NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 367

Long-Term Performance of Geosynthetics in Drainage Applications

Transportation Research Board
National Research Council

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report 367

Long-Term Performance of Geosynthetics in Drainage Applications

ROBERT M. KOERNER, GEORGE R. KOERNER,
AMIRA K. FAHIM, and RAGUI F. WILSON-FAHMY
Drexel University
Geosynthetic Research Institute
Philadelphia, PA

Subject Areas

Bridges, Other Structures, and Hydraulics and Hydrology
Pavement Design
Soils, Geology, and Foundations

Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
Washington, D.C. 1994

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

Note: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers names appear herein solely because they are considered essential to the object of this report.

NCHRP REPORT 367

Project 15-13 FY'90

ISSN 0077-5614

ISBN 0-309-05367-6

L. C. Catalog Card No. 94-61112

Price $21.00

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

FOREWORD

By Staff
Transportation Research Board

This report contains the results of a thorough study of geosynthetics in highway drainage applications. Ninety-one geosynthetic drainage systems in 17 states were exhumed, and the performance of applications was compared against design predictions and construction techniques. These evaluations showed that the existing design methodology is acceptable for granular soils but that the criteria for fine-grained soils may need to be evaluated on a site-specific basis. The report will be of interest to pavement-design and geotechnical engineers in designing drainage applications; it also provides a wealth of information on the subject for researchers.

Geosynthetics are used in several types of drainage applications and are the key to the performance of these systems. Applications include, but are not limited to, pavement edge drains, underdrains, slope drains, drainage behind retaining walls, French drains, and interceptor drains. Subsurface drainage is considered to be important for extending the life of pavements, slopes, and retaining walls. In order for these drainage systems to perform as intended, they need to be properly designed and constructed.

Under NCHRP Project 15-13, "Long-Term Performance of Geosynthetics in Drainage Applications," Drexel University was assigned the following tasks: 1) documenting the design and performance of existing installations of geosynthetics in drainage applications including the appropriateness of use, construction techniques and related problems, failures, mechanisms and their consequences, and factors affecting long-term performance; 2) recommending material properties, test methods, specification values, and design; and 3) recommending construction criteria.

As a result of this project, a large database on field-exhumed geosynthetic drainage systems has been developed. Ninety-one sites (three categories: performing poorly, performing well, and uncertain) solicited from all 50 states have been thoroughly evaluated, and the performance of the applications has been compared with design criteria and construction techniques. These evaluations showed that the existing design methodology is acceptable for granular soils but that the criteria for fine-grained soils may need to be evaluated on a site-specific basis. Also, specific recommendations have been made in regard to construction practices associated with prefabricated-geocomposite-edge drains.

Readers will note that Appendices B through D are not published herein. For a limited time, copies will be available on a loan basis or for purchase ($20.00) on request to NCHRP, Transportation Research Board, Box 289, Washington, D.C. 20055.

CONTENTS

ACKNOWLEDGMENTS

This work was performed by personnel of the Geosynthetic Research Institute of Drexel University. Robert M. Koerner was the Principal Investigator. The authors of the report are Professor Koerner, George R. Koerner, Amira K. Fahim, and Ragui F. Wilson-Fahmy. The individual tasks within the project were carried out as follows:

- Field exhuming and forensic analysis—George R. Koerner;
- Long-term flow tests—Mark H. Wayne;
- Fine fraction filtration tests—Leonard J. Sansone;
- Dynamic-fine fraction filtration tests—Dhani Narejo;
- Design critique—Amira K. Fahim and Ragui F. Wilson-Fahmy; and
- Typing and Report Preparation—Marilyn V. Ashley.

The authors wish to sincerely thank the many state DOT engineers and maintenance personnel who made available the field exhuming sites, supplied information about them, and provided for traffic safety during the exhuming process. The NCHRP project panel was very helpful during the course of the project in review of the various reports, their feedback, and ongoing interest in the research.

LONG-TERM PERFORMANCE OF GEOSYNTHETICS IN DRAINAGE APPLICATIONS

SUMMARY

This study was concerned with the use of geosynthetic materials in transportation-related drainage applications. Included are geotextiles, geocomposite edge drains, geocomposite sheet drains and, to a limited extent, plastic pipe. The application areas investigated were mainly various types of highway edge drains; however, selected cases of retaining wall drains and erosion control systems were also investigated. In many instances, the geotextile was seen to be at the heart of a properly, or improperly, functioning drainage system. Thus the geotextile—serving in the primary function as a *filter*—was the major focal point of the project.

Field Exhuming

Ninety-one field sites were exhumed in 17 states. Table 1 gives an overview of the sites and of their relative performance ratings based on site-specific judgment and functioning of the entire drainage system. The nonacceptable ("D" or "F") sites listed in Table 1 were further assessed by placing the cause of the nonacceptable performance into categories of construction/maintenance, drain component and filter component (see Table 2). Note that the total number exceeds the number of nonacceptable sites due to multiple problems in some cases.

Based on a visual analysis of the field exhumed sites, the following conclusions were drawn regarding each type of drainage system investigated.

- PGEDs—inadequate soil retention by the geotextile filter attached to the drainage core occurred at eight sites (by far the largest single problem that was discovered) . . . this requires a change in the current construction technique so as to guarantee intimate contact with the upstream soil.
- GWUDs—requires constant vigilance against construction/maintenance problems.
- PPUDs—an acceptable status currently exists.
- GSPPs—appears to be somewhat installation sensitive with respect to the geotextile filter.
- GWDFs—an acceptable status currently exists.
- GECFs—needs intimate contact with the subgrade in order to be effective.

TABLE 1. Summary of all exhumed field sites

Type of Drainage System*	No. of Sites	Acceptable Performance (A, B, or C)**	Nonacceptable Performance (D or F)**
PGED	41	27	14
GWUD	25	16	9
PPUD	6	5	1
GSPP	12	9	3
GWDF	3	3	0
GECF	4	3	1
Totals	91	63	28

*where
PGED = prefabricated geocomposite edge drain
GWUD = geotextile wrapped underdrain (stone and perforated pipe)
PPUD = perforated pipe underdrain (no geotextile filter)
GSPP = geotextile socked perforated pipe
GWDF = geotextile wall drain filter
GECF = geotextile erosion control filter
**also
A = all three components (system, drain and filter) functioning as intended
B = one component of above showing less than ideal performance
C = more than one component of above showing less than ideal performance
D = one component of above showing poor performance
F = more than one component showing poor performance, or one component showing failure

TABLE 2. Summary of nonacceptably performing exhumed field sites

Type of Drainage System	Nonacceptable Performance (D or F)**		
	Const./Maint. Component	Drain Component	Geotextile Component
PGED	4	4	10
GWUD	6	1	2
PPUD	1	1	0
GSPP	2	0	1
GWDF	0	0	0
GECF	1	0	1
Totals	14	6	14

Upon retrieving samples of the exhumed drain, filter, and adjacent soils at each field site, a complete forensic analysis was performed. These data were used to compare the field performance (considered to be "ground truth") to published design models for permeability, soil retention, and acceptable levels of geotextile clogging.

Laboratory Evaluations and Test Method Development

In order to model and possibly predict the behavior of the various types of drainage systems used in transportation applications, three different laboratory test methods were investigated or developed. In all cases, the geotextile was the target of evaluation because it was seen to be the problem in the majority of nonacceptable field situations (recall Table 2).

Long-Term Flow (LTF) Tests. Constant head flow permeameters according to a newly developed test method were used. When permeated over a long period of time, the resulting soil/geotextile flow rates indicate one of the three possible results: flow rate equilibrium, excessive clogging, or soil piping. For this project, 32 such columns were constructed and used for up to 5,000 hr. Four different geotextiles, with four different soil types, under clear water and turbid water flow were evaluated. The test results gave accurate indications of the particular phenomenon involved. The test can, and should, be used to assess critical and severe situations involving fine-grained soils either upstream of the geotextile or in the permeating water. Unfortunately, the test takes a minimum of one month to perform and sometimes even longer than several months in order for the flow rates to stabilize into meaningful results.

Fine Fraction Filtration (F^3) *Tests.* In an attempt to hasten the results coming from such a test as LTF, the fine fraction filtration (F^3) test was developed. The test is based on the hypothesis that the fine fraction of the soil upstream of a filter poses the major challenge to its long-term behavior. Thus, the fraction of soil finer than the opening size of the geotextile was used in slurried increments and passed through a horizontally oriented geotextile. As increments of slurry were sequentially introduced into the flow column, the permittivity behavior distinguished among flow rate equilibrium, excessive clogging, or soil piping. These above types of behavior were seen for a series of trial situations.

The researchers then focused on the field-exhumed soils and their respective geotextiles. For the "D" and "F" site soils and their associated geotextiles, the test always indicated when soil retention was the problem or when it was excessive clogging. Unfortunately, the same type of behavior was seen for the "A," "B," and "C" exhumed soils and their associated geotextiles. Thus the F^3 test can distinguish between what type of problem a geotextile might have when confronted with the fines from a particular soil, but it cannot distinguish between when a problem will arise or when the situation will be acceptable. This latter comment defeats the very purpose of the test as a rapid precursor of the likelihood of a field problem. It is felt that the test is essentially academic at this point. Hence the test is *not* recommended for use in assessing highway drainage systems.

Dynamic-Fine Fraction Filtration (D-F^3) *Tests.* Recognizing that turbid water from beneath pavements can impact geotextile filters around highway edge drains in a dynamic manner, a test was devised to simulate this type of behavior. Called the dynamic-fine fraction filtration (D-F^3) test, it uses the same concept as the F^3 test but now in a closed hydraulic system where pulses of energy can be imposed on the slurried water flow regime upstream of the geotextile. The test was again successful in distinguishing among equilibrium, excessive clogging, or soil piping situations, but suffered the same drawback as the F^3 test. That is, the test could not distinguish between cases where field problems were encountered and cases where the geotextiles were functioning properly. Thus the recommendation is the same as with the F^3 test in that the D-F^3 should *not* be continued insofar as an accelerated test method for assessment of geotextile filters for highway drainage systems at this time.

Design Critique

A major task of this project was to critique the available design status for highway drainage systems. This was done via an extensive literature search and a subsequent comparison of the various design methods against the behavior (and known properties) of the field-exhumed sites.

Geotextile Filter Design. The geotextile filter was the main cause of concern in this study. While excessive clogging can be, and was, a problem in a few cases, the lack of soil retention, i.e., excessive soil loss through the filter, was much more common. Intimate contact of the upstream soil was seen to be absolutely necessary as none of the design methods gave accurate predictions of such situations. In this regard, future installations of PGEDs are recommended to be modified insofar as current practice is concerned. By placing these drains against the shoulder side of the excavation and backfilling the pavement side with puddled sand, the soil retention problems should be averted. This is the current construction method being used by the Kentucky DOT. The geotextile design then becomes straightforward because a known type of sand is the adjacent material and it has intimate contact.

Regarding design for other situations, the current criteria for granular soils are quite appropriate. Use of the Christopher and Holtz criteria (which are the current Federal Highway Administration [FHWA] guidelines) should be continued. For fine-grained soils in a noncritical/nonsevere situation, the FHWA guidelines can be continued to be used. However, for critical/severe situations, a laboratory assessment should be considered or the design modified so as to avoid the fine-grained soils altogether, e.g., placing a layer of sand adjacent to the geotextile.

Drain Component Considerations. The various drainage components (core, gravel, or perforated pipe) within geotextile filters performed quite well. With the obvious exception of a pipe with no perforations and prefabricated drainage cores, which filled with fines because of the lack of intimate contact (which is not the fault of the drain), the drains performed acceptably and the current design status should be continued.

Construction/Maintenance Considerations. The geotextile filter, its enclosed drain and its outlet details, can be considered to be a system that obviously requires proper installation and proper maintenance for successful long-term performance. Numerous problems were observed in this regard. Note, however, that none were particularly new or novel to DOT engineers and maintenance crews who are generally well aware of the various situations encountered. Proper maintenance is particularly important and constant vigilance must be practiced.

Recommendations

Of the various drainage systems evaluated, the prefabricated geocomposite edge drains (PGED) were the most provocative due primarily to their lower installation cost over more conventional drainage systems. As currently bid, PGEDs are $1.00 to $2.00 per linear foot less expensive than any other type of highway edge drain system. In the field-exhuming task, problems with PGEDs were indeed encountered. The large majority were observed to be construction related in that intimate contact was not achieved. The puddled sand installation method should be used so as to avoid such retention problems.

Regarding the design methodology for properly functioning geotextile filters, the research showed that permeability, soil retention, and clogging criteria such as the FHWA models are acceptable for granular soils, but the criteria for fine-grained soils when of a critical/severe nature need to be investigated on a site-specific basis. Obviously, avoiding geotextile filters for fine-grained soils in critical conditions in favor of sand filters is an option but sometimes it cannot be accommodated or economically justified. Additional research seems appropriate in this regard.

Regarding laboratory testing, the LTF test should be continued for critical or unusual filtration situations such as dynamic or cyclic flow. This is particularly the case with cohesionless silts and turbid permeants. While it is recognized that this is a time-consuming test and not amenable to rapid results, it is the best laboratory approach that is currently available. Neither the F^3 nor the D-F^3 test is recommended as a rapid precursor test to predict geotextile filter behavior in highway drainage systems. Instead, empirical guides should be followed such as those generated during the field-exhuming phase coupled with the continued development of a database of LTF laboratory tests.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

Proper subsurface drainage has long been recognized as a key element toward improved functionality and lifetime of highway systems (*1*). Such drainage requires proper functioning of both the stone base beneath the pavement and the adjacent highway edge drains. Because the type of stone base is fixed by the initial design and its associated construction method (the tendency toward open-graded base courses should be noted), the edge drain systems are the focus for this particular project. Edge drains can be installed along with the construction of a new highway, installed along with pavement rehabilitation using such methods as "crack and seat," or installed as a retrofit drainage system adjacent to existing pavements. Within the edge drain category, there are several different types, all of which use one or more geosynthetic materials. The different types investigated are as follows. These four variations of edge drains are shown in Figure 1.

- Prefabricated geocomposite edge drains (PGEDs), which consist of a polymer core encompassed by a geotextile filter assembled in a factory and installed in the field as a completely manufactured unit.
- Geotextile wrapped underdrains (GWUDs), which consist of a perforated plastic pipe backfilled with gravel and then encompassed by a geotextile filter around the gravel.
- Perforated pipe underdrains (PPUDs), which consist of a perforated pipe backfilled with gravel having no filter (neither geotextile nor sand).
- Geotextile socked perforated pipes (GSPPs), which consist of a perforated pipe with a geotextile filter surrounding it, i.e., the pipe is "socked," usually with sand used as the backfill material.

Two other types of geotextile filters used in related highway applications and addressed in this project are as follows (see also Figure 1).

- Geotextile wall drain filters (GWDFs), which use geotextiles behind retaining walls as filters to allow water to pass into the geocomposite core drain or natural soil drain, while at the same time retaining the backfill soil.
- Geotextile erosion control filters (GECFs), which are geotextiles used beneath stone rip-rap or other armoring material to prevent erosion on highway slopes or within drainage channels.

In all of these types of drainage systems, the geotextiles play a pivotal role. Acting as a filter, the geotextiles must simultaneously perform three basic mechanisms (*2*):

- The voids must be sufficiently open to allow water to pass through into the downstream drain without building excessive pore water pressures in the upstream soil.
- The voids must be sufficiently tight so to adequately retain the upstream soil materials so that soil loss does not become excessive and clog the downstream drain.
- The geotextiles must perform the previous two conflicting tasks (open voids versus tight voids) over the anticipated lifetime of the drainage system without excessively clogging.

The first mechanism requires a permeability assessment. It is usually done on the basis of a design criterion comparing the permeability of the upstream soil with that of the geotextile. The second mechanism requires an opening size assessment and comparison to the particle size of the upstream soil. The third mechanism is usually addressed on the basis of empirical guidelines or laboratory testing based on the criticality/severity of the site specific application.

OBJECTIVES OF RESEARCH

While the entire drainage system (filter, drain, and associated system) is of interest, it was found immediately from the very first exhumed site that if the geotextile was not functioning, the entire system could not perform properly. Clearly, the geotextile filter was seen to be absolutely essential and hence it became the focal point of the research. Thus, the specific objectives of the project were as follows:

1. Exhume as many sites-of-opportunity as possible to actually witness the performance of the entire drainage system.
2. Perform forensic analyses of the exhumed materials, focusing on the geotextile filter and associated soils, to see which design criteria best fit the observed performance.
3. Use long-term flow tests in the laboratory to observe fundamental behavior using problem-type soils and permeants.
4. Investigate new, and accelerated, laboratory test methods to see if a precursor test could be developed to give an indication of where problems might be encountered in the field.
5. Recommend appropriate design and construction criteria based on the findings of this research effort.

RESEARCH APPROACH

To approach the problem in a systematic manner, the field and laboratory objectives were mobilized simultaneously with

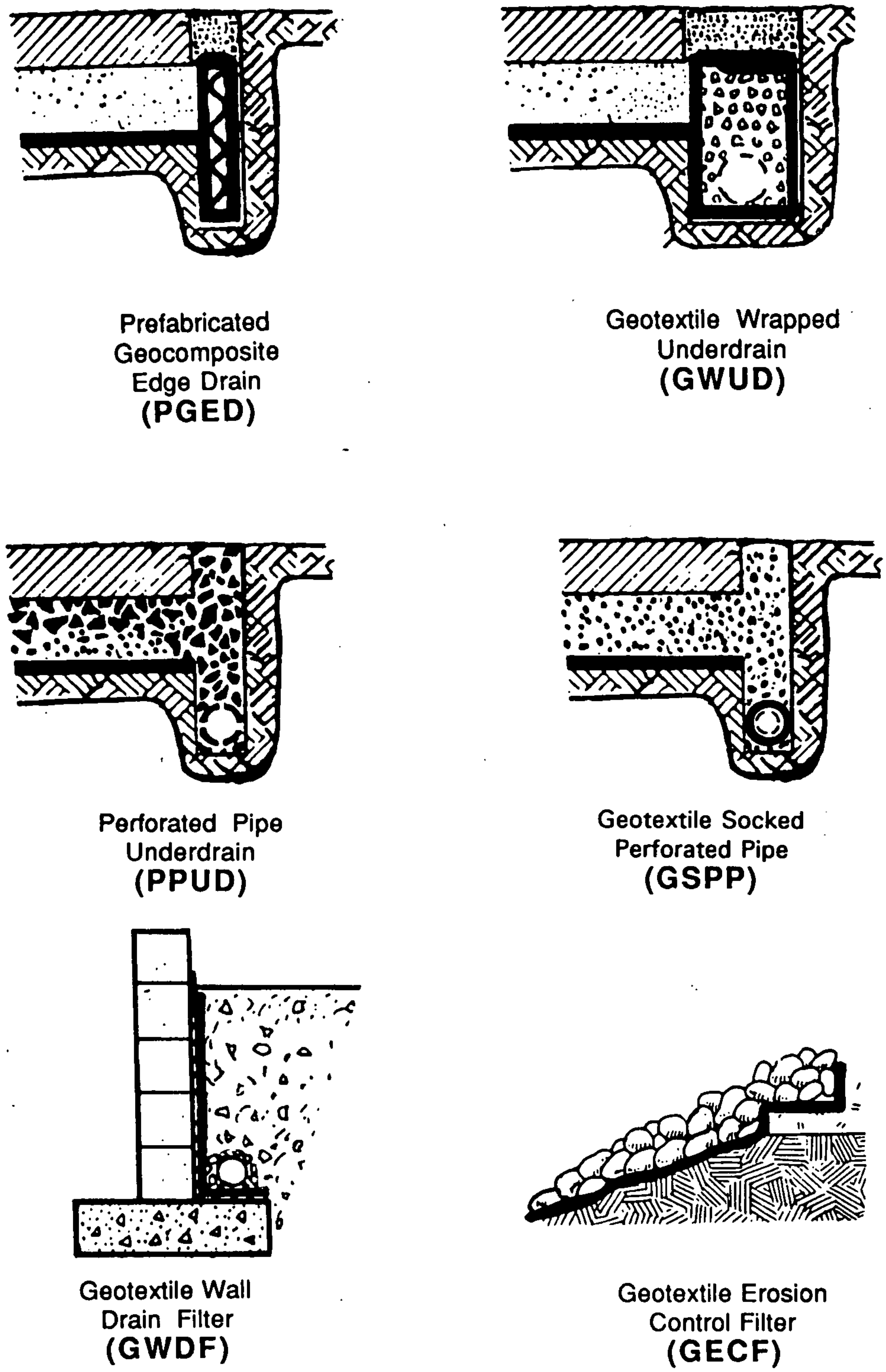


Figure 1. Various types of geosynthetic drainage systems exhumed in this project.

the design corroboration at the end. Figure 2 summarizes the general research approach.

