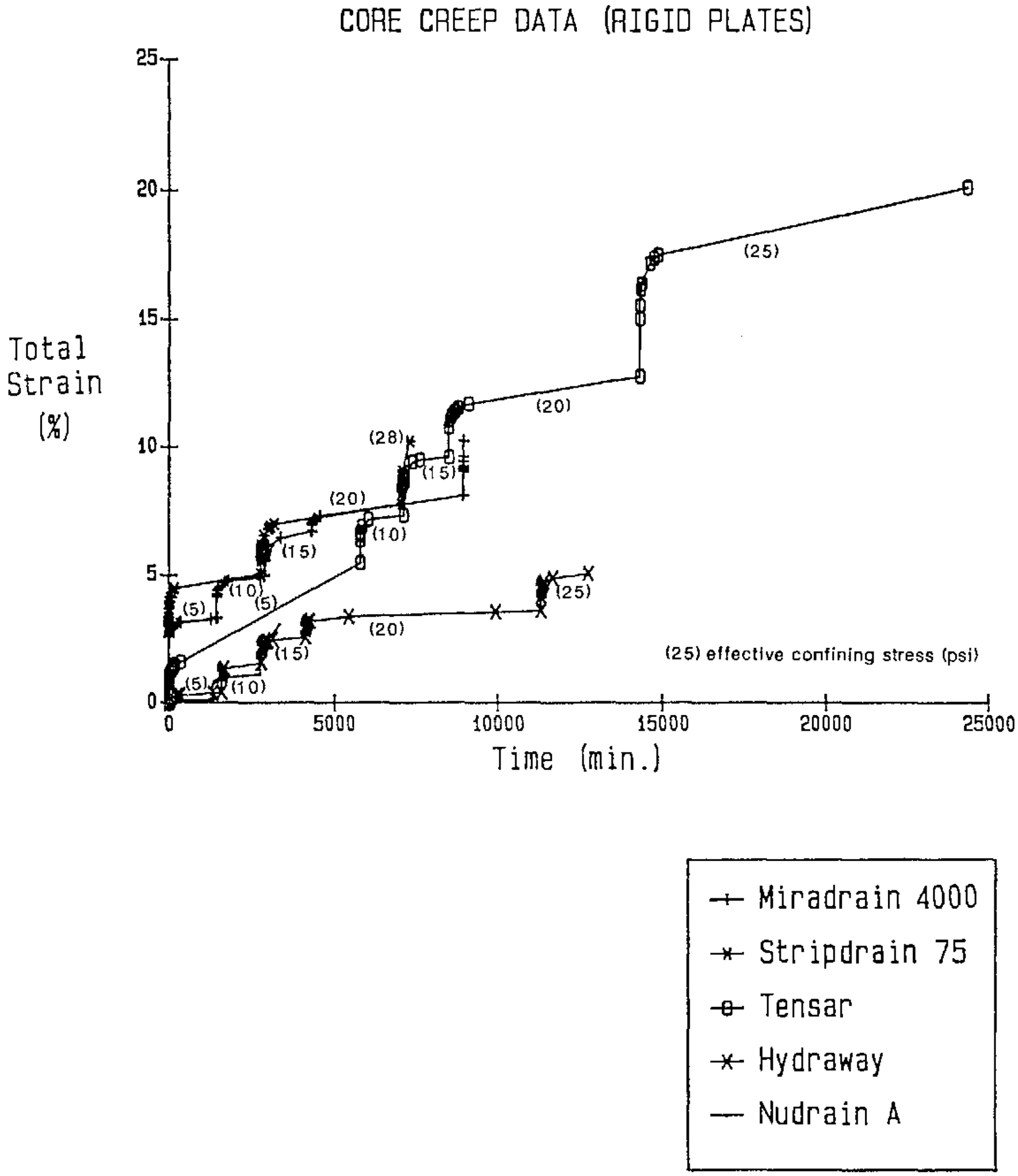


Figure 12 Core creep test results for various geocomposite drain samples.

Although the test arrangement for core creep tests is convenient, and the equipment required is easily obtained, the rigid plate core creep test has limited applicability for determining design parameters. This is because of the unrepresentative boundary conditions imposed on the samples by the use of rigid plates to apply the loading. The rigid plates tend to contact the geocomposite core only at the nodes, and thus induce stress concentrations in the cores far beyond the range of normal working stresses. The stress condition in the cores is not similar enough to service conditions for the test to be directly applicable for determining design parameters. However, the test can be used to determine a conservative relationship between stress and core creep (i.e., greater creep than would occur under the same stress in service).

System Creep Tests:

Because the stress concentrations induced by the rigid metal plates in the core creep test do not represent service conditions, a system creep device was developed and manufactured which utilized a flexible membrane to apply the uniform stress (normal stress only) on the side of the geocomposite geotextile with a rigid plate on the other side (a modified version of the device in Figure 9). The stresses induced in the sample under this loading are believed to much better represent service conditions, such as those experienced by a drain that was placed against a retaining wall and backfilled. In this test, the creep of the geotextile and the core as a system is measured. The intrusion of the geotextile and retained soil into the open spaces of the core, and the deformation of the core itself, during service could cause a significant decrease of the available flow volume in the core. The system creep test was designed to aid in quantifying this behavior in a repeatable manner.

The test procedure begins by cutting a 14-inch diameter sample of the geocomposite material, placing it in a confining chamber (a modified version of that shown in Figure 9) of the same diameter with the fabric side up, and saturating it with water. A flexible rubber membrane is placed on top of the sample and secured. Hydraulic pressure is applied to the flexible membrane after saturating the sample, and the resulting volume change is monitored to obtain the volumetric strain over time. Volumetric strain is defined as change in volume divided by the total sample volume (material and free volume). Once the data had been gathered for a sufficiently long period of time, the stress was increased and the process repeated.

Results of the system creep tests indicate a higher volumetric strain level can be obtained from the system creep test compared to compressive strain in the core creep test which measures linear strain only for the same stress level and duration (see Figure 13). This is due in part to the deflection of the geotextile into the openings in the core. Examination of the test samples after testing often

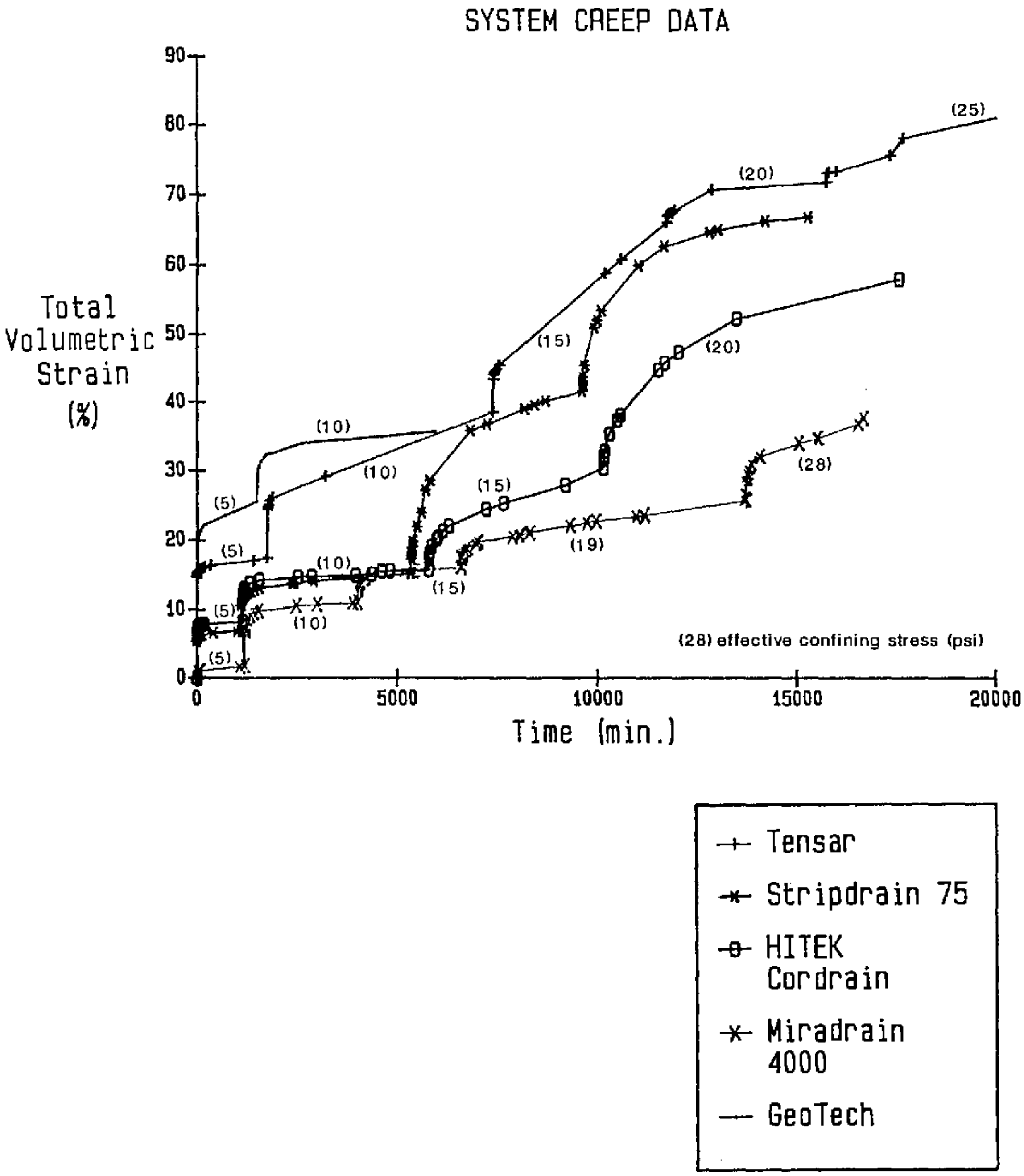


Figure 13 System creep test results for various geocomposite drain samples.

indicated that the geotextile had molded itself completely to the shape of the drainage core. In service, this could mean a nearly complete shutdown of the drainage function of the geocomposite, and possible failure of the drainage system. Volumetric strains as high as 80 percent were obtained for some products under pressures of 25 psi, indicating very high volumetric compression of the geocomposite.