The field-exhuming task proved to be the key element of the project. The lessons learned gave abundantly clear insight as to existing drainage system behavior, as well as to various problems that were encountered.

Three laboratory evaluation tests were undertaken. LTF tests have been conducted by various groups since 1982 and some confidence in the test method has been previously established. While the test takes a long time to perform from a practical perspective, it was included to provide insight into long-term behavior for problematic soils and turbid water permeants. There

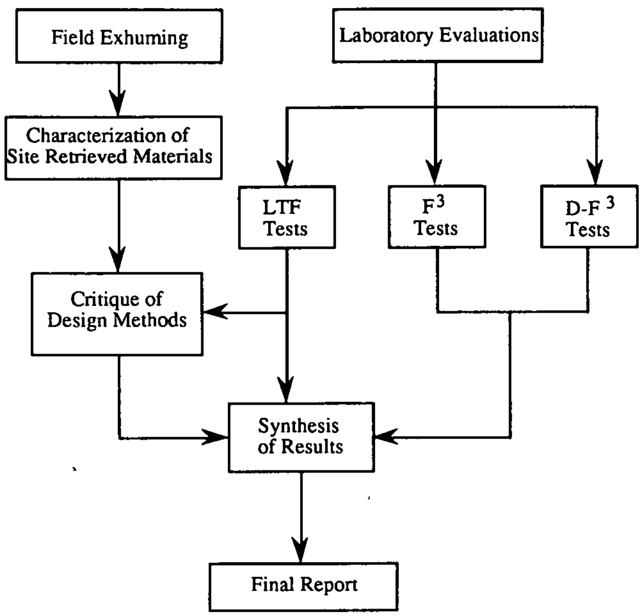


Figure 2. General approach used in this project on the evaluation of long-term performance of geosynthetics in drainage applications.

was also a concerted effort made to develop an accelerated laboratory test method that could possibly act as a precursor of anticipated field behavior. Both tests developed — F^3 and D-F^3 — use the fine fraction of soil to interface with the geotextile filter. The first test uses quasi-static flow conditions, the second is under dynamic flow conditions.

The geotextile design critique leaned heavily on the field exhumed sites for "ground truth." By comparing the field results to the different design methods available in the literature, correlations as to the appropriateness of the various methods were established. Three separate categories were investigated: 1) permeability criteria, 2) soil retention criteria, and 3) excessive clogging criteria.

In general, it is tacitly assumed by most designers that the upstream soil through which water is moving is backfilled tightly against the geotextile filter. Such "intimate contact" is essential for the proper functioning of the filter and its associated downstream drain. If this is not the case, the various design criteria cannot be expected to produce reliable results. In such cases, construction practice must be modified so that intimate contact is ensured.

ORGANIZATION OF REPORT

The findings from the field-exhuming and laboratory studies are presented in Chapter 2; Chapter 3 contains the interpretations, appraisal, and applications. Conclusions and suggested research are discussed in Chapter 4. Appendix A summarizes the field study of the 91 exhumed sites and their respective performance levels. Appendixes B, C, and D are not published herein, but may be obtained on loan by contacting the NCHRP.

CHAPTER 2

FINDINGS

FIELD EXHUMING STUDIES

Selection Criteria

On April 11, 1990, all 50 state department of transportation (DOT) geotechnical and materials engineers were sent a questionnaire regarding a solicitation of field sites for exhumation. The general request was for at least three sites: one suspected of having problems, one suspected of functioning as intended, and one that was questionable or uncertain in its observed behavior. *Thus from the outset, problems were not only anticipated but were actually solicited.* Sites involving the following geosynthetic applications were requested:

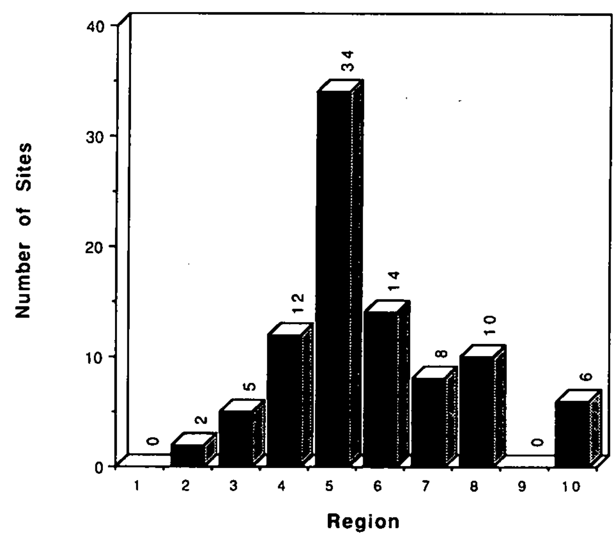
- Geotextile filters around drainage stone, i.e., french drains;
- Geotextile filters around drainage stone containing perforated drainage pipe;
- Geotextile filters directly around perforated drainage pipe;
- Geotextile filters beneath rock rip-rap erosion control systems;
- Geotextile filters beneath gabion erosion control systems;
- Geotextile filters beneath prefabricated erosion control systems, e.g., articulated blocks;
- Geocomposite erosion control systems, e.g., geotextile/plastic mesh systems;
- Prefabricated geocomposite sheet drains behind retaining walls;
- Prefabricated geocomposite sheet drains used to drain earth and rock slopes;
- Prefabricated geocomposite highway edge drains;
- Prefabricated geocomposite interceptor drains; and
- Other related geosynthetic filtration/drainage applications.

In the questionnaire and follow-up conversations, information was requested about the sites and possible traffic control during the exhuming process. With respect to site history, local DOT engineers were asked to identify the drain type, location, age, and perceived performance. Information was also solicited on design traffic number, roadway condition, outlet spacing, outlet conditions, and finally, the overall climatic conditions at the site. Each highway grade and cross section was visually identified.

All other activities (excavation, exhuming, sampling, repair, and restoration) were performed under the auspices of this research project. In total, 91 sites in 17 different states were exhumed. Figure 3 shows the sites by FHWA region and state. The ages of the different sites are shown in Figure 4 and the various climatic conditions encountered are shown in Figure 5.

Exhuming Procedure

Only after the previous information was obtained was a working excavation dug in the shoulder adjacent to the existing highway edge drain. The excavation's dimensions were typically 3 ft wide by 5 ft long by 4 ft deep. Figure 6 shows the typical excavation sequence for sites with PGEDs (which was a similar situation for the GSPPs and GWDFs). Figure 7 shows the typical excavation sequence for sites with GWUDs (which was a similar situation for the PPUDs and GECFs).



FHwA Region	States Included in this Region
1	ME, NH, VT, RI, CT, MA
2	NY, NJ, PR
3	PA, DE, MD, VA, WV
4	TN, KY, NC, SC, GA, AL, MS, FL
5	OH, MI, WI, IL, MN
6	TX, LA, AR, OK, NM
7	MO, IA, KS, NE
8	ND, SD, WY, CO, UT, MT
9	CA, AR, NV, HI
10	WA, OR, ID, AK

Figure 3. Location by FHWA region of 91 sites where geosynthetic drainage systems were exhumed.

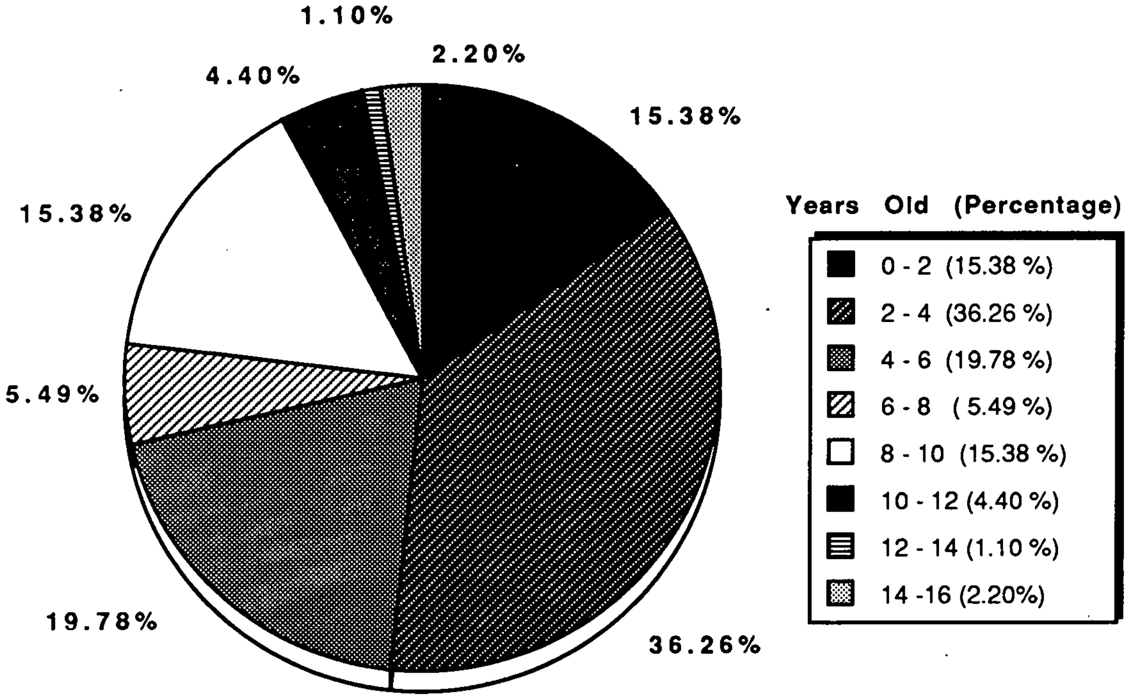


Figure 4. Ages of the exhumed sites.

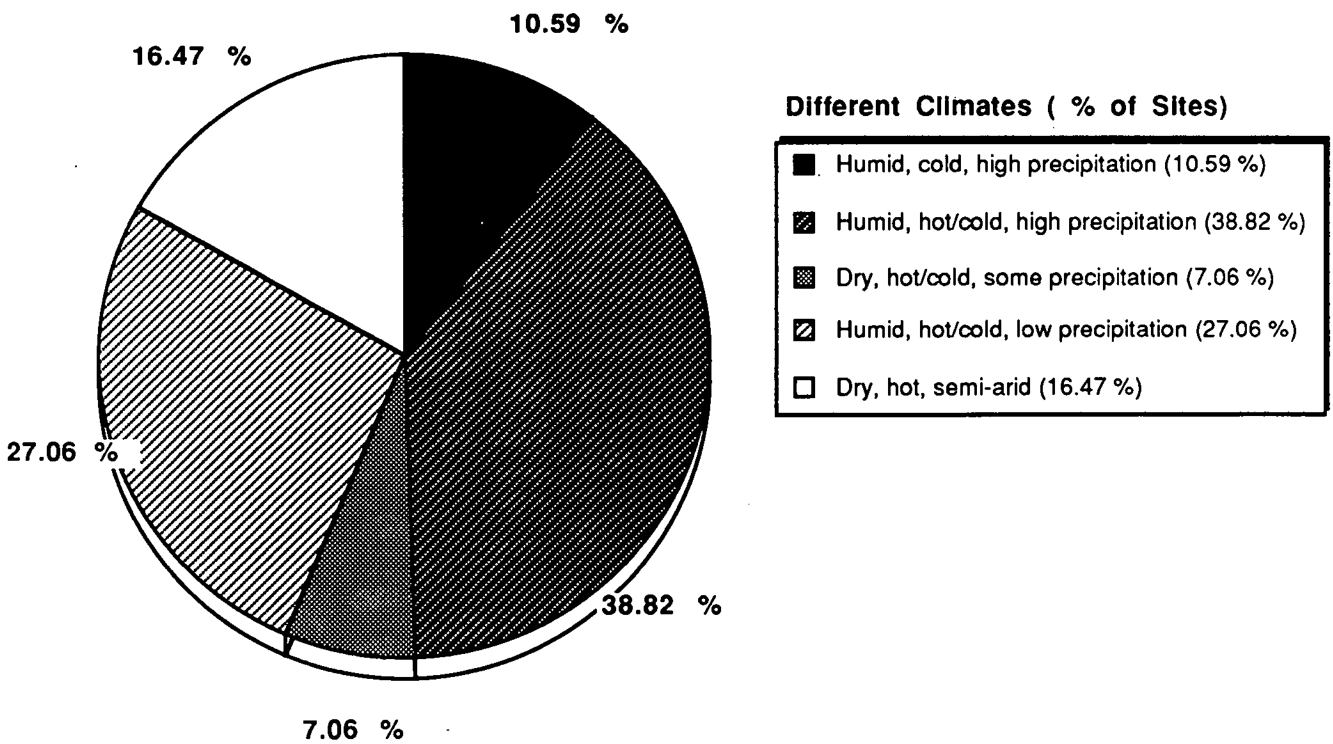
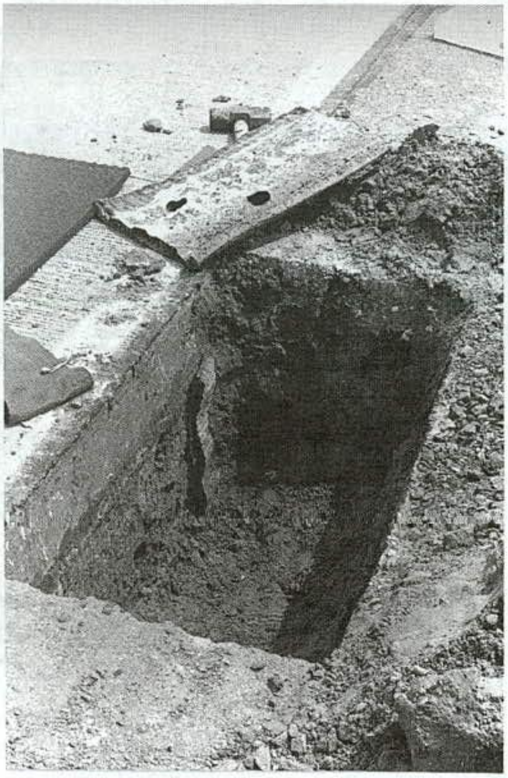


Figure 5. Climatic conditions of exhumed sites.

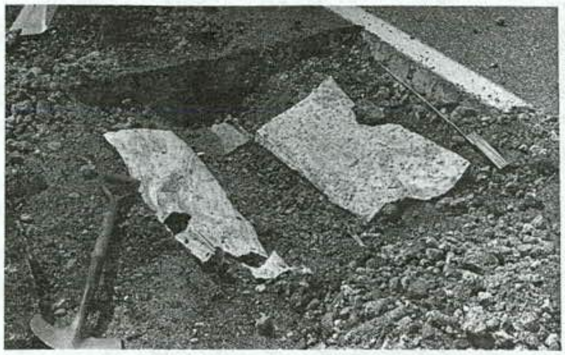
(a) Access pit dug adjacent to PGED drain to be sampled



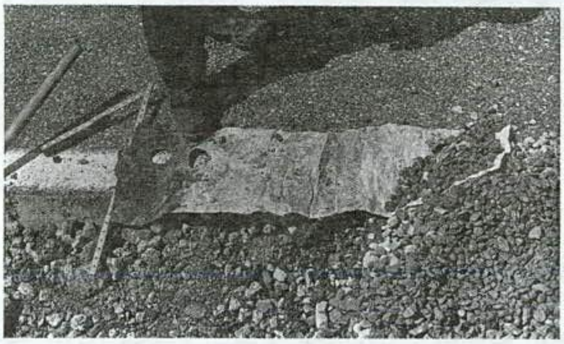
(b) Drain condition after sampling

(c) Close-up view of inside of sampled PGED drain

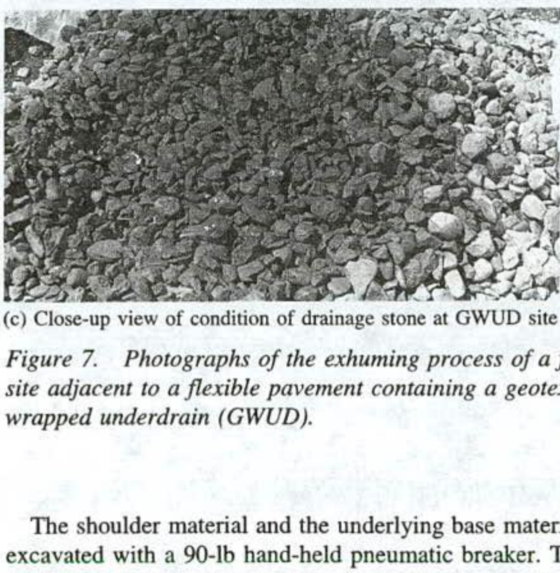
Figure 6. Photographs of the exhuming process of a field site adjacent to a rigid pavement containing a prefabricated geocomposite edge drain (PGED).



(a) Access pit at GWUD site with geotextile folded back from drainage stone



(b) Condition of geotextile filter at GWUD site and exposed drainage stone



(c) Close-up view of condition of drainage stone at GWUD site

Figure 7. Photographs of the exhuming process of a field site adjacent to a flexible pavement containing a geotextile wrapped underdrain (GWUD).