As noted above, the system creep test is more representative of conditions in service than the core creep test. The creep of the geotextile into the core has been identified to be a significant factor in the deformation behavior of the products, and could be the controlling factor in the design of geocomposite drain systems which will be subjected to significant confining stress in service.

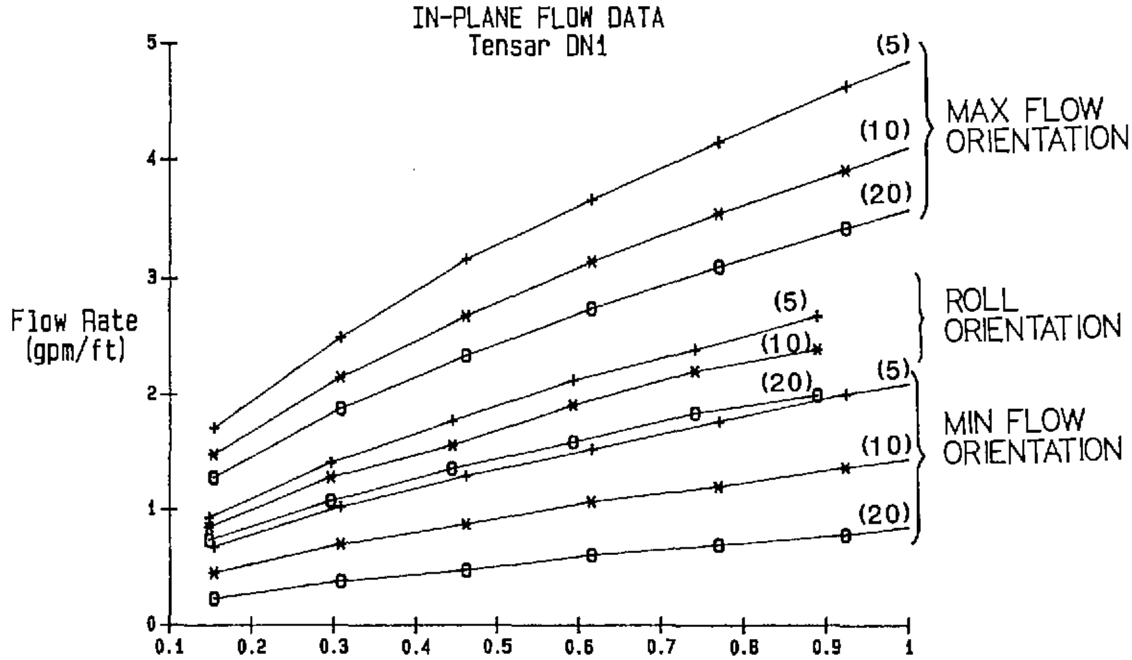
In-Plane Flow Tests:

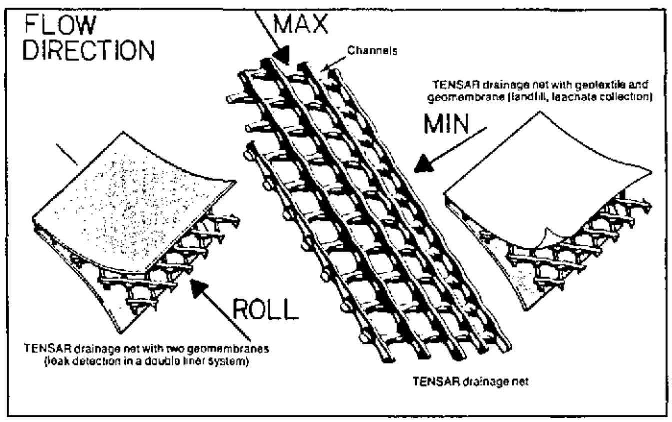
In-plane flow tests were performed to measure the volume of water that could flow through the cores of the geocomposites. It was desired to measure the in-plane flow through the core of several geocomposites under a variety of gradients while the normal confining pressure on the geocomposite was increased, in order to simulate flow conditions in the field.

Initially it was proposed that in-plane flow tests would be performed on six samples. As the research progressed, two factors (test results available from others and the realization of the significance of other variables such as the direction of flow) resulted in the decision to modify the test scope with respect to the number of samples to be tested. The actual number of tests exceeds the proposed scope even though only two products were tested.

Samples of geocomposite approximately 16 in wide by 13 in long were placed in a flow testing machine as shown in Figure 10. An air-filled bladder was inflated against the planar surface of the material to obtain the necessary normal pressure, and flow was initiated through the core of the drain by creating a hydraulic gradient across the sample. The amount of water which flowed through the drain during three consecutive five minute periods was measured and averaged to obtain the flow rate per unit width vs. gradient curves for the geocomposite. Figure 14 shows the flow rates per unit width vs. gradient curves that were obtained.

The results of the in-plane flow tests revealed several important aspects of flow behavior in the geocomposite drain. First, since the flow rate vs. gradient data resulted in curved lines, the flow condition within the core of the product tested is turbulent and Darcy's law will not be completely valid for predicting the flow within them. Second, as would be expected, the higher the normal pressure applied to the samples the lower the flow is for any gradient. Third, it was discovered that the orientation of the sample





Notes:

1. (5) effective confining stress in psi.
2. All flow rates measured 1 hour after load application.
3. Flow rate not corrected for temperature (12°C).

Figure 14 In-plane flow test results for various geocomposite drain samples.

in the device with respect to the primary direction of flow can have a significant effect on the flow rates obtained (see Figure 14). The flow rate corresponding to the most efficient orientation may be at least two to three times greater than the flow rate for a less efficient orientation.

Major conclusions drawn from the in-plane flow tests are:

- Flow values based on Darcy's law calculations and reported in product literature may significantly overestimate the actual flow capacity available due to turbulent (non-linear) flow conditions which may be present.

- The orientation of the sample with respect to the primary direction of flow should always be reported with the results of in-plane flow tests, as this information may be very significant to the flow capacity that one may expect in service.

- The magnitude of normal stress applied to the geocomposite drain and the manner in which it is applied (rigid plate, flexible membrane, etc.) can directly affect the flow rate. Strain of the geocomposite core and fabric under soil pressure will have the effect of reducing the flow capacity in service.

- Creep strain of the geocomposite during testing may further decrease the flow that is observed. Long term in-plane flow tests and/or correlation to system creep test results may be required to adequately predict long-term service flow capacities.

- The in-plane flow rates (at an applied gradient of 1 and normal stress of 10 psi applied for 300 hours) reported in the literature and measured as part of this research range from approximately 75 to less than 0.1 gallons/minute/foot sample width. This extreme range demonstrates the differences in product performance as well as the fact that some products are more suitable for certain applications. Koerner (1986) provided a design guide for flow rate vs. normal pressure for geocomposite drain applications (see Figure 15) which indicates that the capacities of available products exceed anticipated requirements. This guide does not address the influence of gradient or creep which is discussed later in this report.

Recommendations

It is believed that the physical properties and behavior characteristics of geocomposite drains need to be more thoroughly studied and determined before the products can be used with confidence in applications where long-term drain performance is critical. Manufacturers, researchers, and designers have begun to realize the need for more extensive and more standardized testing of these