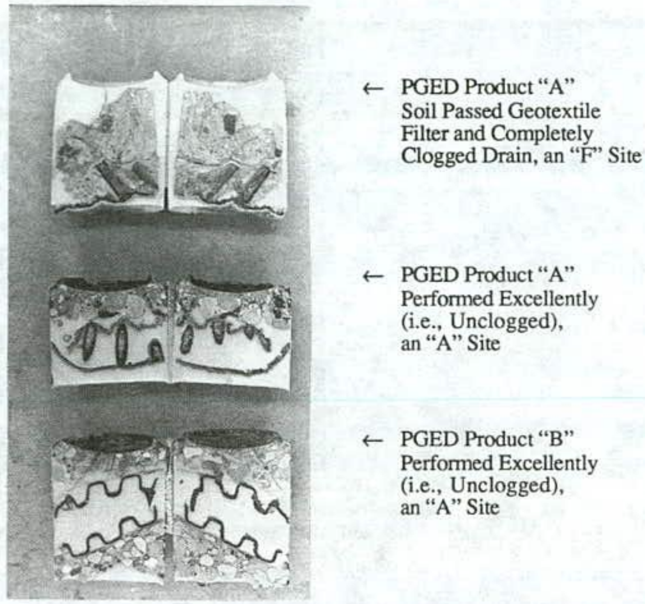


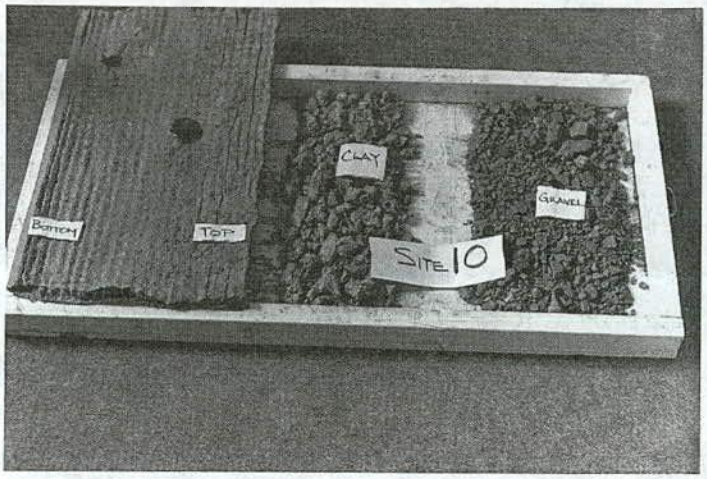
Figure 8. Photographs of epoxy set Shelby tubes of field-retrieved samples, which were sawed along their diameter into two halves illustrating cross sections of various prefabricated geocomposite edge drains (PGEDs) encountered.

The shoulder material and the underlying base material were excavated with a 90-lb hand-held pneumatic breaker. The subgrade was then excavated with a smaller pneumatic clay spade and hand shovel. It is important to note that the entire excavation process was accomplished by hand. This ensured a small and neat excavation, which results in quick and easy remediation. It also helps ensure that the drainage system was not damaged during excavation by large construction equipment working in confined areas.

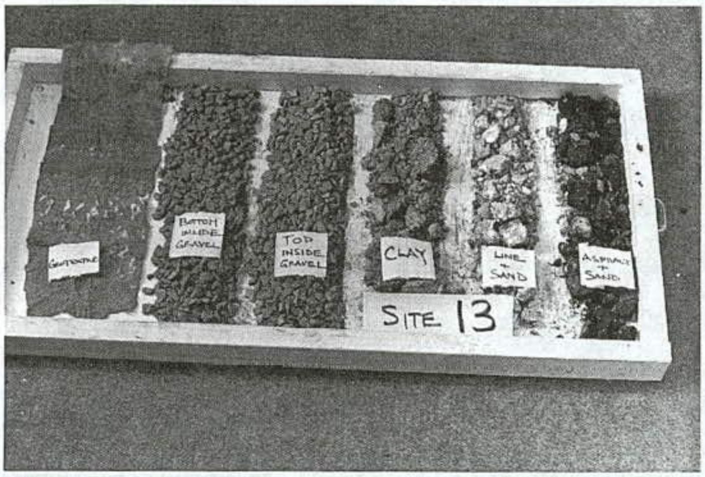
Once the drain was exposed, it was sampled in-place via a Shelby tube sampler in two or three locations. A Shelby tube is a 2.5-in.-diameter seamless steel tube with a sharp cutting edge. The tube was horizontally driven by a sledge hammer through the edge drain or geotextile cross section to trap the interface of the geotextile and adjacent soil. The round holes in the different products can be observed in Figures 6 and 7. The Shelby tube samples were then sealed, capped, and brought back to the laboratory, where they were allowed to air dry. After a week of drying (which caused some amount of shrinkage in the finer grained soils), the samples were infiltrated with a bright yellow-colored resin epoxy and allowed to set for 2 days. After hardening, the samples were cut longitudinally with a diamond saw and inspected under a microscope. As shown in Figure 8 (which includes an "F" site where soil passed the geotextile filter and completely filled the drainage core and two "A" sites where the drainage cores are completely free of soil and functioning excellently), this type of sampling and analysis yielded excellent insight into the mechanisms that influence the performance of the geotextile filter and its behavior with respect to the upstream soil. When shrinkage from air drying some of the samples occurred, the soil pulled away from the Shelby tube rather than the soil-to-geotextile interface. Thus air drying was not felt to be a significant factor in the assessment.

After the Shelby tube samples were taken at the site, a 2-ft-long sample of the prefabricated geocomposite edge drain or of the geotextile filter by itself was completely removed from the exposed drain (see Figure 9a). In addition to sampling the drain or its associated geotextile, grab samples of the soil subgrade, subbase, and base materials were retrieved and brought back to the laboratory for analysis (see Figure 9b). Index properties of these samples (geotextiles and soils) were performed to shed insight into the interaction among the geosynthetic drain, its geotextile filter, and the soil system as a whole. The data were subsequently used to assess the various design methods.

Throughout the entire exhuming and sampling process, each site was videotaped and photographed. This information, in addi-



(a) Field-sampled PGED site showing removed product (with holes from Shelby tube samples), along with the clay soil taken from the shoulder side and the gravel taken from the pavement side of the installed material



(b) Field-sampled GWUD site showing the geotextile filter, various zones of the gravel contained within the geotextile and the different soils adjacent to the drain

Figure 9. Photographs of the method of laboratory cataloging the various geosynthetics and soils retrieved from each field site.

tion to written records, provided adequate documentation to analyze the site and give direction for subsequent laboratory testing.

Upon completing the exhuming process, the drainage system was repaired to return the site to proper functioning. This remediation was done under the inspection of the local DOT engineer or other designated individual. After the repair work was approved, the excavation was backfilled and compacted. If the highway shoulder was paved, an asphalt or concrete cap was placed over the affected area to match the existing surface. The highway shoulder was then put back into service and traffic control was released. The entire exhuming process for each site typically took 4 to 5 hours. A brief letter report was sent to each state contact person as to the results of the exhuming activity with an accompanying videotape in many cases.

Following the exhuming process, the site was documented, its geotextile identified, and then it was assessed for its performance on an overall performance basis. A scale of 100 percent (perfect performance) to 0 percent (complete failure) was used. This scale was subsequently graded on an "A" to "F" basis. The grading designations used were as follows:

TABLE 3. Summary of all exhumed field sites with nonacceptable sites categorized

Type of Drainage System*	No. of Sites	Acceptable Performance (A, B, or C)**	Nonacceptable Performance (D or F)** Const./Maint. Component	Drain Component	Geotextile Component
PGED	41	27	4	4	10
GWUD	25	16	6	1	2
PPUD	6	5	1	1	0
GSPP	12	9	2	0	1
GWDF	3	3	0	0	0
GECF	4	3	1	0	1
Totals	91	63	14	6	14

*where
PGED = prefabricated geocomposite edge drain
GWUD = geotextile wrapped underdrain (stone and perforated pipe)
PPUD = perforated pipe underdrain (no geotextile filter)
GSPP = geotextile socked perforated pipe
GWDF = geotextile wall drain filter
GECF = geotextile erosion control filter
**also
A = all three components (system, drain and filter) functioning as intended
B = one component of above showing less than ideal performance
C = more than one component of above showing less than ideal performance
D = one component of above showing poor performance
F = more than one component showing poor performance or one component showing failure

NOTE: Totals exceed number of sites because some sites include multiple poor-performance problems

A = all three components (filter, drain, and system) were functioning perfectly;
B = one component of the above showed less than ideal performance;
C = more than one component of the above showed less than ideal performance;
D = one component of the above showed poor performance; and
F = more than one component showed poor performance or one component indicated failure.

Descriptions of the 91 exhumed sites and the respective performance levels of each are given in Appendix A.

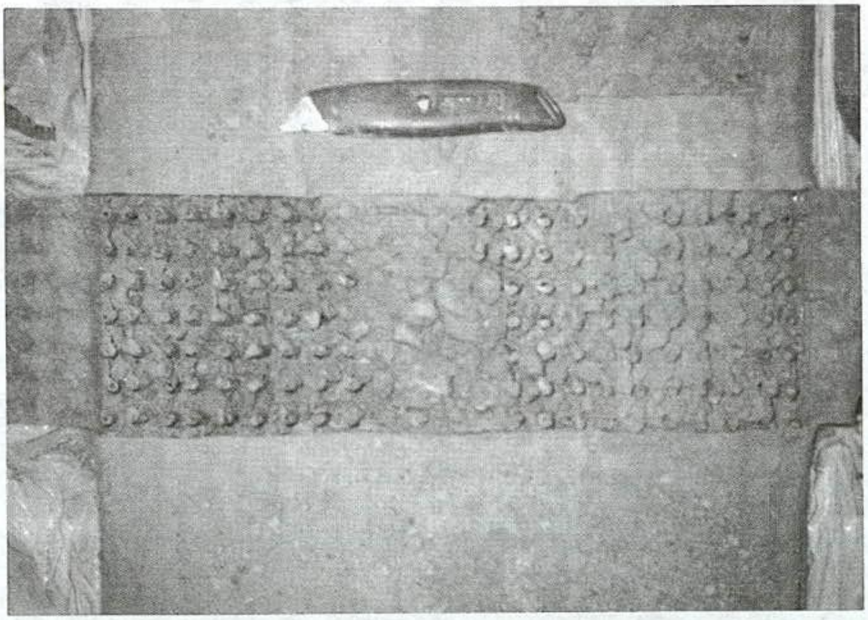
Results of Field Exhuming

Using the information from Appendix A, Table 3 was generated. As can be seen, the analysis of the sites was now taken to a second level whereby the nonacceptable sites, i.e., the "D" and "F" sites, were subdivided as to problems in construction/maintenance, drain component, or geotextile component.

Clearly evident from Table 3 is that construction/maintenance problems continue to be a problem with highway drainage systems; however, this finding is well known to transportation engineers and is a constant "battle" that must be sustained. More surprising is the number of geotextile problems, particularly with the prefabricated geocomposite edge drains (PGEDs). Furthermore, of the 10 specific problems with PGED filters listed in Table 3, eight were of the soil-retention type where soil finer than the openings of the geotextile moved into the drainage core and completely clogged it (see Figure 10). From visual observation at the site and inference from core examination, all indications were that the geotextile was not initially in close contact with the upstream soil or stone base. The resulting voids allowed turbid water to challenge the geotextile directly. The fine particles in suspension, and probably under dynamic load, simply passed through the geotextile and accumulated in the core until its capacity was exceeded. Note that this phenomenon might not be considered to be a geotextile problem, per se, and could also have been put into the construction problem category since it was felt to be construction related. Its categorization, however, is a moot point because it clearly indicated nonacceptable performance. These considerations are further corroborated via the photographs of Figure 11, which show large empty spaces under pavement slabs that undoubtedly left voids upstream of the relatively stiff PGED products. Figure 12 shows the types of excavated materials, i.e., stones and rocks, which give rise to these empty spaces against which the PGED is placed.

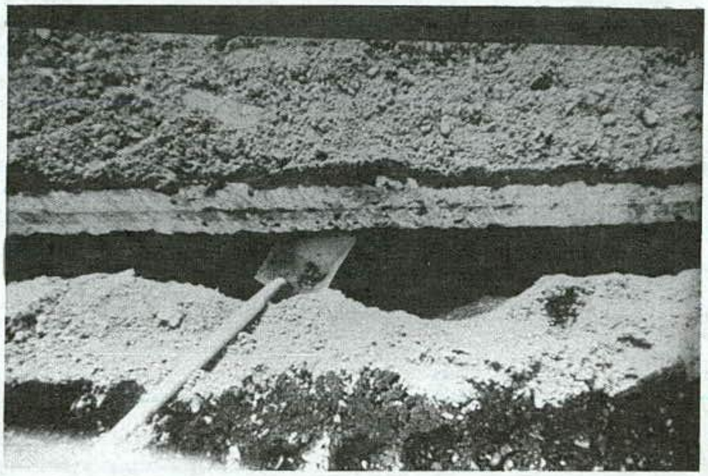
To avoid this obviously unacceptable condition for the installation of PGEDs, it is possible to change the method of installation. Instead of trying to force the core of the PGED to conform to large voids or highly irregular spaces on the pavement side of the excavated trench, the PGED can be shifted to the shoulder side of its excavation. This will leave a space on the pavement side that can be filled with sand and appropriately puddled to fill the space available, *including* any empty spaces that may be present under the pavement slab. The width of this space depends on the width of the trench to begin with, e.g., for a 4.0-in.-width trench and a 1.0-in.-thick PGED product the space to be filled will be 3.0 in. Even with this suggested change in the installation of PGEDs, the installed cost will still represent a savings of over

(a) Geotextile filter cut away from drainage core of PGED (holes are the result of Shelby tube sampling)



(b) Close-up view of soil-clogged PGED drainage core after geotextile filter was removed

Figure 10. Exhumed examples of clogged prefabricated geocomposite edge drain (PGED) cores resulting from fine soil passing through the geotextile filter and clogging the drainage core.



(a) Extensive open space under pavement slab caused by trenching operation for installation of PGED

(b) Large void under pavement caused by removal of coarse soil and/or collapsing conditions during trenching operation for installation of PGED

Figure 11. Machine excavated trench for prefabricated geocomposite edge drain (PGED) placement adjacent to pavement slab showing large voids created by coarse site soils and current method of installation.

$1.00 per linear foot as opposed to other highway drainage systems.

A forensic study was completed for the geotextile and soil materials of each of the 91 sites. The geotextiles were ultrasonically cleaned and were evaluated for their permittivity and permeability (note that permittivity is the permeability divided by the geotextile's thickness) according to ASTM D4491. The value was compared to the manufacturer's literature value because the geotextiles could usually be identified. In the cleaned condition, the apparent opening size according to ASTM D4751 was also determined and compared to the manufacturer's value. Appendix B presents this information for each site. Additionally, the soil upstream of the geotextile was analyzed insofar as particle size, via ASTM D422, and Atterberg Limits (if appropriate), via ASTM D4318 (see Appendix B). The information of Appendix B will be used later to analyze the various design criteria for geotextile filters to see which method(s) can be recommended for general use. Lastly, if soil retention was a problem, the soil

(a) Type of coarse gravel and stones encountered during trenching operation for PGED

(b) Large stones removed from beneath pavement during trenching operation for PGED

Figure 12. Coarse gravel and stones through which excavations for prefabricated geocomposite edge drains (PGEDs) are sometimes made resulting in large voids under pavement slabs as shown in the photographs of Figure 11.

that passed through the geotextile into the drain was carefully removed and analyzed for its particle size characteristics and Atterberg Limits.

Summary of Field Exhuming

The summary of the field exhuming of the 91 sites has provided extremely valuable information. Regarding general comments based on field observations and visual judgment with respect to the three categories that were identified in Table 3, the following problems have occurred:

CONSTRUCTION/MAINTENANCE

- backfill types that are high in clay content
- excessive settlement of backfill trench
- outlet elevation too high for proper drainage
- outlet elevation too low with resulting backflooding
- vegetation and soil around outlet
- outlet headwall (or pipe) damage

- no sealant between pavement and shoulder
- drain too low in cross section
- drain too far from edge of pavement
- guard post penetration into drain

DRAIN COMPONENT

- improper product used (core was too compressible)
- excessive deformation of the core (J-buckling or bending)
- installation damage (edges too sharp or inadequate flexibility)
- asphaltic drain pipe installed which contained no perforations for water inflow

FILTER COMPONENT

- inadequate soil retention (eight sites, all of which were PGEDs)
- excessive soil clogging
- slag precipitation
- inadequate strength (GT and Seam)
- excessive UV degradation

By way of remediating these problems, see the following comments with respect to each particular type of drainage system that was exhumed.

- PGEDs—require a change in the current construction technique so as to achieve intimate contact with the upstream soil,
- GWUDs — require constant vigilance for construction/maintenance problems,
- PPUDs—an acceptable status current exists,
- GSPPs—appear to be somewhat installation sensitive with respect to the geotextile,
- GWDFs—an acceptable status currently exists, and
- GECFs—needs intimate contact with the subgrade in order to be effective.

LABORATORY STUDIES

Background

The development and design of all civil engineering materials, including geosynthetics, uses a design-by-function approach whereby a factor-of-safety is formulated comparing an allowable property with a required property. The allowable property usually comes from a laboratory test method, which is developed and eventually adopted by ASTM (for general materials) or AASHTO (for highway related materials). The test method can be of the performance type that closely simulates the intended behavior, or of the index type, which is used as a general indicator of a phenomenon or as a quality control measure. This chapter presents results using one performance test and attempts to develop two index tests for use in the design of geotextile filters. (Note that the selection of an appropriate design model(s) will be the topic of Chapter 3.)

For all three test methods to be presented in this chapter, the flow (expressed as either flow rate, permeability, or permittivity) is monitored against testing duration or flow increments. The resulting graphical response should take one of three different forms.

1. Flow can decrease over time until the system is nonfunctional, which generally signifies excessive clogging of the geotextile.
2. Flow can increase over time, which generally signifies the lack of soil retention, hence excessive soil loss through the geotextile.
3. Flow can gradually decrease and then reach an equilibrium value, which should be the allowable flow rate for the system, or in some cases the lower bound of allowable flow rate.

Long-Term Flow Tests

The long-term flow (LTF) test was developed as a natural outgrowth of ASTM's gradient ratio test, which is felt to be seriously flawed when evaluating nonwoven geotextiles and fine-grained silt and clay soil types. The gradient ratio test measures piezometric heads which stabilize quickly for woven geotextiles and granular soils for which the test was originally developed. For the more common situations encountered in highway drainage situations this is not the case. Here nonwoven geotextiles and fine-grained soils predominate. Long-term piezometric heads could be measured; however, air entrapment in the measurement system is a common problem as is the interpretation of the numeric value of the gradient ratio. As presented by Koerner and Ko (*3*), the option is to use an LTF test, which is very straightforward to set up and interpret. The test device consists of a flow column with the geotextile mounted horizontally, covered by the site-specific soil and permeated under constant head conditions with the intended liquid, usually deaired tap water. Flow rates through the soil/geotextile system are monitored over time and plotted against the logarithm of time. The test is currently standardized as GRI Test Method GT1 (*4*) and is given in its entirety as Appendix C.

For this project, LTF tests were conducted on four different geotextiles: nonwoven heat bonded polypropylene, nonwoven needle-punched polypropylene, nonwoven needle-punched polyester, and woven monofilament polypropylene. All four geotextile types are commercially available and are used regularly in filtration applications. See Table 4 for the designation and description of the properties of the different geotextiles.

These four types of geotextiles were each used in association with four different soil types. The soils were manufactured blends ranging from 100 percent Ottawa sand to 100 percent loess-type cohesionless silt. The proportions and characteristics of the soils are given in Table 5.

The permeation liquid for one set of 20 columns was clear deaired water, while for another set of 12 columns it was turbid deaired water. The turbidity was created by mixing approximately 3 gm of cohesionless silt per liter of water. The experimental setup is shown in Figure 13. The clear water test columns used deaired water directly and bypassed the turbidity tank. The setup was configured for hydraulic gradients of 0.5, 1.0, and 1.5, and test data were taken for time periods of up to 5,000 hours. The results for both clear and turbid water permeation for the four different geotextiles as they enter their terminal behavior are given in Figures 14 to 17. Reference *5* gives more detail regarding this extensive set of data.

Summary for Clear Water Flow

With the exception of the 5 percent silt–95 percent Ottawa sand mixture, all soil-geotextile systems in which clear water

TABLE 4. Geotextiles used in long-term flow (LTF) tests

Geotextile Type	Designation
nonwoven needle punched polyester heavy weight	NW-NP-PET-H
nonwoven heat bonded polypropylene	NW-HB-PP
woven monofilament polypropylene	W-MF-PP
nonwoven needle punched polypropylene light weight	NW-NP-PP-L

(b) Physical and hydraulic properties

Geotextile Designation	Mass per Unit Area g/m^2 (oz/yd^2)	Thickness mm (mil)	Permittivity sec^{-1}	AOS O_{95} (mm) (U.S. std. sieve)	Mean O_{50} (mm)
NW-NP-PET-H	250 (7.4)	2.7 (105)	1.8	0.125 (#120)	0.122
NW-HB-PP	130 (3.8)	0.76 (30)	2.5	0.090 (#170)	0.088
W-MF-PP	190 (5.7)	0.36 (14)	0.64	0.212 (#70)	0.049
NW-NP-PP-L	160 (4.7)	1.7 (68)	2.9	0.125 (#120)	0.119

TABLE 5. Gradation properties of soils used upstream of the geotextile filters

Soil Type	D_{85} (mm)	D_{60} (mm)	D_{50} (mm)	D_{15} (mm)	D_{10}(mm)	CU
Ottawa sand (100%)	1.0	0.80	0.75	0.65	0.62	1.3
5% - 95% silty sand	1.0	0.69	0.62	0.45	0.40	1.7
25% - 75% sandy silt	1.0	0.54	0.46	0.04	0.02	24.5
Silt (100%)	0.05	0.04	0.03	0.02	0.01	3.2

where $CU = D_{60}/D_{10}$

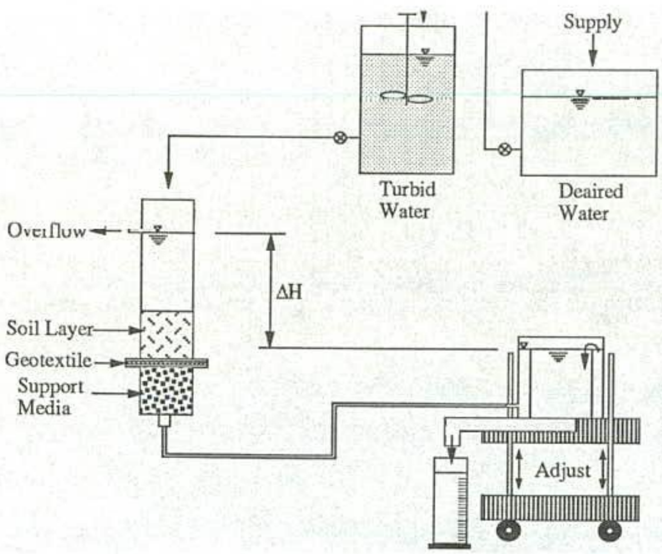
was used as the permeant resulted in stable filtration systems. Flow rates gradually decreased in direct proportion to the amount of silt in the mixed soils. For the case involving the 5 percent silt–95 percent Ottawa sand mixture, it is evident from the curves of flow versus time that except for the NW-HB-PP and NW-NP-PP-L geotextiles, the silt passed through each soil-geotextile system until an equilibrium flow rate was achieved. The soil that passed through each of the soil-geotextile systems was examined through the use of a particle size analyzer and the results substantiated this conclusion (*5*). Such soil loss prevents the buildup of a stable soil network upstream of the geotextile by this fine fraction. From the clear water flow data shown in Figures 15a and 17a, and the analysis on the soil retained on the geotextile, some of the finer particles were not able to pass through the geotextile. This resulted in a fluctuation of flow versus time, which at first glance appears as scatter, when in reality it was various stages of soil filter buildup that was the result of retaining particles smaller than 0.04 mm. Because routine tests involved controlled changes in gradient from 0.5 to 1.0 to 1.5, it is believed that the higher gradient permitted the passage of fines that incrementally made their way to the soil-geotextile interface. However, the flow regime eventually stabilized. Also noted in Figures 14a to 17a is that the 100 percent silt is essentially at the limit of detectability of the experimental system and that the 25 percent/75 percent sandy silt is only marginally higher in its flow rate. Thus the permeability of the silt was controlled in all cases with these two fine-grained soils. Whether, or not, these low flow rates are acceptable, or are to be considered cases of excessive clogging, is related to the site-specific design and required flow rate as described earlier in the design-by-function approach. It should be noted that if lower flow rates than that through silt soils are required, the LTF test can be readily configured in a falling head manner as is conventionally done in routine soil testing work.

Summary for Turbid Water Flow

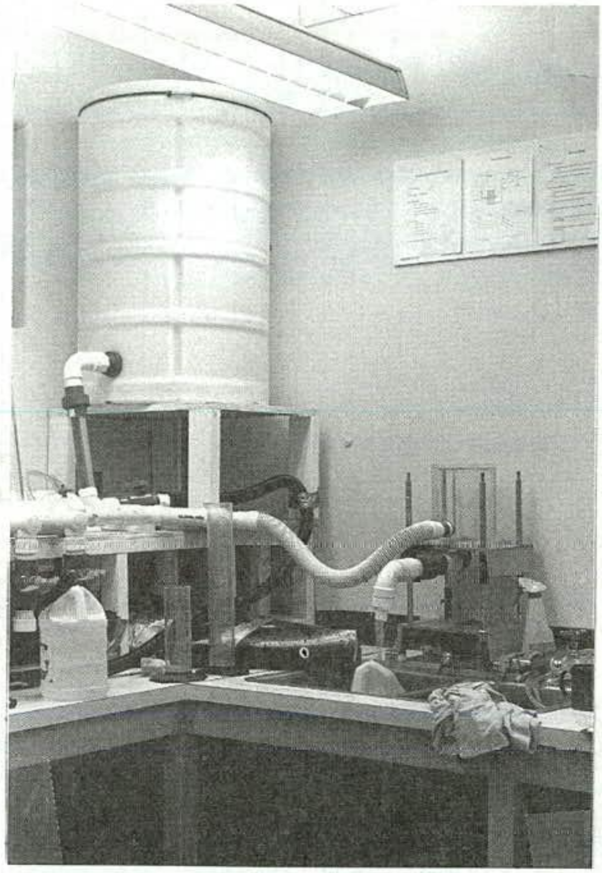
Results for the cases in which fine silt (at an amount of 3 g per liter of water) was added to clear deaired water in a continuously agitated mixing tank and used as a permeant are shown in the graphs of Figures 14b to 17b. Only the two coarser soils were evaluated due to the performance observed in the clear water tests for the two high silt content soils. Review of curves for the 100 percent and 5 percent/95 percent silty sand soils indicates the importance of permitting the passage of finer particles, which ultimately promotes long-term flow. For each of the geotextiles used, the transition time for the majority of silt passage occurs at approximately 1,000 hr. At this point, the fine particles that encounter the soil-geotextile interface begin to pass through the system in a steady state as indicated by the relatively constant slope at this point. From an analysis of the particle sizes that passed through the system, it was evident that the silt suspended in the turbid water was able to make its way through all geotextiles to varying degrees. For these tests, the larger AOS of the woven W-MF-PP geotextile shown in Figure 16b appears to have passed more of the finer particles than the various nonwoven geotextiles.

Fine Fraction Filtration Tests

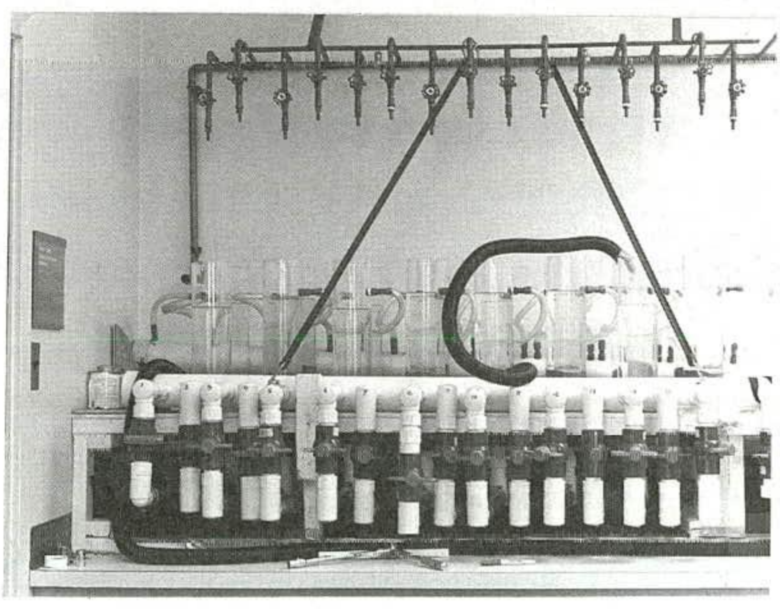
The concept of using the fine fraction of soil to challenge a geotextile filter originates from a 1982 paper by Hoover (*6*).



(a) Schematic of test setup

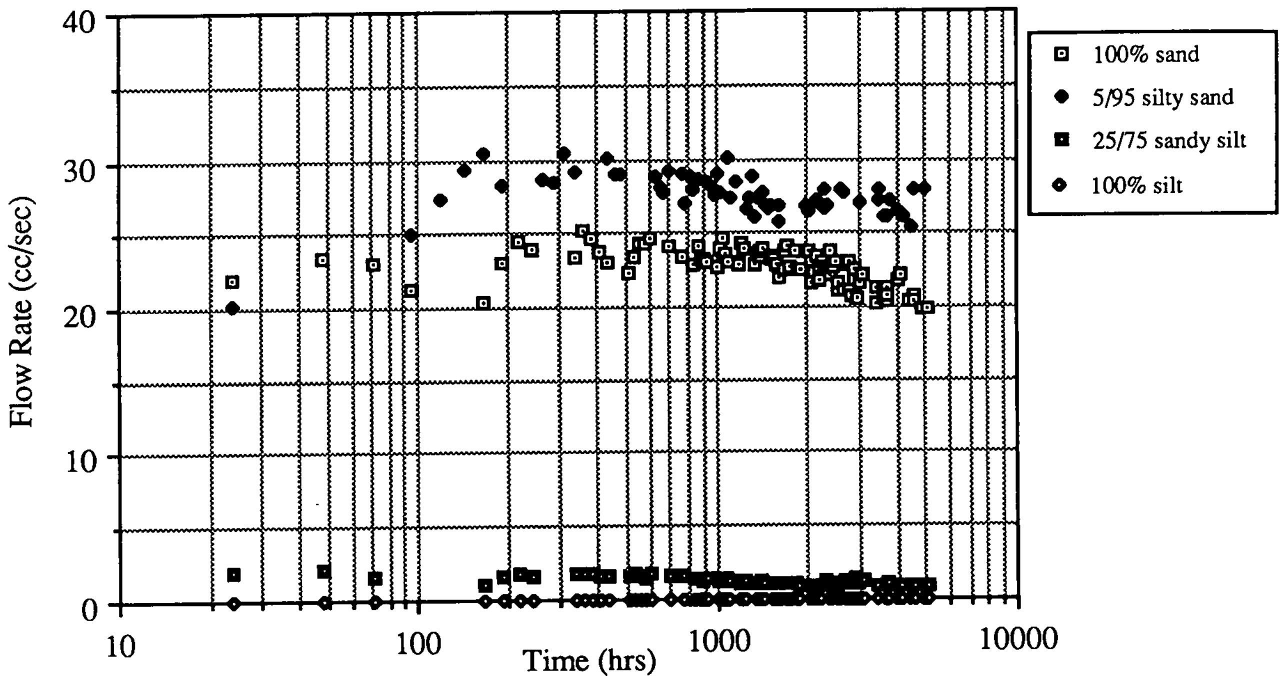


(b) Storage tank and variable head setup for measuring flow rates

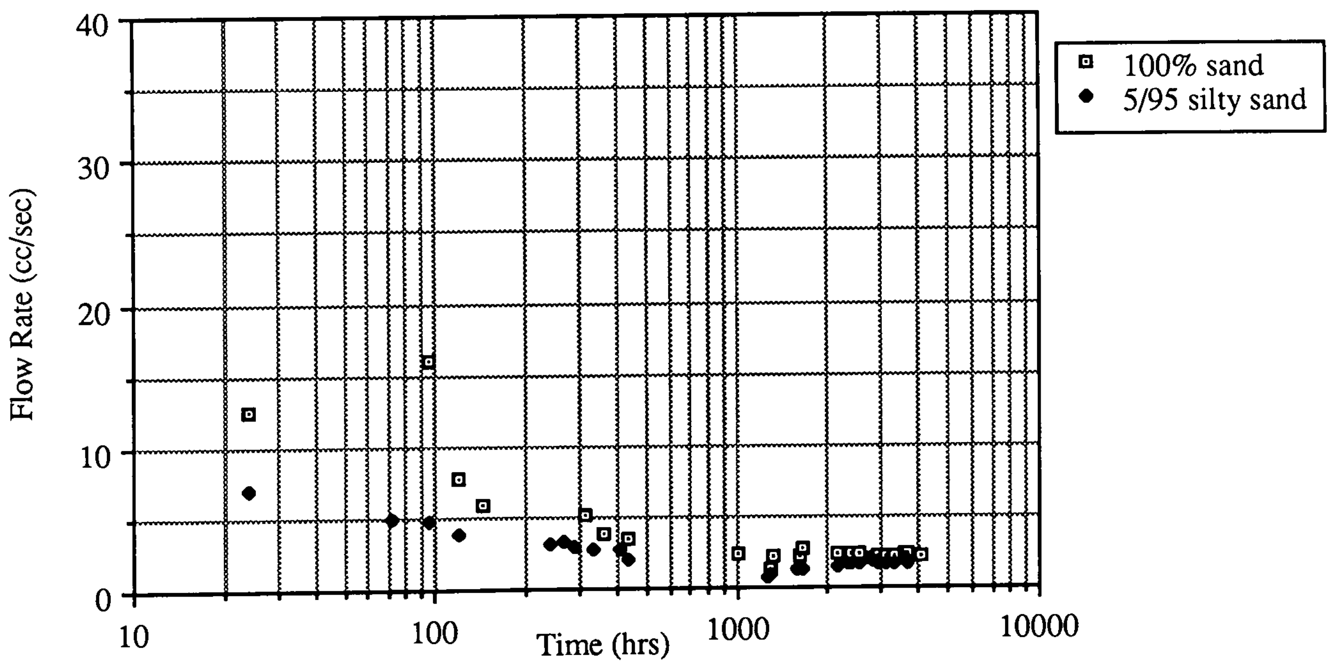


(c) Part of 32-column setup for LTF tests

Figure 13. Experimental setup for conducting long-term flow (LTF) tests.

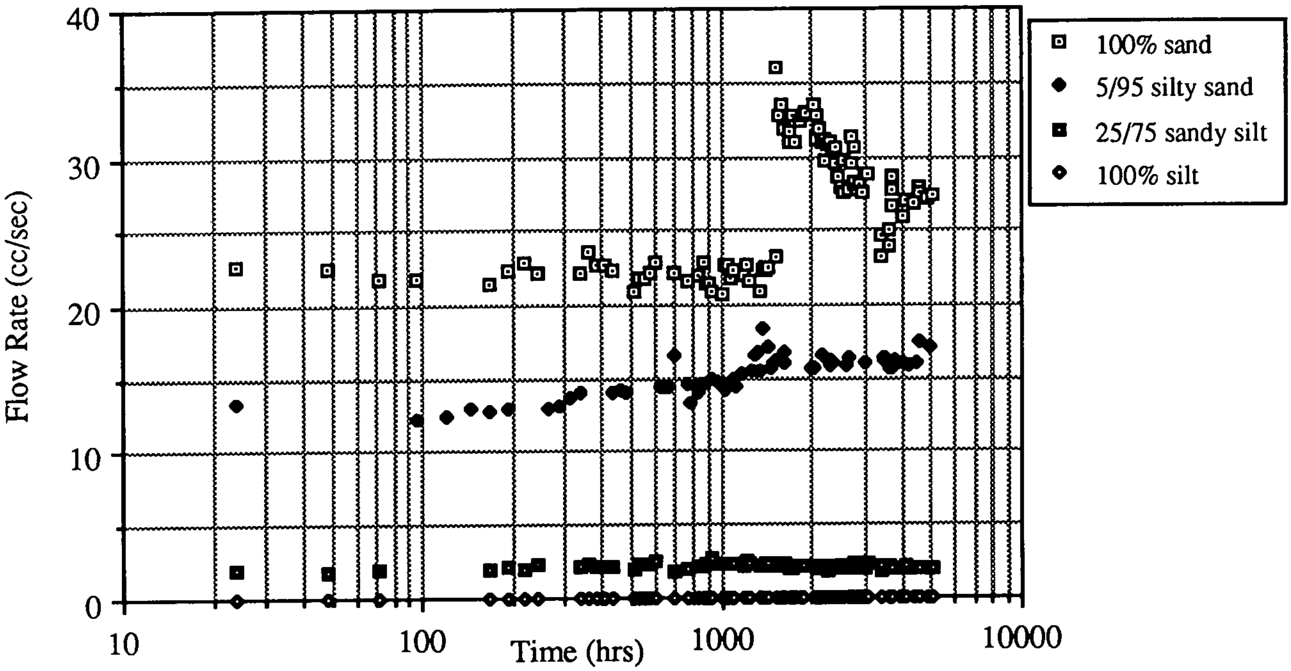


(a) Clear water flow test results

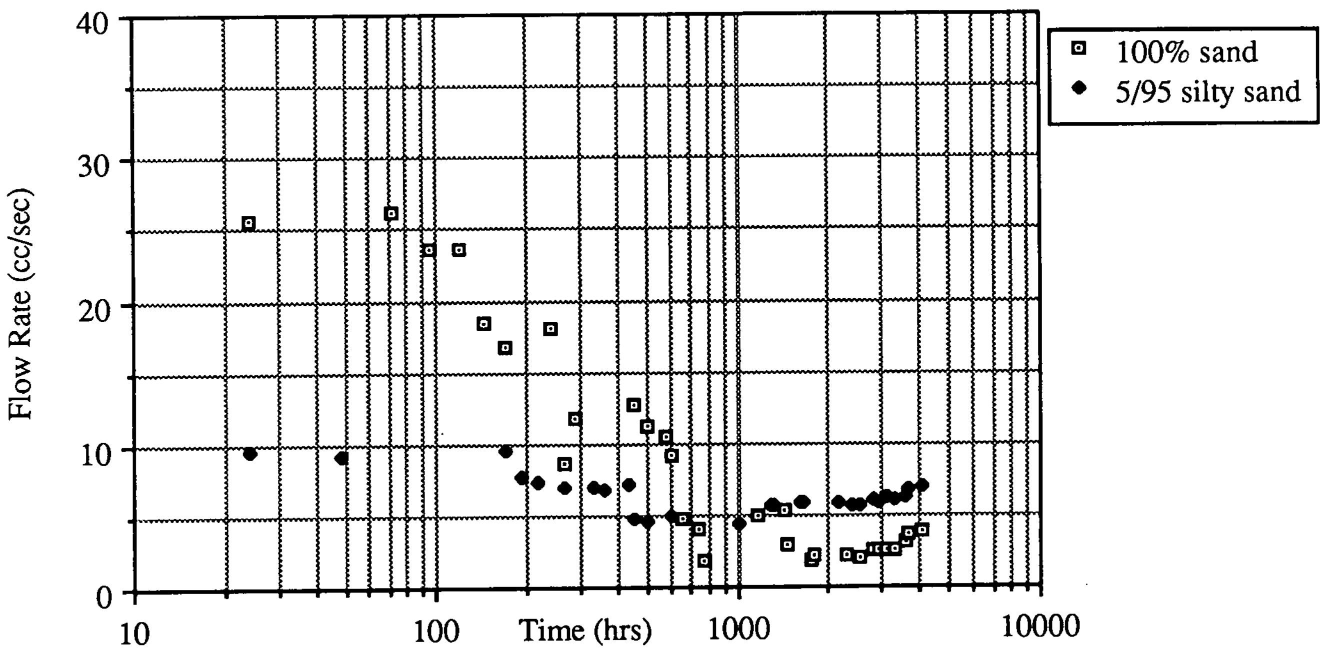


(b) Turbid water flow test results

Figure 14. Long-term flow (LTF) test results of NW-NP-PET-H geotextile.