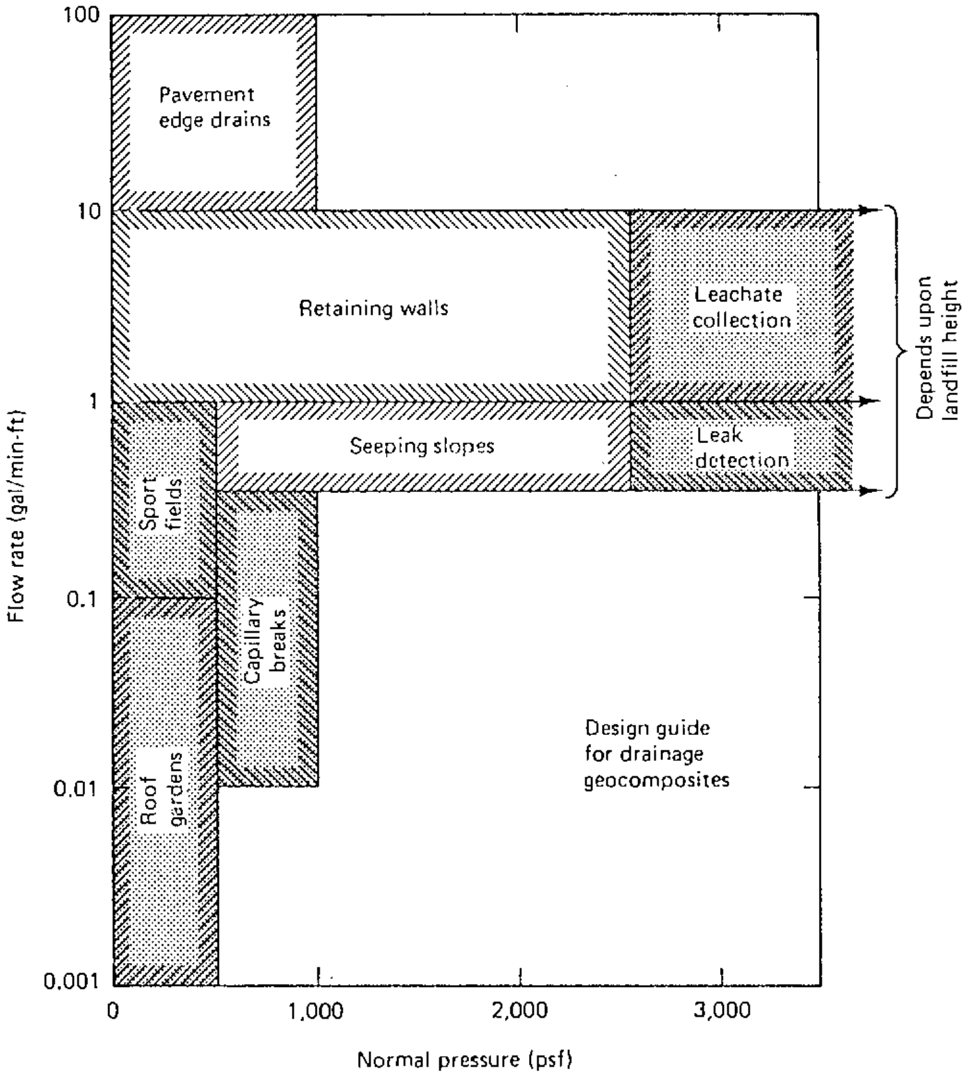


Figure 15 Design guide for geocomposite drains.

products. Unfortunately, most of the testing that has been completed and that is known to be underway is not well coordinated or standardized with respect to scope, method or purpose. Consequently, test information that is available and being developed can be misleading if used by persons unfamiliar with the details and assumptions of the tests.

As part of the H&A research on geocomposite drains, laboratory testing was performed as described above. A major goal of the testing was to gain "hands-on" experience with the tests currently being performed on geocomposite drains so that the tests could be critiqued. Based on an objective review of the tests' purposes, procedures and results, recommendations for future testing have been prepared.

Based on the information available at this time and the testing program described above, recommendations with respect to future testing are as follows:

Compression Tests:

Compression tests on geocomposite drains are normally performed using rigid plates for loading and currently-available loading apparatus. The results are useful primarily as an index test for the preliminary comparison and screening of products.

Compression tests should be performed using ASTM D 1621 (Compressive Properties of Rigid Cellular Plastics) as a general guide. Future tests could be more useful if the following procedures were adopted:

- Sample size should be consistent. Practically, the size should be large enough to minimize the effect of the number and location of the nodes in the sample, yet small enough that the test can be performed using readily-available compression testing machines. A suggested sample size for current products is 12 inches square. A sample that size will fit into most compression machines with minimal modification.

- The tests should be performed with strain rates of 10 percent per minute. The "quick compression" tests will limit and standardize possible effects of loading rate or creep on compressive strength.

- Sample preparation prior to testing should be consistent with respect to temperature and moisture. The samples should preferably be tested at room temperature in both a dry and fully saturated condition.

- Compression test results should not be considered acceptable for use unless the results include the following minimum information: product name and manufacturer; sample size (length, width, thickness); sample description (including whether tested with or without geotextile); geotextile name, manufacturer and description; strain rate; time to yield or failure; sample and room temperatures; sample moisture (wet or dry); all load vs. deformation data; and observations regarding the sample after compression (observed failure condition, cracking, discoloration, condition of core and geotextile, etc.).

Core Creep Tests:

Core creep tests performed using rigid plates are often performed because it is relatively easy to construct a loading box, and the necessary testing apparatus (soil consolidation machine) is readily-available. However, the use of rigid plates on both sides of the sample does not simulate service boundary conditions. Also, without modification oedometer devices, based on the testing for this research, are not suitable for testing geocomposite products that compress significantly under low pressures. Therefore, if core creep tests are performed, the results should be used cautiously and preferably as an index indicator of the core creep properties only.

Recommendations regarding the performance of core creep tests follow:

- Sample size should be as large as possible with the loading apparatus. With readily-available consolidation apparatus and using 30 psi as a maximum applied stress, the samples should be approximately 6 inches square.

- The sample should be tested with the geotextile in place even though in compression the geotextile will not significantly affect the creep of the core. If the test is performed with the core only, the results should be so indentified.

- For consistency the samples should be tested in a plane strain condition using a rigid metal confining box with the sample trimmed as closely as possible to the inner dimensions of the box.

- Initial sample height should be measured with the sample in the confining box while compressed with a small seating pressure (say 1 psi).

- Standard soil consolidation test devices are not always capable of accommodating the strain rates that can be experienced with geocomposite cores. Care should be exercised to maintain the applied pressure within reasonable tolerance (say ±2 percent) for creep testing. The loading sequence may have to be altered to accommodate the test apparatus.

- The loading sequence is very important to the determination of the core properties. Preferably, the sample should be loaded to the stress of interest as quickly as possible to minimize the possible effects of creep at low stresses. At low stress levels, say less than 10 psi, it may be possible to accomplish the test stress in a single increment. At higher stresses, several load increments may be necessary.

If several increments are used, the duration of each stress increment should be constant throughout the loading sequence. A reasonable loading program may be increments of 5 psi each applied at 1 hour periods until the test stress is achieved.

- The test results should be reported with the following minimum information: product name and manufacturer; sample size (length, width and thickness); sample description (including whether tested with or without geotextile); geotextile name, manufacturer name and description; method of confinement; sample test conditions (temperature, wet/dry); loading program (stress levels and duration); deflection vs. time for each load increment; linear strain vs. time for the entire test; and a description of the sample condition after testing.

System Creep Tests:

The system creep test measures the volumetric strain of the system, i.e., the core and geotextile together. Since the system creep test is more realistic with respect to in-situ conditions than the core creep test, system creep tests are preferable for determination of design deformation properties.

Recommendations concerning general standards for the performance of system creep tests are as follows:

- The sample size should be as large as practical. Samples at least 11 inches in diameter are reasonable based on H&A testing. With a relatively large sample possible effects of number and location of nodes is reduced.

- The sample should be prepared and tested with the geotextile attached to the core (normal manufactured condition).

- As a consequence of the testing procedure, the test is always performed on a saturated sample.

- The loading sequence is very important to the determination of the system properties. Preferably, the sample should be loaded to the stress of interest as quickly as possible to minimize the effects of creep at low stress levels. At low stress levels, say less than 10 psi, it may be possible to accomplish the test stress in a single increment and maintain sufficient accuracy in the volume change measurements. At higher stresses, several load increments may be necessary depending on the system for measuring displaced volume. If several increments are used, the duration of each stress increment should be constant throughout the loading sequence.

A reasonable loading program may be increments of 5 psi each applied at 1 hour periods until the test stress is achieved.

- The test results should be reported with the following minimum information: product name and manufacturer; sample size (length, width and thickness); sample description (including whether tested with or without geotextile); geotextile name, manufacturer name, and description; initial sample height; sample test conditions (temperature and saturation); loading program (stress levels and duration); volume change vs. time for each load increment; volumetric strain vs. time for the entire test; and a description of the sample condition after testing.

In-Plane Flow Tests:

ASTM is currently developing a standard for in-plane flow testing of geocomposite drains. The test method used in this research was a modified version of the ASTM draft procedure. Recommendations on the performance of in-plane flow tests on geocomposite drains are as follows:

- The ASTM draft procedure available at the time of this research should be used with modifications as discussed below.

- The tests should be performed using tap water since it is impractical to maintain the necessary volume of de-aired distilled water.

- The method of restricting flow around the sample should be better defined and illustrated. The effects of different restriction methods are undetermined at this time.

- Knowledge of the orientation of the sample with respect to the direction of flow is necessary. Test results that do not indicate the sample orientation are of marginal value.

- The test results should be reported with the following information: product name and manufacturer; sample size (length, width and thickness); sample description (including whether tested with or without geotextile); geotextile name, manufacturer's name and description; initial sample height; sample test conditions (temperature); loading program (stress levels and duration); sample orientation; flow paths (one or both sides of the core); and a description of the sample condition after testing.

These recommendations have been prepared to expedite coordination of the necessary testing of geocomposite drains. The recommendations should be used as guidelines for the development and refinement of currently-available tests, and the interpretation of test data found in technical publications or promotional literature. The designer is cautioned against accepting at face value data that are reported without complete descriptions of the test methods and sample tested.

It is also recommended that standards be established for testing geocomposite drain products to determine design properties including compressive strength, core creep, system creep and in-plane flow capacity.

DESIGN CONSIDERATIONS

Introduction

Geocomposite drains are synthetic products that are used in various civil engineering applications. Because they are manufactured, it is possible within certain limits to specify/control the desired properties of the geocomposite drain geotextile and core. Design engineers should evaluate the requirements for a given project, and select or "design" the geocomposite drain for that specific application. Using the design requirements, the engineer should then determine whether any of the existing geocomposite drains are satisfactory and/or specify the "ideal" drain in a generic-type specification.

The designer should: 1) decide the function of the drain, 2) identify the necessary properties and their required values, 3) confirm the existence of products meeting or exceeding the project requirements, and 4) prepare the project specification. These steps are discussed below.

Generally, the function of the geocomposite drain is to collect subsurface water and discharge it to an outlet(s). Although this function is common to all geocomposite drains, each application may be different with respect to the impact of proper drain performance on the structure and possible secondary functions.

For example, a geocomposite drain placed behind a retaining wall can be vital to the stability of the wall if the natural water table is above the proposed wall footing level and the wall is not designed to withstand hydrostatic pressures. Inadequate drainage due to poor geocomposite drain performance could result in a structural failure or movement of the wall.

Identification of the critical properties and the required values can be accomplished using good geotechnical engineering analysis. The principles of lateral earth pressures, flow nets, and other common geotechnical analysis techniques can be applied to the geocomposite drain application to determine the required properties of the drain (compressive strength, in-plane flow capacity, etc.). After determining the design properties, an appropriate factor of safety should be applied to obtain the required properties. Since the level of understanding regarding long term performance of geocomposite drains is not very advanced, the factor of safety, as discussed in in this volume, should be selected carefully based on an engineering evaluation of the particular application.

Confirming the existence of products with the desired properties is possible using available product information or by performing specific tests to confirm product performance. The designer should be cautious about accepting manufacturer information regarding product performance without proper support documentation. Commonly published information, such as compressive strength, can vary considerably based on the sample size, test conditions, etc.

In a critical design application, the designer might request that the manufacturers of products under consideration perform specific tests under specified conditions to confirm critical properties. In lieu of manufacturer testing, the designer might perform independent tests, in-house or at a commercial testing agency.

In general, the engineer should avoid using "standard" geocomposite drains for different applications without confirming the applicability of the geotextile and core system for each application. Since many of the drain manufacturers can supply various geotextiles with their cores, the number of geotextile/core combinations gives the design engineer considerable latitude to develop a suitable design.

Specific Considerations

There are many variables that should be considered in the design of a geocomposite drain application. Some of the major considerations are:

- Drain orientation
- In-situ stresses
  - Normal and/or shear
  - Magnitude
  - Duration
  - Cyclic vs. constant
- Temperature
  - Cold weather construction
  - Freezing of the drain
- Hydraulic conditions
  - Seepage rate
  - Capability of geocomposite system
  - Direction of flow
- Potential for clogging
- Permeability of the geotextile
- Chemical resistance

The various design considerations are discussed below.

Drain Orientation:

Consideration of drain orientation can be important because it is one factor which determines the in-plane capacity and the hydraulic gradient that will be created in the drain. It is desirable to minimize head loss across the soil/geotextile interface and within the drain. As indicated in Laboratory and Field Testing, in-plane capacity and internal head loss can be significantly different for different orientations of the geocomposite.

Confining Pressure:

The long-term effects of confining pressure on geocomposite drains are not completely understood. However, it is known that the in-plane flow capacity of the drains decreases with increasing normal pressure and time (see Figure 16). The extent of the decrease varies with different drain types and test conditions, but the general relationships are consistent.

All of the research results located as part of this study dealt with the effects of varying normal stresses only. Intuitively, shear stresses could have an effect on the in-plane flow capacity as well. Although the currently-available cores appear to be reasonably stable to working-level shear stresses, the shear stresses could loosen the geotextiles from the core and therefore reduce the tensile capability of the geotextile. Another consideration, particularly if a geocomposite is used on sloped ground, is the tendency of the drain to slide and possibly result in the creation of a potential slippage or failure plane in or on sloping ground.

The magnitude of the in-situ stresses that will be imposed on the geocomposite drain should be carefully evaluated. This evaluation should include consideration of the stresses during construction (compaction equipment, etc.) as well as the long term stresses that will exist throughout the structure design life. Most geocomposite drain research has been conducted with maximum normal stresses of about 30 psi. This corresponds to an embedment depth of about 70 feet (assuming K_0 = 0.5 and an effective unit weight of soil of 125 pcf) in a cohesionless soil.

The duration of the applied stresses can be very important to the evaluation of potential geocomposite drain applications. In some cases (see Figure 16) the effects of time are greater than the effect of increasing normal stress. Most transportation structures and improvements will require a drain that will function satisfactorily for 5 to 40 years and possibly longer. Therefore, if the drain is critical to the structure performance, the design engineer must be confident that the stresses applied to the drain will not result in creep failure during the design life. At the same time, the designer should differentiate clearly between creep failure (structural collapse of the drain core structure) and hydraulic failure (in-place flow capacity less than the design requirement). In some cases the drain may still function satisfactorily after creep failure. However, caution should be exercised in making any assumptions due to the present inability to predict creep performance.

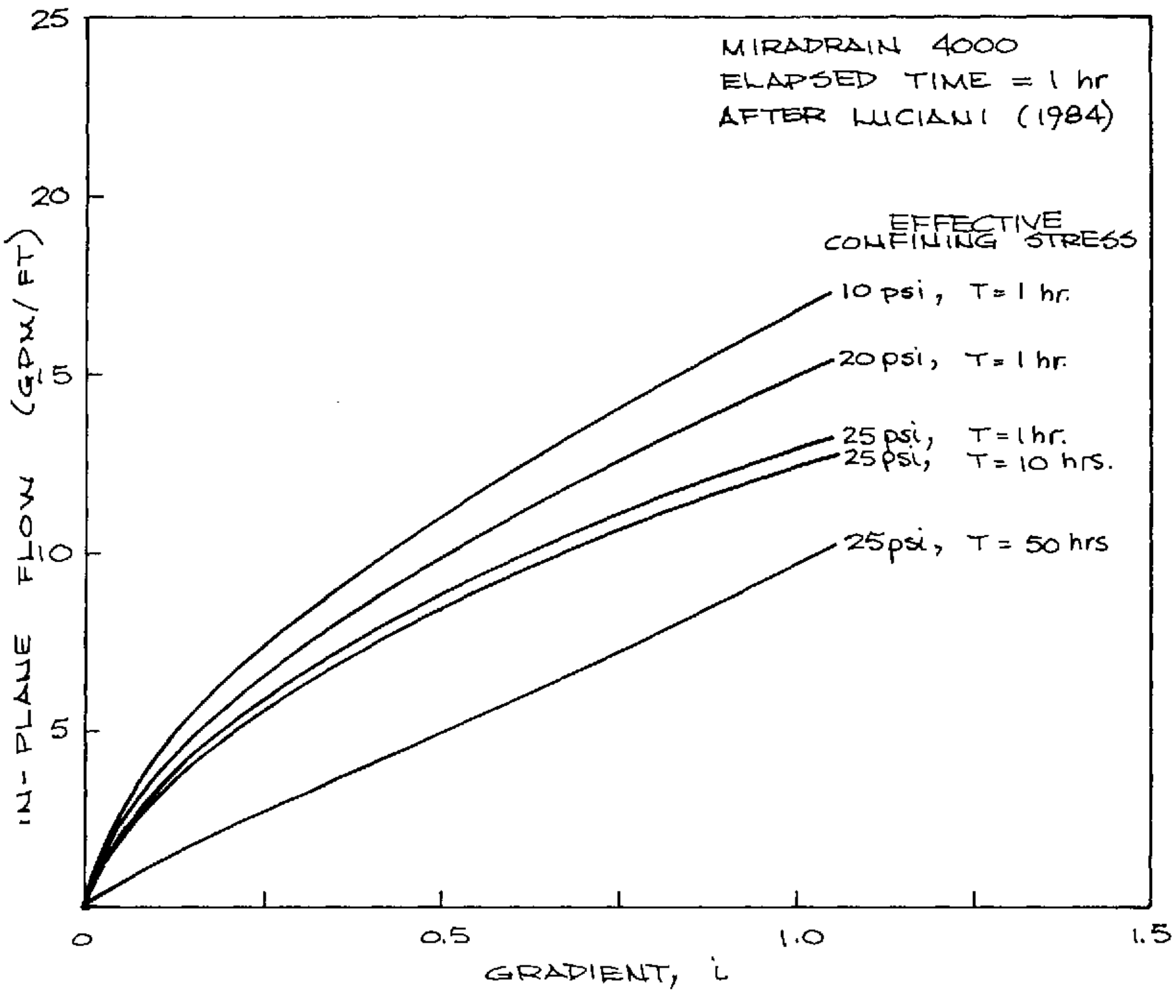


Figure 16 In-plane flow rate vs. gradient for Miradrain[TM] 4000.

Current research in the industry on the creep effects of geocomposite drains is extremely limited. Typical test programs have used loading arrangements with unrealistic boundary conditions (not representative of in-situ conditions) and stress durations of less than one month. The understanding of geocomposite drain creep is not sophisticated enough to accurately extrapolate these limited data (with maximum test duration on the order of 0.03 year) to the end of a 20- or 40- year design life. As a general rule, the design engineer should be cautious when using geocomposite drains in any application where a creep type failure of the drain would have serious implications, or in any application where the confining stress is more than about 1/3 the "quick" compression test yield stress.

Most of the currently available geocomposite drains have not been tested under cyclic stresses. This would be particularly important for pavement edge drains or any other application where cyclic stresses would occur during the design life of the drain. To a limited extent geocomposite drains in almost any of the typical applications may be exposed to cyclic stresses during compaction of adjacent soils.