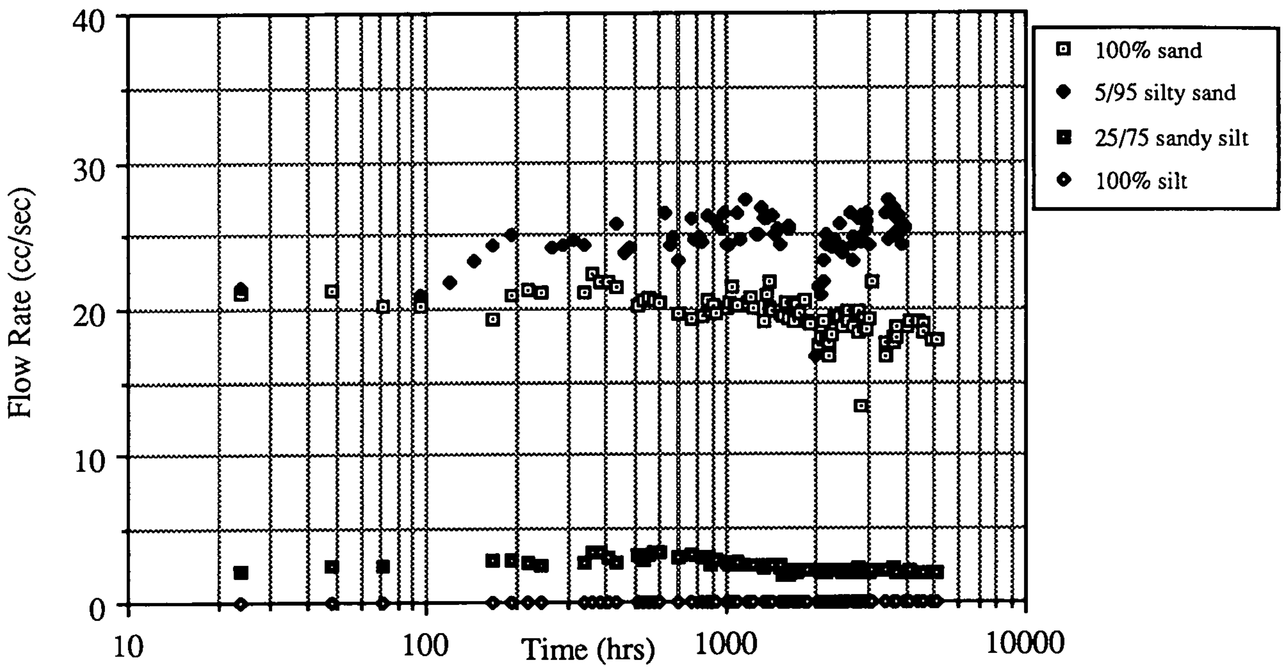


(a) Clear water flow test results

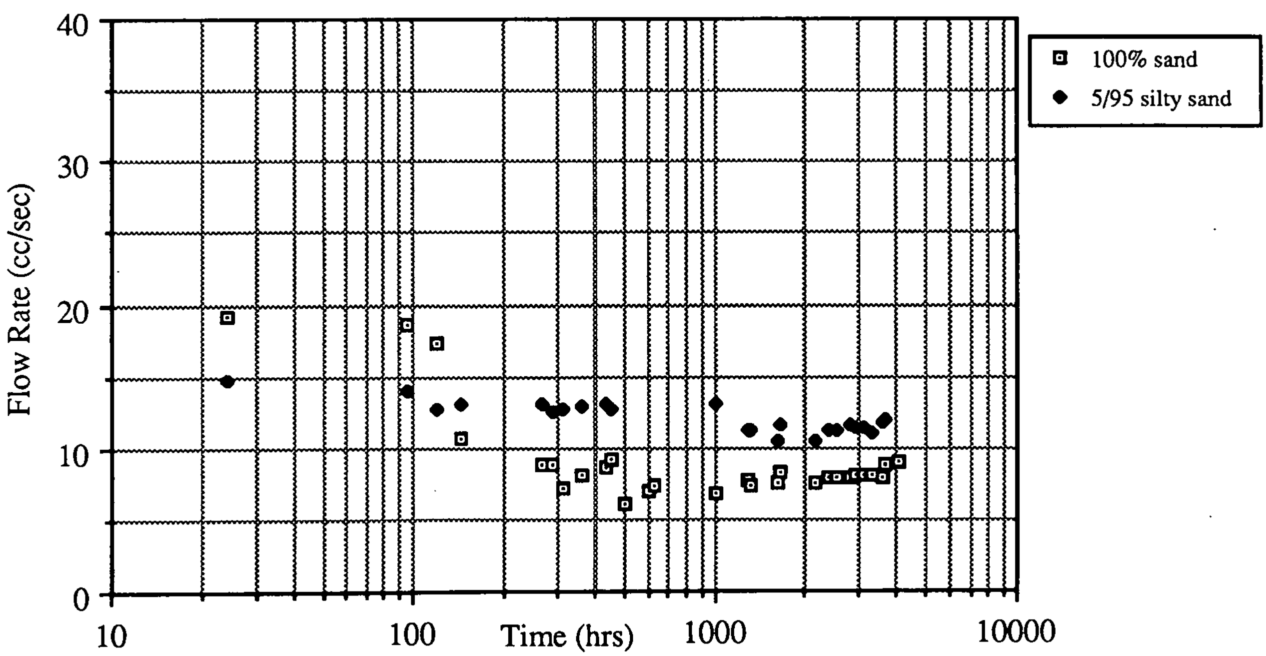


(b) Turbid water flow test results

Figure 15. Long-term flow (LTF) test results of NW-HB-PP geotextile.

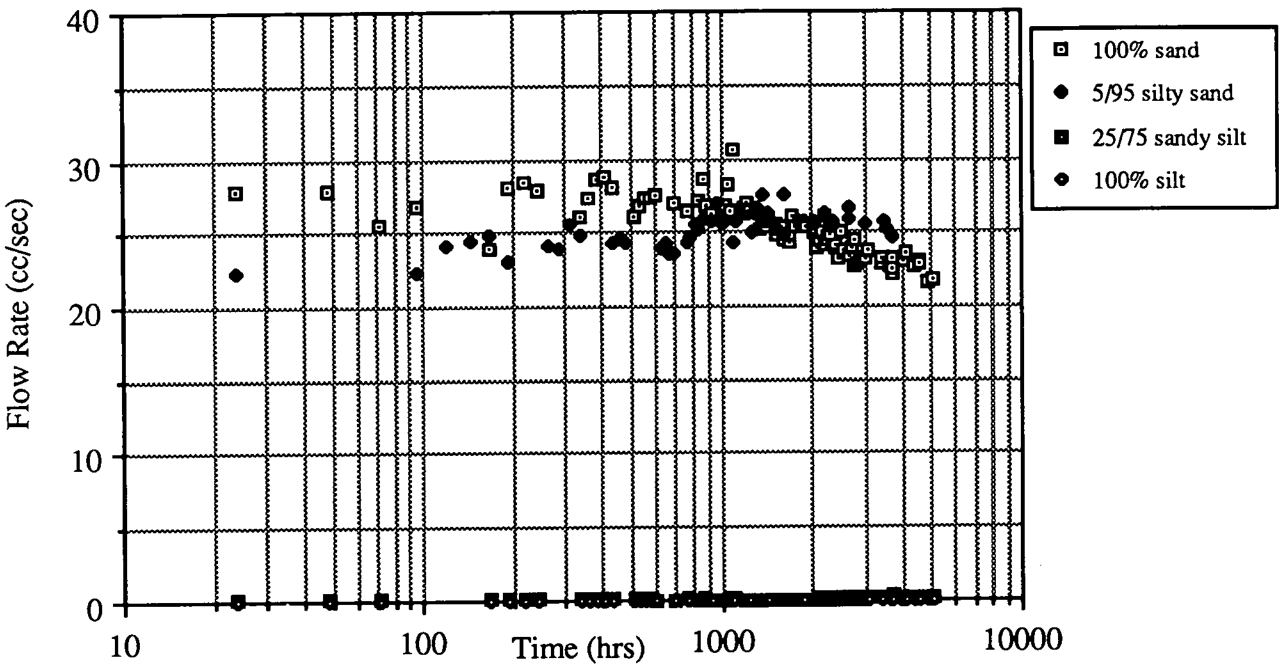


(a) Clear water flow test results

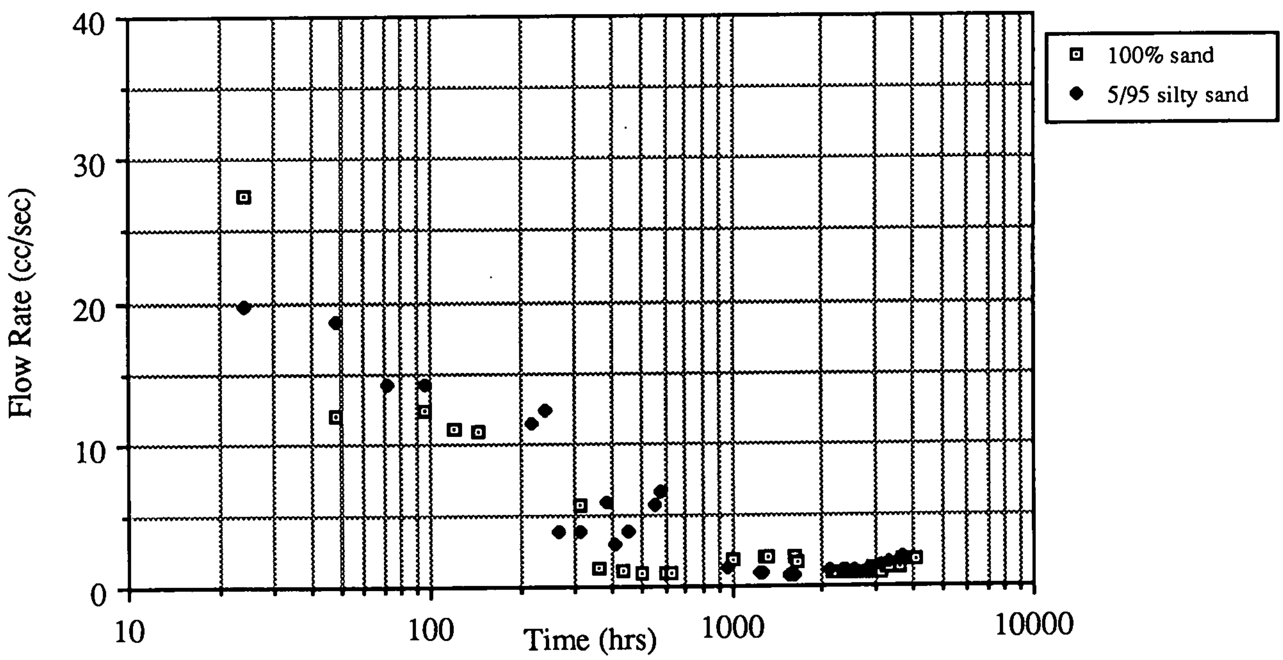


(b) Turbid water flow test results

Figure 16. Long-term flow (LTF) test results of W-MF-PP geotextile.



(a) Clear water flow test results



(b) Turbid water flow test results

Figure 17. Long-term flow (LTF) test results of NW-NP-PP-L geotextile.

His concern was with evaluating different fractions of the upstream soil under the least desirable installation conditions. As will be seen later, it was a very important beginning. This work was later extended by Legge (7), who developed a test procedure using the geotextile in a vertical configuration while accommodating horizontal flow. The soil under investigation was sieved into 85 percent, 50 percent and 15 percent passing fractions, designated as D_{85}, D_{50}, and D_{15} size ranges, respectively, and added to the flow column in a slurry form. From an analysis of the subsequent data, Legge formulated an interface flow capacity value that was indicative of either soil loss, equilibrium, or excessive clogging.

Our adaptation of the above concept and test procedure builds on both Hoover's and Legge's earlier work. During initial trials, a major difficulty arose in building up a uniform soil layer on the geotextile test specimen when positioned vertically. Coarse soils built up a triangular wedge from the bottom of the column upward, leaving the top of the geotextile completely open. Flow rate results depended greatly on the slurry solids content and on the distribution of particle sizes within each fraction. The results were somewhat improved when the flow device was modified to position the geotextile at a 45° angle. However, this orientation was also abandoned when even better reproducibility was achieved using the geotextile mounted horizontally with the flow moving vertically, hence flow trajectories are always perpendicular to the geotextile. Figure 18 gives a schematic diagram and photograph of the test setup, which we call the fine fraction filtration (F^3) test.

The next decision in developing the test had to do with the manner of using the soil under investigation. After numerous trials at using different particle size fractions, it was seen that little information was gained from evaluation of the coarse or medium soil fractions. Thus it was decided to place complete focus on the fine fraction. One of the following three criteria are currently used to select this fine fraction:

- If the geotextile filter is not specifically identified and a number of different geotextiles are being evaluated, the soil sizes passing the #100 and #200 sieves are used.
- If the geotextile filter is specifically identified, the soil fraction equal and finer than its apparent opening sieve (AOS) size is used.
- On the other hand, if the soil sample is extremely fine, such as a silt or dispersive clay, it may be necessary to use the soil mass in its entirety.

In the performance of the F^3 test, one has the choice of controlling the total head loss across the geotextile or of controlling the flow rate through the geotextile. For example, the usual method of performing a geotextile permittivity test (when no soil is involved) is by maintaining the total head loss constant. ASTM D-4491 uses a total head loss of 2.0 in. (50 mm) and monitors the flow rate to arrive at an in-isolation permittivity value for the geotextile test specimen under investigation. In the course of developing an F^3 test protocol, this same constant head procedure is used. As the geotextile becomes "tuned" with soil particles, or begins to become clogged, this procedure is not possible because of the long time required to accumulate a measurable quantity of flow passing through the system. Thus the total head loss is increased, and a constant flow rate procedure is used. This second procedure is continued until the conclusion of the test, which will be the establishment of either flow rate equilibrium or excessive clogging beyond the detection limits of the system. Obviously, if soil loss is indicated, one can continue the testing procedure using the original constant head procedure. The calculations are modified accordingly with the resulting value being permittivity, rather than a coefficient of permeability. This is necessitated because permittivity is independent of thickness (i.e., $\psi = k/t$; where "ψ" is permittivity, k is the permeability coefficient and t is the geotextile/soil column thickness), and the thickness cannot be accurately measured in the test column. Of course, with a suitable estimate of thickness, a system value of k can be obtained.

While somewhat subjective, the current test procedure uses 10 g per liter of dry soil in the particle size range described earlier. A new soil charge is added whenever the downstream flow tube is visually seen to be clear of soil particles passing through the geotextile from the previous soil charge and the head levels in the piezometers have reached equilibrium. The time increment between charges is very much dependent on the soil type and the geotextile type. The time typically varies from 1 to 20 min.

Regarding the limit of detectability of the test device as it appears in Figure 18 and is described above, it is felt that a permittivity of 0.005 sec^{-1} can be accurately obtained. Note that for a geotextile of 0.5 mm thickness, this is equivalent to a permeability coefficient of 2.5×10^{-5} cm/sec, which is in the permeability equivalency range of a silt-type soil. The test is currently written as GRI Test Method GT8 (8). Reproducibility of the F^3 test method has been established by conducting a number of tests on two different geotextiles using the same fine fraction of a well-graded soil as a control. It was seen that some scatter occurred but the general trend is reproducible and the terminal points are reasonably well behaved (9).

Using three different material types, Ottawa sand, fly ash and a local, well-graded, sandy silt with a trace of clay (classified as ML by the Unified Soil Classification System and known locally as the Le Bow soil), along with four different geotextile filters, a series of F^3 tests resulted in the anticipated behavior (9). For example, the Ottawa sand built up a layer on the different geotextiles resulting in equilibrium flow rates. The fly ash went completely through the geotextile because it was all finer than the AOS of the geotextiles and indicated excessive soil loss. The fine fraction of the LeBow soil gradually built up on, or within, the different geotextiles, and flow rates were gradually reduced down to the detectability limit of the system. Thus excessive clogging was indicated. At that point, the F^3 test results looked encouraging. The field-exhumed soils along with their associated geotextiles were subsequently evaluated. Figure 19a shows the F^3 test results for the soil of site #2 with a needle punched nonwoven geotextile taken from the field exhumed PGED. This was an "F" site wherein excessive soil passed through the geotextile and completely clogged the core as shown in Figure 10. The behavior of the experiment was quite clear in that the #200 sieve size soil and finer completely passed through the geotextile. The initial drop was due to some particles being trapped within the geotextile. Repeating the test with the less than #100 sieve size soil gave the result of clogging down to the detectability limit of the system. This substantiated the actual field findings in that the soil found within the core was indeed less than #100 sieve size soil and even 40 percent was less than

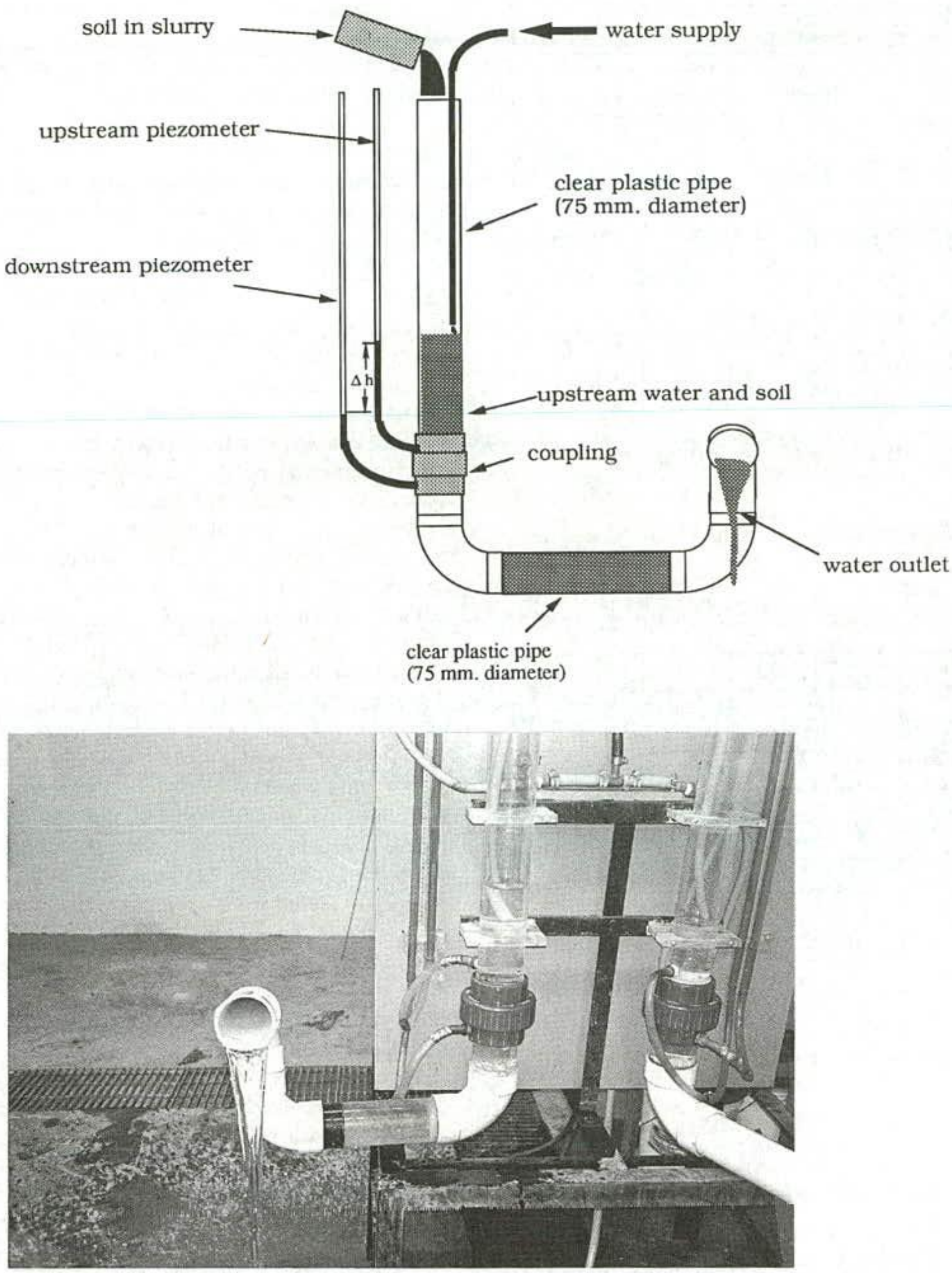


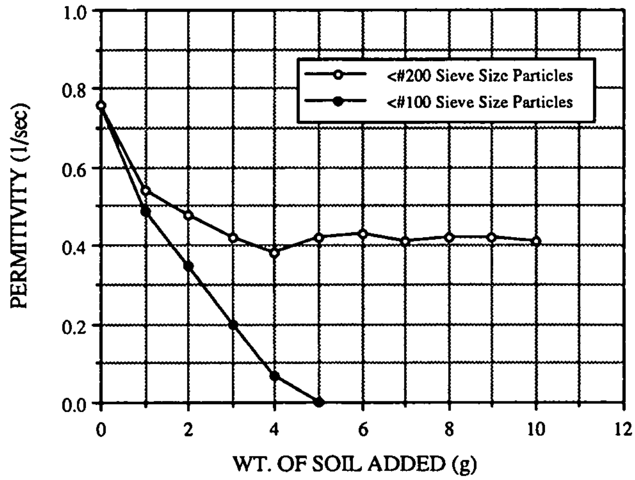
Figure 18. Schematic diagram and photograph of the fine fraction filtration (F^3) test setup.

the #200 sieve. Even further, every one of the eight failures of this type performed similarly.

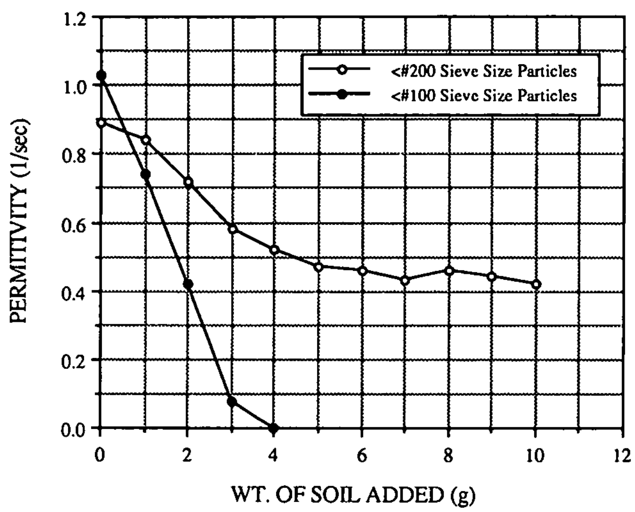
The field-exhumed sites that performed acceptably were then systematically evaluated. For example, site #35 is also a PGED of exactly the same type as site #2; however, the latter was an "A" site. The F^3 test was performed on this soil and its associated geotextile with the results shown in Figure 19b. The less than #200 sieve size soil went through the geotextile indicating soil loss (which did *not* occur in the field) and the less than #100 sieve soil indicated excessive clogging (which also did *not* occur in the field). Furthermore, the two sets of curves shown in Figure 19a and b look remarkably similar to one another, yet one was an "F" site and the other was an "A" site. The evaluation of 33 of the field-retrieved sites (many sites had either insufficient soil or damaged geotextiles, thus all 91 sites could not be evaluated) arrived at essentially the same results.

The conclusion of the F^3 test is that it can distinguish between soils that will pass through a geotextile versus those that will excessively clog. More importantly, however, is the associated conclusion that the F^3 test *cannot* distinguish between soil/geotextile combinations that will be acceptable in the field versus those that will be nonacceptable.

Our final recommendation regarding the F^3 test will be that it is of interest academically, but is not useful to DOT engineers



(a) F^3 test results from field site #2, an "F" site



(b) F^3 test results from field site #35, an "A" site

Figure 19. Fine fraction filtration (F^3) test results using a nonwoven needle-punched geotextile and various fractions of soils taken from two field sites.

at least for its proposed purpose. That purpose was as an accelerated index-type test to see if a particular soil was compatible from a flow rate perspective with a particular geotextile filter.

Dynamic-Fine Fraction Filtration Tests

Dynamic filtration of a geotextile filter is required under certain conditions. These might be any one of the following:

- Highway edge drains adjacent to faulted pavements having saturated subgrades.
- Dynamic loads caused by railroads under saturated ballast conditions.
- Impact loads caused by landing aircraft when striking pavements under saturated conditions.
- Erosion control filters for coastal waterways due to ship wash and wave turbulence.
- Various types of groundwater surges caused by abrupt ground movements or mechanical equipment placed on, or within, the ground surface.

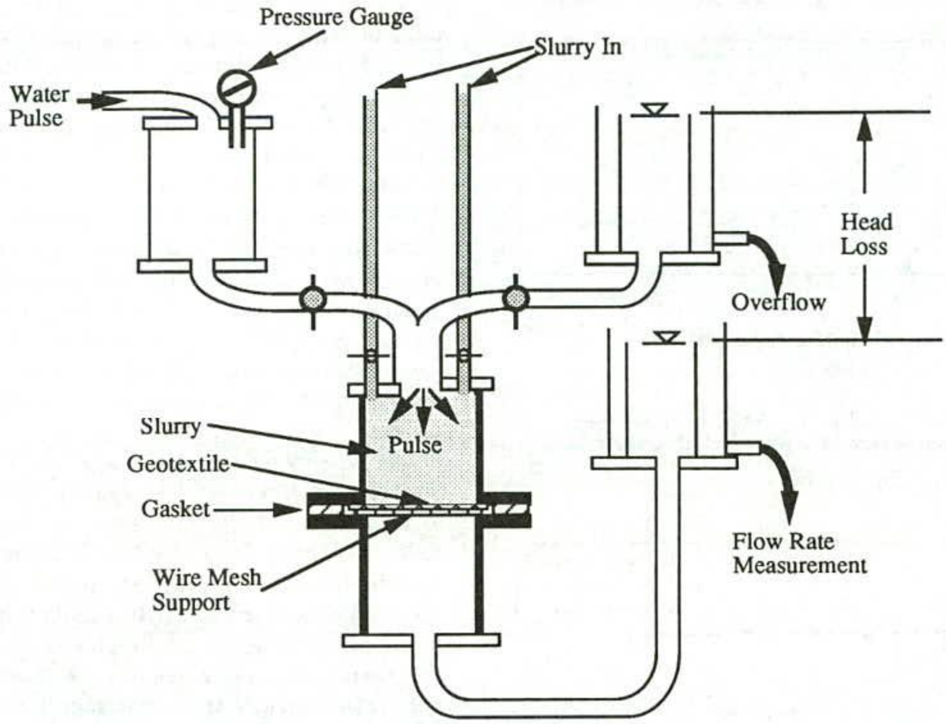
Note that the above situations are not the commonly encountered situations of static or even quasi-static hydrologic conditions for geotextile filters, but they are certainly plausible under the conditions stated above.

The dynamic-fine fraction filtration (D-F^3) test to be used is essentially a fine fraction filtration test, which is now conducted after incremental periods of dynamic pulsing of the hydraulic system (see reference *10*). Between each pulsing cycle, selected increments of soil are added upstream of the geotextile in exactly the same manner as the F^3 test presented previously. The configuration is shown in Figure 20. The geotextile test specimen is 6.0 in. (150 mm) in diameter and is mounted in the permeameter as shown. The soil is added in slurry form from two entry ports. For these tests, each increment of slurry was formed by adding 5 g of dry silt soil to 1.0 L of tap water. The valves are closed after slurry placement and dynamic pulses at a controlled pressure are then applied. For the test results to follow, the rate was 2 to 3 pulses per sec. Pulses were applied until the water in the upper cylinder became visually clear. This condition was generally reached after flow volumes through the system were about 15 L of water. Between each cycle of adding soil and pulsing as described above, flow rate measurements under a constant total head of 2.0 in. (50 mm) were conducted. Note that this is the ASTM D-4491 laboratory protocol for hydraulic permittivity testing with the geotextile used in-isolation. A series of test results plotting the measured flow rate versus cumulative soil added to the system was conducted and will be described.

Figure 21a illustrates the behavior of a 4.5 oz/yd^2 (150 g/m^2) nonwoven needle-punched geotextile to three different materials. The fly ash, with particle sizes less than the opening size of the geotextile, moved completely through it. The well-graded sand with particle sizes all larger than the opening size of the geotextile, initially decreased the flow rate and eventually came to equilibrium. The fine fraction of Le Bow soil (a well-graded local soil consisting of sand, silt, and clay and designated SW-ML) gradually decreased the flow rate until the limit of the system was reached. This lower limit is estimated to be about 5.0 cc/sec flow rate or 0.010 sec^{-1} permittivity. Clearly, the soil type is an important consideration in dynamic soil filtration involving geotextiles.

Figure 21b test results are from the same soil as described previously, i.e., the Le Bow soil, but now used in different size fractions. Note that the #80 sieve size (approximately the AOS of the geotextile) showed a clogging tendency, the #100 sieve size took considerably longer to reach the lower limit, and the #200 soil size passed through the geotextile in its entirety. Thus not only is soil type important, soil size is also an important consideration in dynamic soil filtration involving geotextiles.

Attempts at using the D-F^3 test were now tried on several of the field retrieved soils and their associated geotextiles. Exactly the same response as shown in Figures 19a and b resulted.



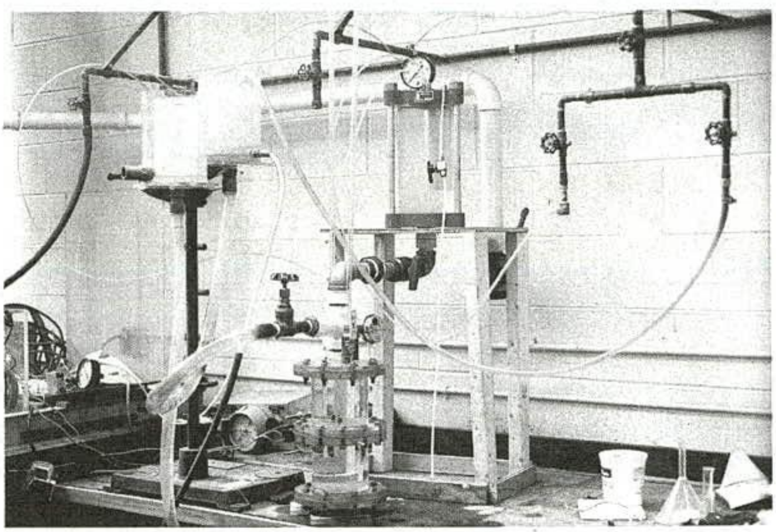


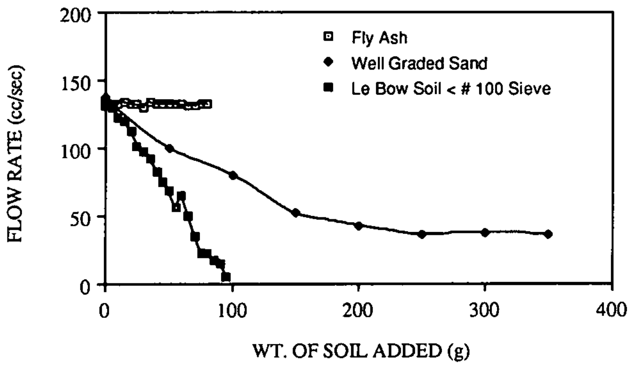
Figure 20. Schematic diagram and photograph of dynamic-fine fraction filtration (D-F^3) test setup.

That is, the D-F^3 test cannot distinguish between acceptable and nonacceptable field sites. The only meaningful difference between the F^3 test and D-F^3 test is that the dynamic pulses cause the soil loss or clogging behavior to occur more rapidly.

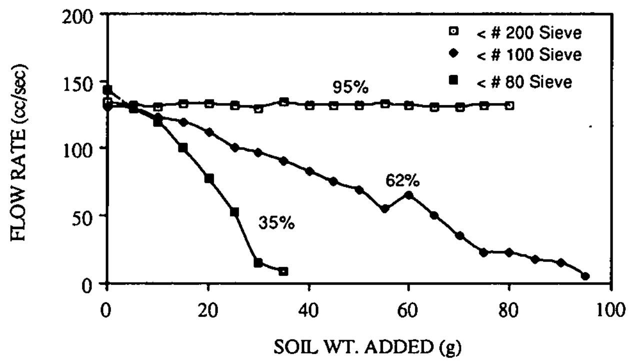
Obviously, the researcher's final recommendation is the same as for the F^3 test, i.e., that the D-F^3 test is *not* suited for a rapid index-type test to indicate when field problems in highway drainage situations may occur or not.

Summary of Laboratory Studies

As shown in the project flow chart of Figure 2, three laboratory tests were investigated or developed. The LTF tests were instructive in that the various soil/geotextile/permeant combinations gave insight into the types of soils and permeants which are of concern to geotextile filters. Undoubtedly for clear water flow, the soils containing 25 percent, or higher, of fine-grained



(a) D-F^3 test results using a light nonwoven needle punched geotextile with three different soils



(b) D-F^3 test results using a light nonwoven needle punched geotextile with the LeBow soil in different functions

Figure 21. Typical test results using the D-F^3 test setup.

silt lead to very low equilibrium flow rates. They indeed can be cases of excessive clogging depending on the site-specific design requirements. The granular soils containing 5 percent silt were generally cases of loss of this silt component that may lead to soil retention problems depending on the nature of the downstream drain capacity. The 100 percent sand soils resulted in stable flow rates in all cases.

Conversely, turbid water flow is seen to be a different situation than clear water flow. In all cases, flow rates are much lower than for clear water. For the soils containing 25 percent fine grained silt, or higher, the lower limit of detection of the test method was reached almost instantly. For soils containing 5 percent silt or less, equilibrium was reached albeit at a relatively low value. The design requirement will dictate if such values are excessively low, or not.

The two newly developed tests, F^3 and D-F^3, were meant to give a rapid indication of the suitability of a candidate geotextile to a particular soil type. By using only the fine fraction of the soil it was hoped that an accelerated test method would act as an indicator of the LTF test and indeed of the field situation itself. While both tests could distinguish between excessive soil loss or excessive clogging, neither test could separate out acceptable from nonacceptable field sites. With ground truth from the field exhuming sites and verification from the laboratory test results, it is concluded that neither the F^3 nor the D-F^3 test was successful in its mission. Hence, these particular two tests are not recommended for further investigation.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATION

GEOTEXTILE FILTER DESIGN

It is well established that the design of a geotextile filter has three distinct requirements: adequate permeability, proper soil retention, and long-term (i.e., nonexcessive clogging) performance over the service lifetime of the system. As will be seen in the following tables, there have been many attempts at providing design criteria for these three requirements. In a certain manner, these various design criteria can be investigated since "ground truth" has been established by virtue of the 19 field-exhumed sites and a complete documentation of the various geotextile and soil characteristics is available (see Appendices A and B).

Permeability Criteria

A summary of the most widely used permeability criteria is available from Christopher and Fischer (*11*) and is reproduced in Table 6. In the table it should be noted that the Christopher and Holtz criterion (*18*) is currently used by the Federal Highway Administration (FHWA) in their widely offered training courses to state DOT engineers and designers. The various qualitative comments in the remarks column of Table 6 have been used in the past in a somewhat loosely defined manner. The description in Table 7 is from Carroll (*16*) who provided an early guideline.

Using each of the design criteria in Table 6 against each of the 91 field-exhumed sites given in Appendix A, with the specific geotextile and soil characteristics given in Appendix B, a comparison has been made; see Table 8. The check (√) signifies agreement with field observations, while the (x) signifies disagreement with the field observations. By disagreement is meant that the criterion suggested "no problem" whereas one was actually observed in the field, i.e., a "D" or "F" site. Additionally, the (x) signifies disagreement if the criterion suggested a "problem" whereas none was observed in the field, i.e., an "A," "B," or "C" site. Also note that when the geotextile performance is a "D" or "F," the mechanism of soil retention or clogging must be identified. The subscript "r" is for retention problems, while the subscript "c" is for clogging problems. For a check (√) to be given to a criterion it must have predicted the proper type of failure mechanism, i.e., clogging in this comparison table. The N/A sites are for those conditions where the geotextile mechanically failed and are therefore not applicable for such a permeability comparison.

The results of the comparison given in Table 8 appear to indicate that all permeability criteria are reasonable for the acceptable A, B, and C field sites. For the few nonacceptable D

TABLE 6. Existing geotextile permeability criteria, after Christopher and Fischer (*11*)

Source	Criterion	Remarks
Giroud (12)	$k_g \geq 0.1\ k_s$	No factor of safety is applied
FHwA - NC/NS, e.g., Calhoun (13); Schober and Teindl (14); Wates (15); Carroll (16); Haliburton, et al. (17); Christopher and Holtz (18) and numerous others	$k_g \geq k_s$	For use with noncritical applications, nonsevere soil conditions and steady state flow
FHwA - C/S, e.g. Carroll (16); Christopher and Holtz (18)	$k_g \geq 10\ k_s$	For use with critical applications and severe soil or dynamic hydraulic conditions
French Committee on Geotextiles and Geomembranes (19)	Based on permittivity ψ with $\psi \geq 10^{3-5}\ k_s$	For following conditions: • Critical use $10^5\ k_s$ • Less critical use $10^4\ k_s$ • Clean sand use $10^3\ k_s$

where NC/NS = noncritical/nonsevere, see Table 7 for description
C/S = critical/severe, see Table 7 for description
and k_g = permeability of the geotextile
k_s = permeability of the upstream soil
ψ = permittivity of the geotextile (= k_g/t)
t = thickness of the geotextile

TABLE 7. Qualitative guidelines for evaluating the critical nature or severity of geotextile filter applications, after Carroll (*16*)

(a) Critical vs. Noncritical Conditions		
Item	Critical	Noncritical
1. Risk of loss of life and/or significant structural damage due to drain failure:	High	None
2. Evidence of drain clogging before potential catastrophic failure:	None	Yes
3. Repair costs vs. installation costs of drains:	Much greater	Equal or less
(b) Severe vs. Nonsevere Conditions		
Item	Severe	Nonsevere
1. Soil to be drained	Gap-graded, pipable and dispersible	Well-graded uniform
2. Hydraulic gradient	High	Low
3. Flow conditions	Dynamic cyclic or pulsating	Steady State

and F field sites, no method was particularly superior over the others. The methods of Giroud and FHWA (noncritical/nonsevere) appear to be slightly better than the others insofar as agreement is concerned. An additional analysis of the data will be given in the summary of this section. Here Table 8 will be further subdivided on the basis of soil type.