Until additional creep testing is performed to verify the long term performance of geocomposite drains within the normal working stress range, it seems reasonable, as a rule of thumb, to stress the drains to a maximum of 1/3 of their yield stress as measured in a "quick" compression test. This preliminary recommendation is based on engineering judgement more so than actual test results; therefore, the designer should exercise his own judgement given the particular application and the products under consideration.

Temperature:

None of the geocomposites tested in compression as part of this research demonstrated any significant temperature effects. This result is not unanticipated because while normal construction temperature ranges may seem extreme (say 10 to 100^{o} F), this range is small in comparison to the temperature range required to significantly affect the physical properties of most polymers.

A more significant temperature effect is the possibility of the geotextile, or the soil or water adjacent to the geotextile freezing and drastically reducing the effective permeability. Adequate frost protection should be provided so that the drain can continue to function as designed throughout normal cold weather. This concept is particularly important for drains behind retaining walls. Adequate wall thickness, nonfrost susceptible soil and/or other insulation should be provided.

In some applications it may be possible for soil and/or groundwater adjacent to the geocomposite drain to freeze and compress the drain against a wall or other relatively fixed surface. Water freezing in a confined space can create pressures as large as 30,000 psi, far in excess of the yield stress of geocomposites. Therefore, it is conceivable that geocomposite drains will be crushed if the adjacent soil freezes in a confined condition.

Hydraulic Conditions:

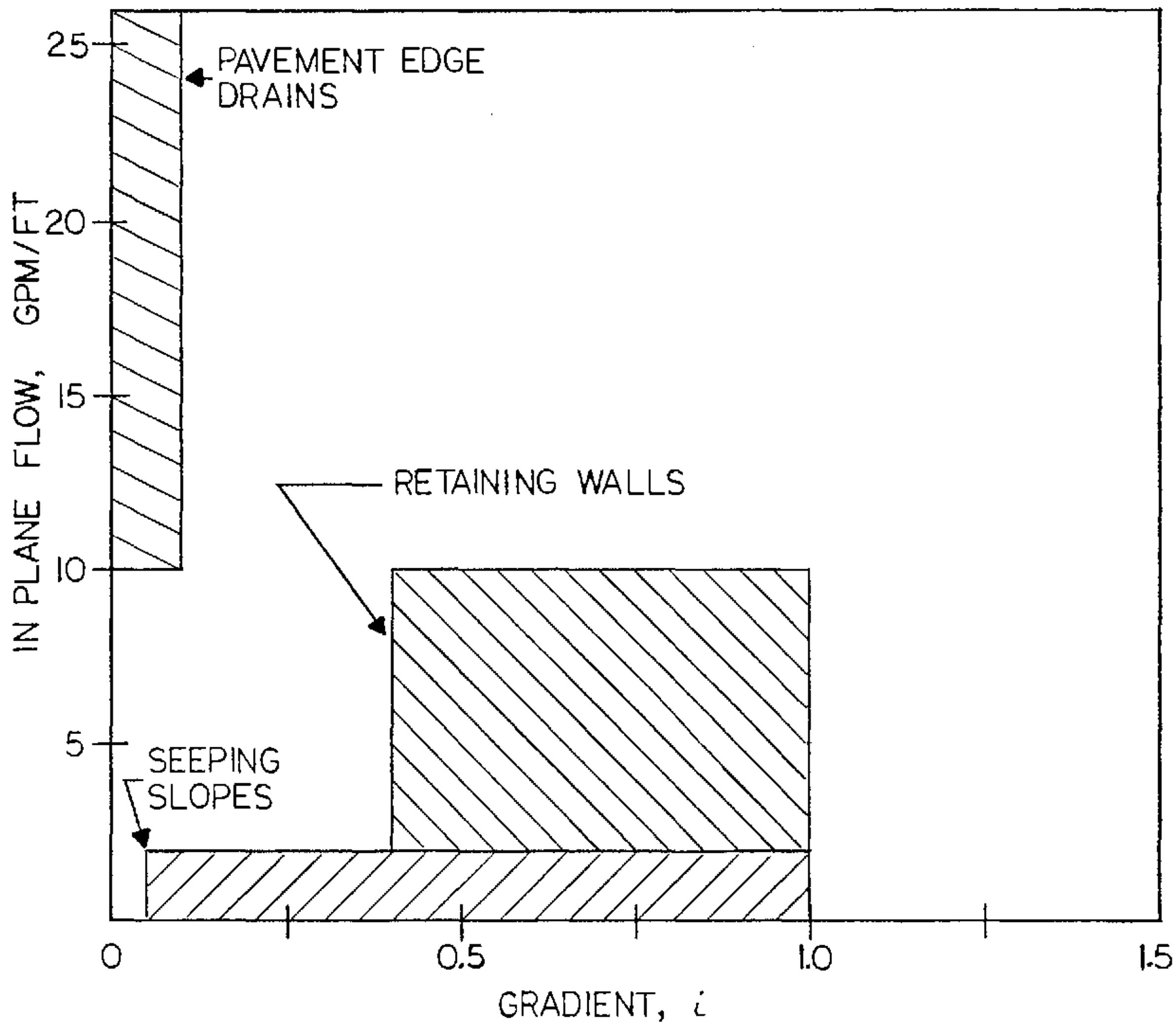
In most applications of geocomposite drains the in-plane flow capacity will far exceed the seepage flow from the adjacent soil. Consideration of the seepage rate from the soil is important for selecting the most cost effective drain and also for the spacing of weep holes or outlets.

Koerner (1986) presents design guidance on the required in-plane flow rate as a function of normal pressure for various geocomposite drain applications (see Figure 15). Using that information, Figure 17 was developed to include the effects of hydraulic gradient on the evaluation of acceptable geocomposite drains. It should be noted that Figure 17 can be used as a preliminary design guide, but still does not include the potentially significant creep characteristics.

The engineer should not be unduly influenced by drain promotional literature or by the high in-plane flow rates reported by some of the manufacturers. The designer should verify all the relevant test conditions used in reported tests and be certain that the test conditions simulate as closely as possible the application conditions before relying on in-plane flow values reported by manufacturers.

It is possible to compare the hydraulic properties of geocomposite drains to coarse aggregate drains using available laboratory test results for geocomposite drains and assumed flow performance for the coarse aggregate drains in lieu of actual tests (see Figure 18). It is obvious from this figure that the in-plane flow of a typical geocomposite drain is less than the theoretical flow through the conventional coarse aggregate drains.

Using the design guides (Figures 15 and 17, neither of which account for creep effects) and geotechnical analytical techniques such as flow nets, etc., it is possible to estimate the required in-plane flow rate (capacity) for a given design application. The required in-plane flow rate should be increased by a reasonable factor of safety. The factor of safety should be determined by the designer after considering design factors such as the importance of the drain to design performance, the design life, the consequences of drain failure, uncertainty of soil properties, and the cost of possible conservatism. There is currently very little guidance available in the engineering literature on appropriate factors of safety relative to geocomposite hydraulic capacity. In addition, there is little useful information and much uncertainty on the long-term hydraulic

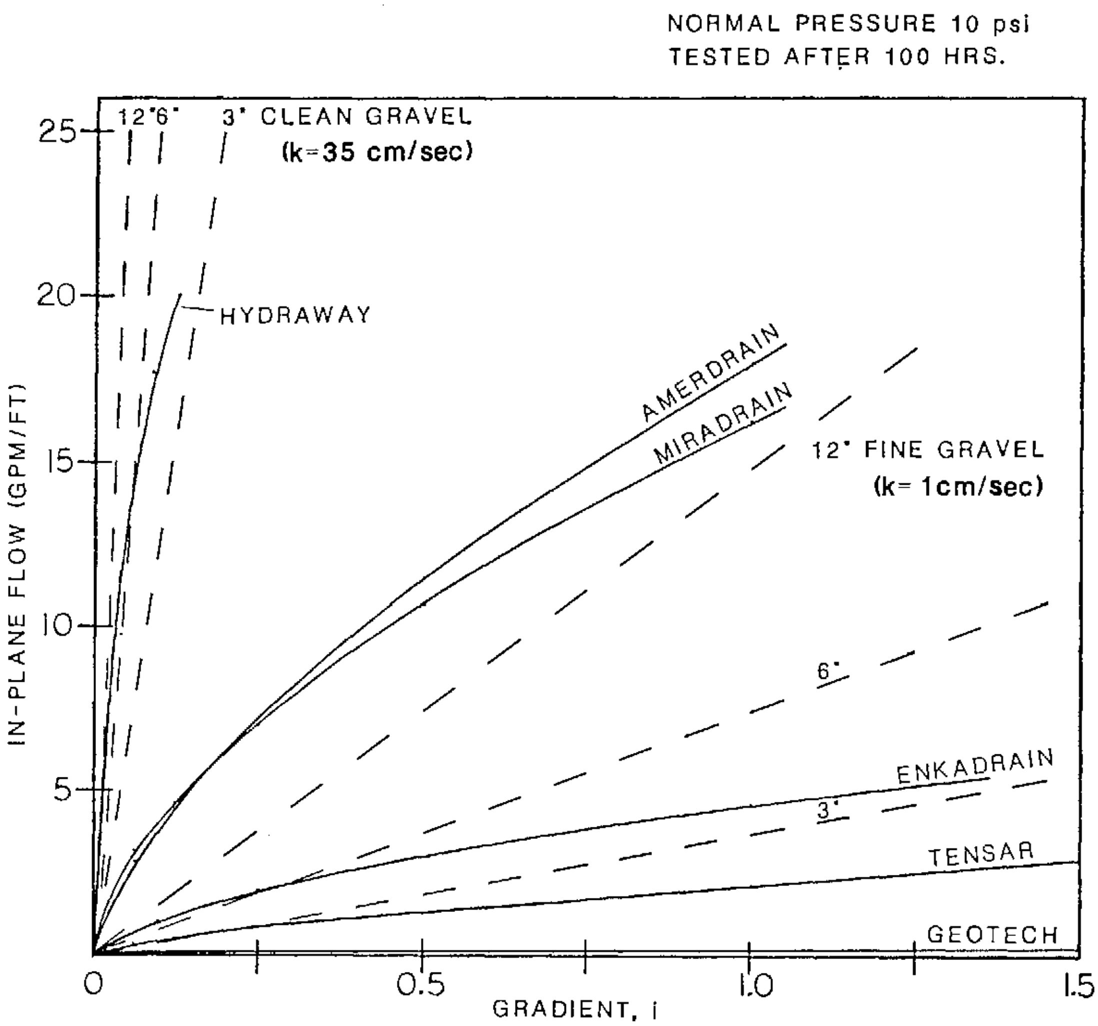


Note:

Boundaries of in-plane flow rate and gradient are approximate.

In-plane flow rates from Koerner (1986).

Figure 17 In-plane flow rate design guide for geocomposite drains.



Note:

Flow in gravel assumed to be laminar (Q=kiA).
Drain data from Luciani (1985).

Figure 18 Comparison of hydraulic capacities of geocomposite and coarse aggregate drains.

properties of geocomposites in service. It is therefore important to exercise care and judgement when assessing long-term hydraulic capacity and performance. Considering the current state of knowledge, it is believed prudent to use higher factors of safety (ratio of available hydraulic capacity to the anticipated seepage rate, at the design confining pressure, as measured using appropriate test procedures) for geocomposite hydraulic design than are used for other geotechnical design applications such as bearing capacity or slope stability. The factor of safety used should also reflect the nature of the application and the consequences of poor performance. Based on the very limited data available, factors of safety on the order of 3 to 7 may be reasonable for most applications. Additional research and experience with these products is necessary to confirm appropriate design methods and factors of safety.

Clogging Potential:

Clogging potential of the geotextile in a geocomposite drain is a major consideration in the design. The potential for clogging may affect the selection of the geotextile used in an application as well as the soil to be used as backfill adjacent to the drain.

Current understanding of geotextile clogging is not very far advanced. However, design criteria based in part on experimental laboratory data and empiricism have been established. Such criteria are presented in the FHWA Geotextile Engineering Manual (Christopher and Holtz, 1984). The design engineer should consider development of the geotextile requirements an important part of the overall geocomposite drain design and use the most current research as a guide.

The possibility of the core clogging with soil particles is less likely than geotextile clogging. However, if the geotextile is damaged or if construction seams are improperly constructed, soil particles may enter the core. If the hydraulic conditions (gradient, volume of flow, etc.) permit, fine-grained soil particles may accumulate in the core and eventually reduce the hydraulic capacity of the core or collector pipes. In most cases the use of good design and construction practices should be adequate to prevent any significant clogging of the core.

Hydraulic Properties of the Geotextile:

Determination of the critical hydraulic properties is a subject of considerable recent and on-going research. Unfortunately, until standard tests of the critical properties (filtering and clogging) are developed, implemented and evaluated, uncertainty will continue to exist regarding geotextile hydraulic properties.

One distinction that the design engineer should be aware of is the difference between permeability and permittivity. Permeability is the coefficient of proportionality in Darcy's Law (Q = kiA). In order to measure the coefficient of permeability it is necessary to know the thickness of the geotextile to calculate the gradient. This introduces several complications including the fact that the thickness will be a function of the confining stress and media, and that the hydraulic gradient in laboratory tests is usually considerably larger than in-situ gradients. For these reasons permeability is currently considered a less desirable comparative index when considering alternative geotextiles.

A better measure of the hydraulic properties of a geotextile is permittivity, defined as the volumetric flow rate per unit area under a given hydraulic head. Permittivity is not a function of the geotextile thickness. ASTM standards have been developed for the measurement of geotextile permittivity. If the values are not reported by a manufacturer for a given geotextile, the design engineer should request and confirm the information before using the geotextile in a geocomposite drain application.

The designer is referred to Christopher and Holtz (1984) for guidance in the design and specification of the geotextile hydraulic and physical properties.

Chemical Resistance:

Resistance of the polymer core and geotextile to chemical attack is not of primary importance to the design of the geocomposite drain unless the presence of certain chemicals is expected or anticipated in the vicinity of the drain during its useful life. Certain polymers (polystyrene and polyethylene for example) are subject to softening by petroleum products such as gasoline. In a highway setting, the presence of petroleum products should be anticipated. The drain designer should take into account the risk of potential exposure of the drain to chemicals.

Another consideration which is important is the low resistance of some polymers to ultraviolet radiation. Prolonged exposure of some geocomposite drains to sunlight can cause deterioration of the geotextile and core, and cracking of the polymer core. This is particularly true of ABS, polypropylene, and polyethylene polymers. Care should be taken to protect these products from sunlight while in service and while stored on the job site.

Most polymer manufacturers have made available chemical resistance charts for their products which list a variety of potential softening agents along with the relative resistance of the polymer to attack by that agent. A brief condensation is available in the following table, which lists polymers often used in geocomposite drains along with their relative resistance to some common softening agents (Koerner, 1984).

Resistance to Deterioration

Solvent	Low Density Polyethelene	High Density Polyethelene	Polymer: Polypropylene	Polymer: Nylon	Polystyrene
Acids	Poor to Good	Good	Good to Excellent	Poor	Good to Excellent
Bases	Good to Excellent	Good to Excellent	Good to Excellent	Excellent	
Oxygenated Solvents	Poor to Good	Poor to Good			
Aromatic and Hydrogenated Solvents	Fair	Fair	Good	Good	
Petroleum Solvents	Poor to Fair	Fair to Good	Good	Excellent	Poor
Weatherability	Poor	Poor	Poor	Fair	Poor

Other Considerations:

In addition to the considerations discussed above, there are other aspects of geocomposite design and construction to be considered. Some of these are the connection of the geocomposite drain to a collection pipe, the design life of the drain in general, and construction procedures.

If a collector pipe is used in the design, it is important to develop and maintain contact between the geocomposite drain and the collector pipe, and to size the collector pipe and to space the discharge points from the collector pipe to minimize head losses within the collection system. Any head loss within the collection system reduces the head available to cause water flow through the soil and geotextile and within the plane of the drain.

Most geocomposite drain manufacturers recommend typical collector pipe details for their particular product. An example of one such detail is shown in Figure 19.

The design life of the geocomposite drains with respect to their chemical resistance is dependent on the chemicals to which the drain is exposed, the concentrations of the chemicals, and the duration of contact. The polymer products typically used for geocomposite drains are generally resistant to most chemicals normally found in subsurface soils and