Soil Retention Criteria

A summary of the most widely used soil retention criteria is available from Christopher and Fischer (*11*) and is reproduced in Table 9. In the table it should be noted that the Christopher and Holtz reference is currently used by the FHWA (in a slightly abridged manner) and will be identified as such hereafter. Furthermore, it will be identified as FHWA (S) for steady state flow and FHWA (D) for dynamic flow.

As readily seen from the above table there have been a large number of attempts at providing a generalized criterion for soil retention. Using the 91 field-exhumed sites, with their respective geotextile and soil characteristics, an assessment of the various criteria has been made (see Table 10). In obtaining the data for this assessment, the various soil fraction(s) required by the different criteria—e.g., D_{15}, D_{50}, D_{85}, and D_{90}—were obtained by direct sieving of the upstream soil. When an insufficient amount of soil was available, an estimation was made using the D_{10} and CU values that were always directly measured. For the geotextile opening size values, direct measurement was more difficult to perform since the geotextile was field retrieved after years of service. For sites where the geotextile could be ultrasonically cleaned, the opening size was determined by direct experimentation with dry sieving of glass beads, i.e., ASTM D4751. This was not possible at some sites because of damage to the geotextile in removing it from the core or its contained soil. However, knowing the type, style, and manufacturer of the specific product that was used allowed for identification of the O_{95} value in all cases. For those criteria requiring other geotextile opening size characteristics, e.g., O_{15}, O_{50}, or O_{95}, the typical porometry of that type of geotextile was used based on the known O_{95} value. See reference 2 for the porometry of different styles of manufactured geotextiles.

From the summary given at the bottom of Table 10, it can be seen that with the exception of Giroud's method (which only deals with granular soils; hence the large number of nonapplicable sites), a number of soil retention prediction criteria are quite acceptable. The criteria of Task Force #25, FHWA (steady flow), Ogink, the French Committee, and Carroll have similarly good results. To be noted is that the eight PGED sites that showed soil retention failures have been listed in the table as N/A. This was done since no criterion was seen to accurately predict the field situation of lack of contact with the upstream soil. Such situations must be handled by proper installation techniques. In the summary of this section to follow, the criteria will be further subdivided into soil types for additional commentary.

Long-Term Performance Criteria

The long-term geotextile filter performance criteria (sometimes called criteria against excessive clogging) that are available have been assembled by Christopher and Fischer (*11*); see Table 11. In the table, it should be noted that Christopher and Holtz (*18*) is the criteria currently used by the Federal Highway Administration and will be identified as such. Note that the table is not as structured as the previous criteria for adequate permeability and soil retention but can be nevertheless used for this purpose. As noted in Table 11 for critical/severe applications, laboratory experiments are required. These experiments will be (one or more) of the following: 1) gradient ratio tests, 2) long-term flow tests, or 3) hydraulic conductivity ratio tests. See Koerner et al. (*28*) for a description of these tests and for additional references.

Regarding the noncritical/nonsevere applications, the results of all 91 field-exhumed sites have been used—with their respective geotextile and soil characteristics—to make a comparison (see Table 12). The assumption in making the comparison is,

TABLE 8. Assessment of permeability criteria from Table 6 against findings of field exhuming study

Site No.	Soil Type	GT Perf.	Giroud	FHwA-NC/NS	FHwA-C/S	French Committee 1	French Committee 2	French Committee 3
1	SC	F_r	√	√	√	-	√	x
2	SM	F_r	√	√	√	-	√	x
3	SW-SM	A	√	√	√	-	x	x
4	SW	A	√	√	x	x	x	-
5	SP	A	√	√	√	x	x	-
6	SW	A	x	x	x	x	x	-
7	SC	D_r	√	√	√	-	√	x
8	SM	C	√	√	√	-	x	x
9	CL-ML	F_c	x	x	x	-	x	√
10	ML	D_r	√	√	√	-	√	x
11	SM	F_r	√	√	√	-	x	x
12	SM	A	√	√	√	-	x	x
13	ML	C	√	√	√	-	√	x
14	SM	A	√	√	√	-	x	x
15	SW-SC	B	√	√	x	-	x	x
16	SW-SM	B	√	√	x	-	x	x
17	SC	B	√	√	√	-	√	x
18	CL	A	√	√	√	-	√	√
19	SC	A	√	√	√	-	√	x
20	CL	C	√	√	√	-	√	√
21	SP	A	√	x	x	x	x	-
22	SM-SC	A	√	√	√	-	√	x
23	CL-ML	A	√	√	√	-	√	√
24	ML	C	√	√	√	-	√	x
25	SM-SC	F_c	x	x	x	-	√	√
26	SW-SM	A	√	√	√	-	x	x
27	SM	A	√	√	√	-	√	x
28	SW-SM	A	√	√	√	-	x	x
29	SC	F_r	√	√	√	-	√	x
30	SM-SC	A	√	√	√	-	x	x
31	SW	B	√	√	x	x	x	-
32	SM	C	√	√	√	-	x	x
33	ML	A	√	√	√	-	√	x
34	CL	A	√	√	√	-	√	√
35	CL	A	√	√	√	-	√	√
36	CL	A	√	√	√	-	√	√
37	CL	A	√	√	√	-	√	√
38	CL	A	√	√	√	-	√	√
39	CL	A	√	√	√	-	√	√
40	CL	A	√	√	√	-	√	√
41	CL	B	√	√	√	-	√	√
42	CL	B	√	√	√	-	√	√
43	SM	C	√	√	√	-	√	x
44	SM	A	√	√	√	-	√	x

Site No.	Soil Type	GT Perf.	Giroud	FHwA-NC/NS	FHwA-C/S	French Committee 1	French Committee 2	French Committee 3
45	SC	B	√	√	√	-	√	x
46	SC	C	√	√	√	-	x	x
47	SW	C	√	√	x	x	x	-
48	SP	C	√	√	√	x	x	-
49	SW	F_{uv}	N/A	N/A	N/A	N/A	N/A	N/A
50	CL-ML	A	√	√	√	-	√	x
51	SM	A	√	√	√	-	x	x
52	CL	A	√	√	√	-	√	√
53	CL	A	√	√	√	-	√	√
54	SC	A	√	√	√	-	√	√
55	SC	D_r	√	√	√	-	√	√
56	SP	A	√	√	x	x	x	-
57	SM	A	√	√	√	-	x	x
58	SC	F_c	x	x	x	-	x	x
59	SM	A	√	√	√	-	x	x
60	SW-SM	D_r	N/A	N/A	N/A	N/A	N/A	N/A
61	SC	A	√	√	√	-	x	x
62	SW-SM	A	√	√	√	-	x	x
63	SM	A	√	√	√	-	x	x
64	SC	B	√	√	√	-	√	x
65	SC	A	√	√	√	-	√	x
66	SM-SC	A	√	√	√	-	x	x
69	SC	A	√	√	√	-	√	x
73	SC	B	√	√	√	-	√	x
75	SC	D_r	√	√	√	-	x	x
76	SC	D_r	√	√	√	-	x	x
77	SC	A	√	√	√	-	x	x
78	SC	F	N/A	N/A	N/A	N/A	N/A	N/A
79	SC	A	√	√	√	-	√	x
80	SC	B	√	√	√	-	√	x
81	SC	B	√	√	√	-	√	x
82	SM	B	√	√	√	x	x	-
83	SM	B	√	√	x	x	x	-
84	SM	A	√	√	√	x	x	-
85	SM	A	√	√	√	-	√	x
86	GW	A	√	√	x	x	-	-
87	SC	A	√	√	√	-	√	√
88	SW-SM	A	√	√	√	-	x	x
89	SC	A	√	√	√	-	√	√
90	SM	A	√	√	√	-	x	x
91	SC	B	√	√	√	-	√	√
TOTAL		√	78	77	69	0	44	21
TOTAL		x	4	5	13	12	37	49
No GT or N/A		-	9	9	9	79	10	21

TABLE 9. Existing geotextile retention criteria (modified after Christopher and Fischer (*11*))

Source	Criterion	Remarks
AASHTO Task Force #25 (20)	50% ≤ 0.074 mm, O_{95} < 0.59 mm 50% > 0.074 mm, O_{95} < 0.30 mm	no limitations on geotextile type nor soil type
Calhoun (13)	$O_{95}/D_{85} \leq 1$	Wovens, soils with ≤ 50% passing No. 200 sieve
	$O_{95} \leq 0{\cdot}2$ mm	Wovens, cohesive soils
Zitscher (21)	$O_{50}/D_{50} \leq 1.7$–2.7	Wovens, soils with CU ≤ 2, D_{50} = 0.1 to 0.2 mm
	$O_{50}/D_{50} \leq 2.5$ to 3.7	Nonwovens, cohesive soil
Ogink (22)	$O_{90}D_{90} \leq 1$	Wovens
	$O_{90}/D_{90} \leq 1.8$	Nonwovens
Sweetland (23)	$O_{15}D_{85} \leq 1$	Nonwovens, soils with CU = 1.5
	$O_{15}D_{15} \leq 1$	Nonwovens, soils with CU = 4.0
Rankilor (24)	$O_{50}/D_{85} \leq 1$	Nonwovens, soils with $0.2 \leq D_{85} \leq 0.25$ mm
	$O_{15}/D_{15} \leq 1$	Nonwovens, soils with D_{85} > 0.25 mm
Schober & Teindl (14) (with no factor of safety)	$O_{90}/D_{50} \leq 2.5$–4.5	Woven and thin nonwovens, dependent on CU
	$O_{90}/D_{50} \leq 4.5$–7.5	Thick nonwovens, dependent on CU, silt and sand soils
Giroud (12)	$O_{95}/D_{50} \leq$ (9–18)/CU	Dependent on soil CU and density Assumes fines in soil migrate for large CU values
Carroll (16)	$O_{95}/D_{85} \leq 2$–3	Wovens and nonwovens
FHwA via Christopher and Holtz (18)	$O_{95}/D_{85} \leq 1$–2	Dependent on soil type and CU
	$O_{95}/D_{15} \leq 1$ or $O_{50}/D_{85} \leq 0.5$	Dynamic , pulsating and cyclic flow, if soil can move beneath geotextile
French Committee on Geotextiles and Geomembranes (19)	$O_f/D_{85} \leq 0.38$–1.25	Dependent on soil type, compaction, hydraulic and application conditions
Fischer et al. (25)	$O_{50}/D_{85} \leq 0.8$ $O_{50}/D_{15} \leq 1.8$–7.0 $O_{50}/D_{50} \leq 0.8$–2.0	Based on geotextile pore size distribution, dependent on CU of soil
Luettich et al. (26)	design charts	Based on geotextile void size, soil size and type, hydraulic conditions and other factors

where O_x = geotextile opening size corresponding to "X" particle size based on dry glass bead sieving
O_f = filtration opening size based on hydrodynamic sieving
D_y = soil particle size corresponding to "Y" percent passing
CU = coefficient of uniformity = D_{60}/D_{10}

TABLE 10. Assessment of soil retention criteria from Table 9 against findings of field exhuming study

					FHwA								Luettich, et al.			
Site No.	Soil Type	GT Perf.	Task Force #25	Giroud	Steady Flow	Dynamic Flow	Zitscher	Qgink	Sweetland	Rankilor	Schober/ Teindl	Fischer, et al.	Steady Flow	Dynamic Flow	French Committee	Carroll
1	SC	F_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	SM	F_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3	SW-SM	A	√	x	√	x	N/A	√	√	√	√	√	√	√	√	√
4	SW	A	√	√	√	√	N/A	√	√	√	√	√	√	√	√	√
5	SP	A	√	√	√	√	N/A	√	√	√	√	√	√	√	√	√
6	SW	A	√	√	√	√	N/A	√	√	√	√	√	√	√	√	√
7	SC	D_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8	SM	C	√	N/A	√	x	√	√	x	x	√	√	x	x	√	√
9	CL-ML	F_c	√	N/A	√	x	x	√	x	√	x	x	x	x	√	√
10	ML	D_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11	SM	F_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	SM	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
13	ML	C	√	N/A	√	√	√	√	x	x	x	x	√	√	√	√
14	SM	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
15	SW-SC	B	√	√	√	x	N/A	√	√	√	√	√	√	√	√	√
16	SW-SM	B	√	√	√	x	N/A	√	√	√	√	√	√	√	√	√
17	SC	B	√	N/A	√	x	√	√	x	x	√	x	√	x	√	√
18	CL	A	√	N/A	√	√	√	√	x	x	√	√	√	x	√	√
19	SC	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
20	CL	C	√	N/A	√	x	√	√	x	√	x	x	√	x	√	√
21	SP	A	√	√	√	√	N/A	√	√	√	√	√	√	x	√	√
22	SM-SC	A	√	N/A	√	x	√	√	x	x	√	√	√	x	√	√
23	CL-ML	A	√	N/A	√	√	√	√	x	x	√	x	√	x	√	√
24	ML	C	√	N/A	√	√	√	√	x	x	√	x	√	x	√	√
25	SM-SC	F_c	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
26	SW-SM	A	√	√	√	x	N/A	√	√	√	√	√	√	√	√	√
27	SM	A	√	N/A	√	x	√	√	x	x	√	√	x	√	√	√
28	SW-SM	A	√	√	√	x	N/A	√	√	√	√	√	√	√	√	√
29	SC	F_r	x	N/A	x	√	x	x	√	√	x	x	x	x	x	x
30	SM-SC	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
31	SW	B	√	√	√	√	N/A	√	√	√	√	√	√	√	√	√
32	SM	C	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
33	ML	A	√	N/A	√	√	√	√	x	x	√	x	x	x	√	√

TABLE 10. Assessment of soil retention criteria from Table 9 against findings of field exhuming study (*Continued*)

Site No.	Soil Type	GT Perf.	Task Force #25	Giroud	FHwA		Zitscher	Qgink	Sweetland	Rankilor	Schober/ Teindl	Fischer, et al.	Luettich, et al.		French Committee	Carroll
					Steady Flow	Dynamic Flow							Steady Flow	Dynamic Flow		
34	CL	A	√	N/A	√	√	x	√	x	x	x	x	√	x	√	√
35	CL	A	√	N/A	√	√	x	√	x	x	x	x	√	x	√	√
36	CL	A	√	N/A	√	√	x	√	x	x	x	x	√	x	√	√
37	CL	A	√	N/A	√	√	√	√	x	x	√	x	√	x	√	√
38	CL	A	√	N/A	√	√	√	√	x	x	√	x	√	x	√	√
39	CL	A	√	N/A	√	x	x	√	x	x	x	x	x	x	√	√
40	CL	A	√	N/A	√	√	√	√	x	x	√	x	√	x	√	√
41	CL	B	√	N/A	√	√	√	√	x	x	x	x	√	x	√	√
42	CL	B	√	N/A	√	√	x	√	x	x	x	x	√	x	√	√
43	SM	C	√	N/A	√	x	√	√	x	x	√	x	√	x	√	√
44	SM	A	√	N/A	√	x	√	√	x	x	x	x	√	√	√	√
45	SC	B	√	N/A	√	x	√	√	x	x	√	x	√	√	√	√
46	SC	C	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
47	SW	C	√	√	√	√	N/A	√	√	√	√	√	√	√	√	√
48	SP	C	√	√	√	x	N/A	√	√	√	√	√	√	√	√	√
49	SW	F_{uv}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
50	CL-ML	A	√	N/A	√	√	√	√	x	x	√	x	√	x	√	√
51	SM	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
52	CL	A	√	N/A	√	√	√	√	x	x	√	x	√	x	√	√
53	CL	A	x	N/A	√	√	x	√	x	x	x	x	√	x	√	√
54	SC	A	√	N/A	√	x	x	√	x	x	x	x	x	x	√	√
55	SC	D_r	x	N/A	x	x	x	x	√	√	x	x	√	√	x	x
56	SP	A	√	√	√	x	N/A	√	√	√	√	√	√	√	√	√
57	SM	A	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
58	SC	F_c	√	N/A	√	x	√	√	x	x	√	x	√	√	√	√
59	SM	A	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
60	SW-SM	D_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
61	SC	A	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
62	SW-SM	A	√	N/A	√	x	N/A	√	√	√	√	√	√	√	√	√
63	SM	A	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
64	SC	B	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
65	SC	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
66	SM-SC	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
69	SC	A	√	N/A	√	x	√	√	x	x	√	x	√	√	√	√
73	SC	B	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
75	SC	D_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
76	SC	D_r	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

TABLE 10. Assessment of soil retention criteria from Table 9 against findings of field exhuming study (*Continued*)

Site No.	Soil Type	GT Perf.	Task Force #25	Giroud	FHwA Steady Flow	FHwA Dynamic Flow	Zitscher	Qgink	Sweetland	Rankilor	Schober/ Teindl	Fischer, et al.	Luettich, et al. Steady Flow	Luettich, et al. Dynamic Flow	French Committee	Carroll
77	SC	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
78	SC	F	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
79	SC	A	√	N/A	√	x	√	√	x	x	√	√	x	√	√	√
80	SC	B	√	N/A	√	x	√	√	x	x	√	x	√	√	√	√
81	SC	B	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
82	SM	B	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
83	SM	B	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
84	SM	A	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
85	SM	A	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
86	GW	A	√	√	√	√	N/A	√	√	√	√	√	√	√	√	√
87	SC	A	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
88	SW-SM	A	√	√	√	x	N/A	√	√	√	√	√	√	√	√	√
89	SC	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
90	SM	A	√	N/A	√	x	√	√	x	x	√	√	√	√	√	√
91	SC	B	√	N/A	√	x	√	√	√	√	√	√	√	√	√	√
Total	√		72	14	73	24	49	73	28	30	61	47	67	50	73	73
Total	x		4	1	2	51	10	2	47	45	14	28	8	25	2	2
No GT or N/A			15	76	16	16	32	16	16	16	16	16	16	16	16	16

TABLE 11. Existing long-term performance against excessive clogging criteria after Christopher and Fischer (*11*)

A. Critical/severe applications

Perform soil/geotextile filtration tests.
(e.g., Calhoun (13); Haliburton et al. (17); Haliburton and Wood (27); Giroud (12); Carroll (16); Christopher and Holtz (18); Koerner (2))

B. Noncritical/nonsevere applications

1. Perform soil/geotextile filtration tests.
2. Minimum pore sizes alternatives for soils containing fines, especially in a noncontinuous matrix:

   (a) $O_{95} \geq 3D_{15}$ for $CU \geq 3$
   (FHwA via Christopher and Holtz (18))
   (b) $O_{15}/D_{15} \geq 0.8$ to 1.2
   $O_{50}/D_{50} \geq 0.2$ to 1.0
   (Fischer, et al., (25))
   (c) $O_f \geq 4D_{15}$
   (French Committee on Geotextiles (19))

3. For $CU \leq 3$, geotextile with maximum opening size from retention criteria should be specified.

4. Apparent open area qualifiers

   Woven geotextiles: Percent Open Area: ≥ 4% to 6%
   (Calhoun (13); Koerner (2))
   Nonwoven geotextiles: Porosity ≥ 30% to 40%
   (Christopher and Holtz (18); Koerner (2))

of course, that the 91 sites are indeed "noncritical/nonsevere" applications. As noted in Table 7 this is somewhat subjective but the assumption is nevertheless made.