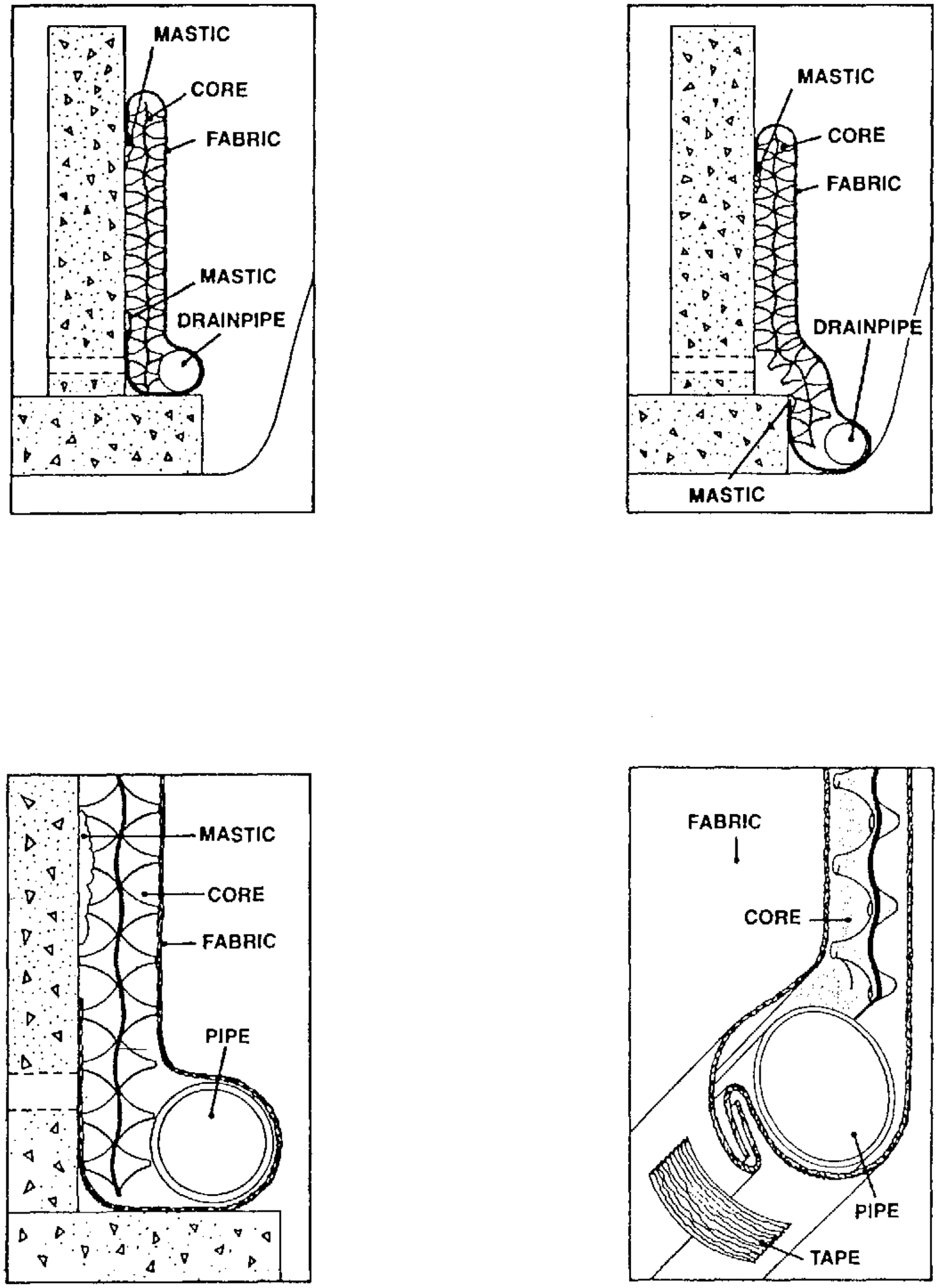


Figure 19 Typical details for the drain/collector pipe connection.

groundwater. However, the designer should be aware that there is a difference in the degree of degradation between the various polymers when exposed to some of the chemicals (in particular petroleum products). Therefore, the polymer composition of the geocomposite drain may be a design concern depending on the current chemical environment and that anticipated in the future.

Construction considerations include storage and handling prior to installation, as well as, protection after installation. Specifically, the drain products should be protected from the elements (in particular sunlight), and should not be handled or installed when the products are brittle due to excessively low ambient temperatures. After the drain product is installed, it should be protected from detrimental sunlight and possible damage as a result of fill placement.

Specifications

Preparation of specifications for geocomposite drains can be a difficult process due to the uncertainties in the design requirements (seepage rates, lateral pressures, etc.), the diversity of the available products, and the variation in and limited number of test procedures used to evaluate the products. It should be recognized that similar uncertainties exist in the design of coarse aggregate drain systems; however, the designer is usually more at ease specifying more "tried and true" gravel or stone drains.

The process of preparing a specification for geocomposite drains is similar to that for other products such as waterproofing membranes, etc. Possible specification types include performance, generic, and approved products. However, the specification type is in part dependent on the ability to specify and test the critical properties of the product.

A performance specification is appropriate if the desired performance can be well specified which is not the case with most geocomposite drain applications. Therefore, the performance specification is in general not recommended.

Preparation of a generic specification for a given application can be a very involved process depending on the project requirements and the properties that are considered critical. Test procedures exist for some of the potentially critical properties and are being developed for some others. However, there are still many properties, such as creep, for which there are no known test standards being developed.

A true generic specification with only the required performance standards and appropriate test methods is not feasible at this time. Until the understanding of geocomposite drain performance advances and standard tests are developed to quantify critical properties, a combination generic/product type specification is the most appropriate approach. Using available design guides and product information, the designer can identify available products that satisfy the design criteria. It is also recommended that the specifications include the general design criteria and a provision for the Contractor to submit alternative products for consideration as "equivalents."

The requirements of any specification will be dependent on the proposed application and in particular on the soil/drain interaction. For instance, compressive strength will be more critical with a deep wall than for pavement edge drains. However, there are many requirements that will be common to many geocomposite drain applications.

Currently available test procedures that might be appropriate for a geocomposite application are listed for reference below:

Core:

Property	Test Method
Specific Gravity	ASTM D792
Water Absorption	ASTM D570
Fungus Resistance	ASTM 2170
Tensile Strength	ASTM D638
Compressive Strength	ASTM D2990

Geotextile (Christopher and Holtz, 1984):

Property	Test Method
Mechanical Strength - Uniaxial Loading	
a) Tensile strength and elogation	
1) Grab strength	ASTM D-1682, Method 16 at 12-inch/min (Fed. Std. 191, Method 5100/5.9)
2) Strip tensile strength	ASTM D-1682, Methods 18 and 20 at 12-inch/min
3) Wide width strength	ASTM Proposed
b) Poisson's Ratio	No Test
c) Stress-Strain Characteristics (Tensile Modulus)	Wide Width

Property	Test Method
d) Dynamic Loading	No standard
e) Creep Resistance	See Christopher and Holtz (1984)
f) Friction/adhesion (slick, rough, smooth)	Modified Corps of Engineers EM1110 using Ottawa 20-30 Sand
g) Seam strength	a-1, a-2, or a-3, above (depends on requirements)
h) Tear strength	ASTM D-1117 - Method 14 (Fed. Std. 191, Method 5136)
Mechanical Strength - Rupture Resistance	
a) Burst strength	Mullen Burst - ASTM D-3736, Method 4 (Fed. Std. 191, Method 5122)
b) Puncture resistance	Modified ASTM D-751 using 5/16 inch flat-tipped pod
c) Penetration resistance (Dimensional stability)	No standard
d) Fabric cutting resistance	No standard
e) Flexibility (stiffness)	Modified ASTM D-1388 - Method 5 using 2-inch x 12-inch sample (Fed. Std. 191, Method 5206)
Endurance Properties	
a) Abrasion resistance	Modified ASTM D-1175 using Calibrase wheels - 1,000 cycles and 2.2-pound load (Fed. Std. 191, Method 5304)
b) Ultraviolet (UV) radiation stability	ASTM D-4355
c) Chemical and Biological resistance	No standard for geotextiles (For textiles: Fed. Std. 191, Methods 5760, 5762, 2015, 2016, and 2053)

Property	Test Method
d) Wet and dry stability	No standard
e) Temperature stability	No standard
Hydraulic	
a) Opening Characteristics	
1) Apparent Opening Size (AOS)	ASTM proposed
2) Poremetry (pore size distribution)	Use AOS for O_{95}, O_{85} O_{50}, O_{15}, and O_5
3) Percent open area (POA)	U.S. Army Engineers Waterways Experiment Station AD-745-085
4) Porosity	No standard
b) Permeability (k) and permittivity	ASTM Proposed
c) Soil retention ability	Empirical relations to opening characteristics
d) Clogging resistance	No standard - see Soil-Fabric Tests
e) In-plane flow capacity (transmissivity)	Koerner and Bove, 1983

SUMMARY

Although geocomposite drains are relatively new products, their applications are becoming more widespread and innovative. As the relative cost of the coarse aggregate drain increases with time due to higher material, labor and equipment costs, there is every reason to believe that geocomposite drains will become more widely used.

With this increased use will come a better understanding of the critical properties of geocomposite drains in different applications and the experience that comes with usage. At this time our understanding of the critical properties, as discussed in this report, is limited and without the experience gained over time, designers should be cautious in using geocomposite drains in critical applications.

This report is a synopsis of the currently available technical information with recommendations concerning the future application and testing of geocomposite drains. With the guidance provided in this report it is hoped that designers can ask the right questions of the manufacturers, and collectively the industry can work toward an improved understanding of these products that will be used widely in the future.

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Appendix A: Summary of Polymer Properties

Plastics (high polymers) have significantly different structures and properties than most ordinary building materials. Their stress - strain behavior lies somewhere between that of crystalline solids and viscous liquids, and depends both on the rate and temperature of loading. Overall, they are considerably lower in strength and stiffness, and higher in deformation ability than most other materials used in construction.

References on the properties of various polymers which have proven useful and informative in this study include: The Modern Plastics Encyclopedia, Van Krevelen's Properties of Polymers: Correlations with Chemical Structure, and The Encyclopedia of Polymer Science and Technology. Koerner's Construction and Geotechnical Methods in Foundation Engineering also contains a summary table of the properties of selected polymers that is quite useful.

Seven polymers are considered here, ranging in tensile strength from 21 to 8000 psi. They are: ABS, Nylon 6, Polyethylene (low and high density), Polypropylene, Polystyrene, and Expanded Polystyrene Foam. A section on the properties of each of these polymer types follows.

Polymer: ABS (Acrylonitrile-Butadiene-Styrene).

The following description of ABS, written by Robert Cleereman, was obtained from The Modern Plastics Encyclopedia: "ABS resins are copolymers made of acrylonitrile, butadiene, and styrene. Acrylonitrile provides resistance to chemical attack and heat, as well as high strength. Styrene provides easy processability, rigidity, and gloss. Butadiene acts as the reinforcing agent to provide impact strength and toughness at room temperature and under cold weather conditions. Varying the ratio of these components can yield a tremendous variety of ABS products."

ABS has a fairly high tensile yield strength (4000 to 5500 psi), and also a high tensile modulus (230 to 330 ksi) making it quite stiff. It also has a high compressive yield strength (4500 to 8000 psi) and compressive modulus (140 to 300 ksi). Cleereman also states that the Styrene-acrylonitrile matrix of ABS is brittle, and that it is the addition of the Butadiene rubber that makes this product tough and gives it high load carrying ability. This brittleness is evident in the elongation at break values for ABS which range from 5 to 70 percent in tension, which are low when compared to most polymers.

ABS has a specific gravity from 1.01 to 1.04. It is chemically resistant to soil, ordinary runoff, and biological attack, but may be softened by exposure to gasoline, vegetable oils, ketones, esters, and chlorinated hydrocarbons. Being a styrenic based polymer, ABS possesses low resistance to ultraviolet light, and can lose 50 percent of its original properties after six months outdoor sunlight exposure if unprotected or unstabilized.

Polymer: Nylon 6.

Nylon is a generic term used to describe the family of thermoplastic polyamide resins, of which there are several members. Nylon 6 is one of the most common members of this family, being used as a multifilament textile fiber, as well as for injection molded and extruded parts. Its general attributes include a high resistance to abrasion, durability, toughness, high heat resistance, resistance to biological attack, and a general chemical inertness.

Nylon 6 has a very high tensile yield strength (5000 to 8000 psi), and a fairly large plastic region (elongation at break, 100 to 300 percent). Its tensile modulus is high at 100 to 380 ksi. Nylon also possesses a high compressive yield strength (13000 to 16000 psi) and compressive modulus (250 ksi). It is the strongest polymer in this study.

The specific gravity of Nylon 6 is 1.12 to 1.14. It is chemically resistant to most compounds, except to strong acids, phenols, and oxidizing agents. Nylon is hygroscopic to a varying degree, tending to a water content of 2.5 percent or less. Although it is resistant to attack by bacteria and fungi, its weatherability is only fair, due to its low ultraviolet resistance. Carbon black is often added to the polymer to improve the U.V. resistance.

Polymer: Polyethylene.

There are hundreds of compounds in the family of polymers referred to as polyethylenes. The chemical variations within this family give rise to a wide variety of physical properties, which may be controlled and enhanced by the use of additives and different manufacturing processes. The structural attributes which have the greatest effects on the physical properties of polyethylene monomers include the resin density, degree of side branching, and crystallinity.

In general, low density polyethylenes have a high degree of side branching, while high density polyethylenes have a low degree. An increase in the amount of side branching of the polymer molecules tends to have the effect of reducing the density and crystallinity of the material (and thus the strength), because it is more difficult for branched molecules to form a crystalline structure.

Unlike most polymers which are almost completely amorphus, polyethylene's structure is partially crystalline. The degree of crystallinity varies with the density. High density polyethylene (HDPE), whose specific gravity ranges from 0.94 to 0.965 typically possesses a high ratio of crystallinity (85 to 95 percent), while low density polyethylene (LDPE), whose specific gravity ranges from 0.91 to 0.925 typically has a lower crystallinity (65 to 75 percent). This crystalline phase enables polyethylene to retain its strength over a large temperature range, even though it melts at a fairly low temperature (150°F).

The mechanical properties of polyethylene also vary with density. Generally, strength, modulus, and brittleness increase with increasing density. Increasing density and crystallinity cause HDPE to have a higher tensile strength, tensile modulus, and compressive strength than LDPE, although LDPE has a higher elongation at break (up to 800 percent, as opposed to 20 to 130 percent for HDPE), which indicates that LDPE has greater plasticity. HDPE has tensile yield strength in the range 3000 to 4000 psi, tensile modulus of 60 to 180 ksi, and compressive yield strength of 2700 to 3600 psi. LDPE has a tensile yield strength in the range 800 to 1200 psi, a tensile modulus of 14 to 38 ksi, and a compressive yield strength of 400 to 1000 psi. Both HDPE and LDPE are considered low strength and low stiffness polymers by comparison to ABS, nylon, polyproplyene, or polystyrene.

Among polyethylene's commercially desirable properties are extreme ease of fabrication, retention of flexibility at low temperatures, and resistance to chemical solvents and biological attack. Polyethylene is resistant to most chemicals, including acids, as opposed to nylon, which is softened by acids. Possible softening agents for polyethylenes are aromatic hydrocarbons, benzene, carbon tetrachloride, Camphor oil, gasoline (LDPE), and naphtha. The weatherability of polyethylene is not good, due to low ultraviolet resistance, but improves markedly upon the addition of carbon black to the mixture.

Polymer: Polypropylene.

Polypropylene is a thermoplastic, polyolefin resin that is similar to polyethylene; however, polypropylene is usually harder, stronger, and has a higher melting point (325 to 335°F) than polyethylene. A fairly crystalline polymer (45 to 60 percent), its physical properties are sensitive to the method of manufacture used. Useful attributes include high tear resistance, heat resistance, and resistance to a wide variety of chemicals including acids, bases, and most solvents, except oxidizing chemicals.

Polypropylene has a specific gravity of 0.90 to 0.91, making it the lightest polymer of those discussed herein (except for Expanded Polystyrene Foam). This also makes polypropylene tend to float when submerged. Polypropylene has medium to high strength characteristics, with a tensile yield strength of 4500 to 5500 psi, a tensile modulus of 165 to 225 ksi, a compressive yield strength of 5500 to 8000 psi, and a compressive modulus of 150 to 300 ksi.

Polypropylene has poor weatherability, due to low UV resistance; however, the weatherability may be improved by the use of additives. It is chemically inert to most organic chemicals and to biological attack, but benzene, carbon tetrachloride, and petroleum products may cause swelling.

Polymer: Polystyrene.

Polystyrene is one of the most common polymers in existence. This is due to its versatility, ease of processing, and extremely low cost. It is often used for applications in which the full range of properties of more expensive polymers need not be utilized. In its unaltered state, it is a clear rigid material with a tensile strength of 8000 psi, but numerous modified polystyrenes offer a relatively wide range of properties. It is considerably more brittle, and less extendable than many other polymers, but the use of additives and copolymers can improve these properties. Polystyrene is resistant to a variety of chemicals, although it is reactive to a wider range of compounds than other polymers.

With a specific gravity of 1.03 to 1.06 it is one of the lighter polymers, although not as light as polypropylene. High impact polystyrene, which has a tensile yield strength of 2900 to 4900 psi and a tensile modulus of 260 to 465 ksi, is a fairly stiff and brittle polymer (elongation at break, 13 to 50 percent), but not an extremely strong one. Its compressive strength is 4000 to 9000 psi.

Polystyrene has the poorest weatherability of any of the polymers in this study. It is very sensitive to ultraviolet radiation and exposure, and tends to develop craze cracks when placed outdoors for any length of time. Additives can have a mediating effect on this property to some extent.

Polymer: Expanded polystyrene foam.

R. C. Westphal, in the Modern Plastics Encyclopedia, states the following about expanded polystyrene foam: "Expandable polystyrene beads may be prepared by polymerization of styrene monomer in aqueous suspension in the presence of a volatile organic blowing agent." The rigidity and easy processing of polystyrene make it ideal for foam molding, and polystyrene foam is used for a broad array of products, from fast food containers to packing material. One of the main commercially useful properties of this form of polystyrene is its insulating value. (Thermal conductivity = 0.25 Btu/sq ft/hr/°F/in) It can be manufactured in a range of densities (1 to 5 lb./cf.) all of which are considerably less than that of water. These materials float quite well, and may experience significant bouyant forces when submerged.

The tensile strengths of expanded polystyrenes are very low (21 to 172 psi) when compared to other (non-expanded) polymers, and they tend to be extremely compressible. They exhibit no real compressive yield point, but deflect to large strains under relatively small stresses. The compressive strengths (at 10 percent strain) are quite low (13 to 130 psi), exhibiting the low moduli of these materials.

The expanded polystyrenes tend to absorb a small amount of water when wet (2 to 6 percent), and are not very resistant to certain chemicals, especially petroleum products such as gasoline.

The following table lists some commonly accepted values for the physical properties of the polymers discussed above. Most of the information contained in the table was derived from Modern Plastics Encyclopedia and Encyclopedia of Polymer Science and Technology.

Table 5 Typical polymer properties.

Polymer Type	Tensile Yield (psi)	Tensile Break (psi)	Tensile Modulus (ksi)	Compr. Yield (psi)	Compr. Modulus (ksi)
ABS	4000-5500	4800-6300	230-330	4500-8000	140-300
Nylon 6	5000-8000	10000-11800	100-380	13000-16000	250
HDPE	3000-4000	3100-5500	60-180	2700-3600	N.A.
LDPE	800-1200	600-2300	14-38	N.A.	N.A.
PP	4500-5400	4500-6000	165-225	5500-8000	150-300
HIPS	2900-4900	3200-4900	260-465	4000-9000	N.A.
Exp. PS	N.A.	21 - 172	N.A	13 -130	N.A.

Legend:

ABS - Acrylonitrile-Butadiene-Styrene
Exp.PS - Expanded PolyStyrene Foam
HDPE - High Density PolyEthylene
HIPS - High Impact PolyStyrene
LDPE - Low Density PolyEthylene
PP - PolyPropylene

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. **Highway Design and Operation for Safety**
   Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. **Traffic Control and Management**
   Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. **Highway Operations**
   This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. **Pavement Design, Construction, and Management**
   Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. **Structural Design and Hydraulics**
   Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. **RD&T Management and Coordination**
   Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. **Highway Design and Operation for Safety**
   Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. **Traffic Control and Management**
   Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. **Highway Operations**
   This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. **Pavement Design, Construction, and Management**
   Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. **Structural Design and Hydraulics**
   Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. **RD&T Management and Coordination**
   Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.

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