Observing the totals of nonacceptable predictions listed in Table 12, it is seen that all criteria have a large number of x's, but that the FHWA method via Christopher and Holtz (*18*) is somewhat preferable to the others. Within this large disagreement group, however, all but two were predicted as failures but were actually acceptable (A, B, or C) field sites. Thus they were conservative in their prediction and statistically could be referred to as false-positive predictions, i.e., the error is on the safe side. There were three nonacceptable clogging sites (all with fine-grained soils); however, none of the criteria predicted the poor performance. Of course, these by their very outcome are of a severe nature and perhaps none of the criteria should be expected to predict proper performance under such adverse conditions. Clearly, laboratory tests are warranted for such conditions. In the summary of this section, further subdivision of these data is made based on soil type, and the situation is more clearly identified.

SUMMARY ASSESSMENT OF DESIGN CRITERIA

At the outset, it should be recognized that the quest for a simplistic criterion based on one (or a few) soil characteristics versus one (or a few) geotextile characteristics to predict adequate permeability, proper soil retention, and long-term (i.e., nonexcessive clogging) performance is not an easy task. The collection of design criteria presented in Tables 6, 9, and 11 for the three mechanisms shows that there have been many attempts.

Using the 91 field sites as ground truth, the performance of the various geotextiles was compared to the various design models. Note that 6 of the field sites had no geotextiles involved, 1 was ultraviolet light degraded and 2 were mechanically punctured, so that there were 82 possible comparisons to be made to each criterion in each of the three design categories. Furthermore, those PGED sites with lack of intimate contact were not included in the soil retention analysis because these failures were considered to be installation related. The results were given in Tables 8, 10, and 12 for permeability, soil retention, and excessive clogging, respectively. The summary reached from these three tables is given in Table 13a, b, and c for permeability, soil retention, and excessive clogging, respectively. However, the results have been further subdivided according to the particle size characteristics of the upstream soil. The subdivisions in Table 13 are made in accordance with recommendations of the Unified Soil Classification System.

- granular soils with ≤ 12 percent passing the #200 sieve
- mixed soils with 13 to 49 percent passing the #200 sieve
- fine-grained soils with ≥ 50 percent passing the #200 sieve

Regarding *permeability* criteria, it is noted in Table 13a that the Giroud and FHWA-NC/NS criteria are preferable in correlating their predicted behavior with the field sites. Furthermore, it is seen that their predictions cover the entire spectrum of possible soils. In light of the FHWA method being widely used by most state departments of transportation, it is felt that the current status should continue. The most recent FHWA criterion via Christopher and Holtz (*29*) is as follows:

TABLE 12. Assessment of long-term clogging criteria from Table 10 against findings of field exhuming study

Site No.	Soil Type	GT Perf.	FHwA	Fischer, et al.	French Committee	Site No.	Soil Type	GT Perf.	FHwA	Fischer, et al.	French Committee
1	SC	F_r	√	x	√	48	SP	C	-	-	-
2	SM	F_r	√	√	√	49	SW	F_{uv}	N/A	N/A	N/A
3	SW-SM	A	-	-	-	50	CL-ML	A	√	√	√
4	SW	A	-	-	-	51	SM	A	√	√	x
5	SP	A	-	-	-	52	CL	A	√	√	√
6	SW	A	-	-	-	53	CL	A	√	√	√
7	SC	D_r	√	√	√	54	SC	A	√	√	√
8	SM	C	√	√	x	55	SC	D_r	√	√	√
9	CL-ML	F_c	x	x	x	56	SP	A	-	-	-
10	ML	D_r	√	√	√	57	SM	A	x	x	x
11	SM	F_r	√	√	x	58	SC	F_c	x	x	x
12	SM	A	√	√	√	59	SM	A	x	x	x
13	ML	C	√	√	√	60	SW-SM	D_r	N/A	N/A	N/A
14	SM	A	√	√	√	61	SC	A	√	x	x
15	SW-SC	B	-	-	-	62	SW-SM	A	-	-	-
16	SW-SM	B	-	-	-	63	SM	A	x	x	x
17	SC	B	√	√	√	64	SC	B	√	√	√
18	CL	A	√	√	√	65	SC	A	√	x	x
19	SC	A	√	√	x	66	SM-SC	A	√	x	x
20	CL	C	√	√	√	69	SC	A	√	√	√
21	SP	A	-	-	-	73	SC	B	√	√	√
22	SM-SC	A	√	√	√	75	SC	D_r	√	x	√
23	CL-ML	A	√	√	√	76	SC	D_r	x	x	x
24	ML	C	√	√	√	77	SC	A	√	√	√
25	SM-SC	F_c	x	x	x	78	SC	F	N/A	N/A	N/A
26	SW-SM	A	-	-	-	79	SC	A	√	√	x
27	SM	A	√	√	√	80	SC	B	√	x	√
28	SW-SM	A	-	-	-	81	SC	B	√	√	√
29	SC	F_r	√	√	√	82	SM	B	x	√	x
30	SM-SC	A	√	√	x	83	SM	B	x	x	x
31	SW	B	-	-	-	84	SM	A	x	x	x
32	SM	C	x	√	x	85	SM	A	x	x	x
33	ML	A	√	√	√	86	GW	A	-	-	-
34	CL	A	√	√	√	87	SC	A	x	x	x
35	CL	A	√	√	√	88	SW-SM	A	-	-	-
36	CL	A	√	√	√	89	SC	A	√	√	√
37	CL	A	√	√	√	90	SM	A	√	√	√
38	CL	A	√	√	√	91	SC	B	x	x	x

Table 12. Continued

Site No.	Soil Type	GT Perf.	FHwA	Fischer	French Committee
39	CL	A	√	√	√
40	CL	A	√	√	√
41	CL	B	√	√	√
42	CL	B	√	√	√
43	SM	C	√	√	√
44	SM	A	√	√	√
45	SC	B	√	√	√
46	SC	C	√	x	√
47	SW	C	-	-	-

Site No.	Soil Type	GT Perf.	FHwA	Fischer	French Committee
Total	√	-	52	47	43
Total	x	-	14	19	23
No GT or N/A		-	25	25	25

A. Critical/Severe Applications
k (geotextile) $\geq 10\ k$ (soil)
B. Less Critical/Less Severe (with clean medium to coarse sands and gravels)
k (geotextile) $\geq k$ (soil)

The permeability should be based on the actual geotextile open area available for flow. For example, if 50 percent of the geotextile area is to be covered by flat concrete blocks, the effective flow area is reduced by 50 percent.

Regarding *soil retention* criteria, it is noted in Table 13b that a number of criteria are acceptable based on correlations of their predicted behavior with the field sites. For example, Task Force #25, FHWA (S), Ogink, the French Committee and Carroll all give good results. It is recommended, however, to follow the criterion used by the FHWA via Christopher and Holtz. Their latest revision as shown below is from reference *29*.

Soil Type	Steady State Flow	Dynamic, Pulsating, and Cyclic Flow
< 50% Passing #200 sieve	$O_{95} \leq BD_{85}$ where $B = 1$ for $2 \geq CU \geq 8$ $B = 0.5$ for $2 < CU \leq 4$ $B = 8/CU$ for $4 < CU < 8$	$O_{95} \leq 0.5\ D_{85}$
≥ 50% Passing #200 sieve	$O_{95} \leq D_{85}$ (for wovens) $O_{95} \leq 1.8\ D_{85}$ (for nonwovens) and for both $O_{95} \leq 0.3$ mm (> No. 50 sieve)	$O_{95} \leq 0.5\ D_{85}$

Regarding *excessive clogging* criteria, it is noted in Table 13c that none of the criteria are applicable nor needed for granular soils. The reason being that granular soils are not troublesome soils with respect to excessive long-term clogging and the permeability and soil retention criteria should be adequate to properly design geotextile filters. This was indeed seen to be the case. Regarding mixed soils with 13 to 49 percent passing the #200 sieve, no available criterion appeared to be outstanding. However, as noted in the footnote, all but two of the disagreements were with sites predicted as failures but were actually acceptable (A, B, or C) field sites. For those few situations remaining it is necessary to require laboratory testing when in critical/severe situations. The long-term flow test described previously is recommended. For fine soils with greater than 50 percent passing the #200 sieve, the FHWA criterion via Christopher and Holtz (*18*) is the best and its agreement is excellent. Here again, the latest revisions of the FHWA criteria are recommended for use; see Christopher and Holtz (*29*). They are as follows:

A. Critical/Severe Applications[1]

Select geotextiles meeting permeability, retention and NC/NS clogging conditions and perform soil/geotextile filtration tests before specification, prequalifying the geotextile, or after selection before bid closing. Alternative: use approved list specification for filtration applications. Suggested performance test method: Gradient Ratio ≤ 3

B. Less Critical/Nonsevere Applications

1. Perform soil/geotextile filtration tests.
2. Alternative: $O_{95} > 3D_{15}$ for $CU > 3$
3. For $CU \leq 3$, geotextile with maximum opening size possible (lowest AOS No.) from retention criteria should be specified.
4. Apparent Opening Area Qualifiers[2]
   Percent Open Area: ≥ 4% (for wovens)
   Porosity[2] ≥ 30% (for nonwovens)

It should be noted that the above recommendations for critical/severe applications call for the gradient ratio test (ASTM D5101) with the resulting gradient ratio value being 3.0, or less. For reasons described in this report, the long-term flow (LTF) test is favored. The LTF test procedure is given as Appendix C.

Finally, it should be mentioned that geotextile survivability against damage from installation stresses is absolutely essential for a properly functioning geotextile filter. As was seen in Site No. 60 and Site No. 78 where the geotextile was torn and punctured, respectively, a failed geotextile completely defeats the potential functioning of the geotextile filter. However, these were the only two geotextile field failures that were physically torn, punctured, or burst. In general, it is felt that the current recommendations are adequate in this regard. The currently used FHWA geotextile survivability guidelines are reproduced in Table 14.

[1] Filtration tests are performance tests and cannot be performed by the manufacturer as they depend on specific soil and design conditions. Tests are to be performed by specifying agency or representative. Note that experience is required to obtain reproducible results in the gradient ratio test.

[2] Porosity requirement based on graded granular filter porosity.

TABLE 13. Summary of analysis of geotextile filter design models based upon comparison to results of field exhumed studies

(a) Permeability criteria from Table 7

Source	Reference	Granular Soil ≤ 12% pass #200		Mixed Soil 13-49% pass #200		Fine Soil ≥50% pass #200	
		Agree	Disagree	Agree	Disagree	Agree	Disagree
Giroud	12	15	1	44	2	19	1
FHwA - NC/NS	18	14	2	44	2	19	1
FHwA-C/S	18	7	9	43	3	19	1
French 1	19	0	9	0	3	n/a	n/a
French 2	19	0	15	25	21	19	1
French 3	19	0	7	6	37	15	5

NC/NS = noncritical, nonsevere conditions
C/S = critical, severe conditions

(b) Soil retention criteria from Table 10

Source	Reference	Granular Soil ≤ 12% pass #200		Mixed Soil 13-49% pass #200		Fine Soil ≥50% pass #200	
		Agree	Disagree	Agree	Disagree	Agree	Disagree
TF #25	20	16	0	38	2	18	1
Giroud	12	14	1	n/a	n/a	n/a	n/a
FHwA (S)	18	16	0	38	2	19	0
FHwA (D)	18	7	9	1	39	16	3
Zitscher	21	n/a	n/a	37	3	12	7
Ogink	22	16	0	38	2	19	0
Sweetland	23	16	0	12	28	0	19
Rankilor	24	16	0	12	28	2	17
Schober	14	16	0	36	4	9	10
Fisher	25	16	0	30	10	1	8
Luettich (S)	26	16	0	35	5	16	3
Luettich (D)	26	15	1	34	6	1	18
French	19	16	0	38	2	19	0
Carroll	16	16	0	38	2	19	0

S = steady flow conditions
D = dynamic flow conditions
n/a = not applicable

(c) Excessive clogging criteria from Table 12

Source	Reference	Granular Soil ≤ 12% pass #200		Mixed Soil 13-49% pass #200		Fine Soil ≥50% pass #200	
		Agree	Disagree	Agree	Disagree	Agree	Disagree
FHwA	18	n/a	n/a	33	13*	19	1
Fisher	12	n/a	n/a	28	18*	19	1
French	19	n/a	n/a	24	22*	19	1

*all but 2 disagreements were predicted as failures but were actually A, B or C sites in the field.
n/a = not applicable

TABLE 14. AASHTO-ABC-ARBTA joint committee minimum geotextile properties recommended for drainage (filtration) geotextiles[1,2]

Property	Drainage[3] Class A[4]	Drainage[3] Class B[5]	Test Method
Grab Strength (lb)	180	80	ASTM D4632
Elongation (%)	n/a	n/a	ASTM D4632
Seam Strength[6] (lb)	160	70	ASTM D4632
Puncture Strength (lb)	80	25	ASTM D4833
Burst Strength (lb./sq. in)	290	130	ASTM D3787
Trapezoidal Tear (lb)	50	5	ASTM D4533

1. Acceptance of geotextile material shall be based on ASTM D4759.
2. Contracting agency may require a letter from the supplier certifying that its geotextile meets specification requirements.
3. Minimum; Use value in weaker principal direction. All numerical values represent minimum average roll value (i.e., test results from any sampled roll in a lot shall be or exceed the minimum values in the Table). Stated values are for noncritical, nonsevere applications. Lot samples according to ASTM D4354.
4. Class A drainage applications for geotextiles are where installation stresses are more severe than Class B applications, i.e., very coarse sharp angular aggregate is used, a heavy degree of compaction (>95% AASHTO T99) is specified or depth of trench is greater than 10 ft.
5. Class B drainage applications are those where geotextile is used with smooth graded surfaces having no sharp angular projections, no sharp angular aggregate is used; compaction requirements are light, (<95% AASHTO T99), and trenches are less than 10 ft in depth.
6. Values apply to both field and manufactured seams.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

FIELD CONCLUSIONS

As noted from the field exhumed findings reported in Chapter 2 and completely documented in Appendix D, the status of design, construction, and performance of the various types of highway edge drains is quite good with the exception of prefabricated edge drains (PGEDs). For the other types of edge drains examined, the incidence of nonacceptable performance, i.e., "D" and "F" sites, is very low. Figure 22a presents a bar chart of the different drainage systems where it is seen that 18 out of 34 "D"and "F" sites were associated with PGEDs. Furthermore, 10 nonacceptable conditions were associated with the geotextile in PGEDs—8 were soil retention problems and 2 were excessive clogging problems. This poor performance of geotextiles on PGEDs can be further seen in the bar chart of Figure 22b. Here the 10 nonacceptably performing geotextiles ("Ds" and "Fs") are again seen, but now contrasted to very acceptable performance on other types of drainage systems that were exhumed in the course of the study. When viewing the photographs of Figures 10, 11, and 12, the reason for the nonacceptable situation becomes clear. Without intimate contact of the geotextile to the upstream soil or stone base beneath the pavement, empty spaces beneath the pavement readily exist; see Figure 23a. In these voids, turbid water—probably under dynamic conditions—interfaces the geotextile directly and passes through it into the drainage core. Depending on the gradient of the highway (hence the slope of the PGED), it is only a matter of time until the core becomes filled with settling fines and becomes excessively clogged.

Of course, one option is to avoid the use of PGEDs in favor of some other type of highway drainage system like GWUDs, PPUDs, or GSPPs. At issue with such a strategy is cost. Installed costs (via a random selection of bid prices in 10 states) shows PGEDs to be approximately $1.00 to $2.00 per linear foot less expensive than any other highway drainage system. Such a unit cost difference represents a very large cost savings to a state DOT in favor of its use of PGEDs.

Recommended to alleviate the problem of soil loss through the geotextile filters of PGED is to move the system to the shoulder side of the trench as indicated in Figure 23b. The pavement side, i.e., upstream side, is now backfilled with sand and is water puddled into the spaces beneath the pavement, at the same time the water is densifying the sand backfill to achieve intimate contact. The geotextile on the drainage core of the PGED is now filtering water from within the sand backfill, which is well within the state of the art of both design and practice.

To be recognized in this regard is that the Kentucky DOT is doing precisely what is recommended above. However, their reasoning is to avoid core bending and J-buckling, which has been observed in some of their exhuming studies (*30,31*), as well as in this research study. Interestingly both objectives of achieving intimate contact and avoiding core distortion are met by the subtle move suggested in Figure 23b.

The photographs of Figure 24 illustrate that the recommended concept is viable and is actually being accomplished. The upper photograph shows the installation equipment train. A dump truck leads a continuous disc excavator, which cuts a 4.0-in.-wide (typically) trench adjacent to the pavement and simultaneously loads the dump truck with the excavated soil. A pickup truck pulling the PGED on a "lazy Susan" deployment trailer places the PGED. A laborer ensures that it is upright in the trench and against the shoulder side of the trench.

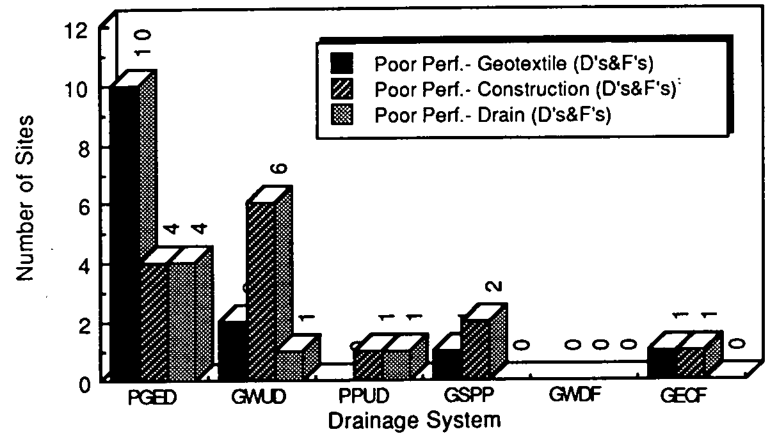
The lower photograph of Figure 24 illustrates the sand backfilling operation. A dump truck discharges directly into a funnel shaped sand hopper, which discharges the sand into the trench. A water truck follows the sand hopper, puddling the sand into the available slot and possible voids that may be beneath the pavement slab. The sand hopper is shown in Figure 25. For a well-graded concrete sand as backfill material, an estimated 1.0 gallon per linear foot of water is necessary (*32*). The recommended gradation of the sand backfill is given in Table 15, after Raymond and Bathurst (*33*).

Currently there is a task group working within ASTM Committee D35 on a draft standard entitled "Standard Practice for the Installation of Geocomposite Drains." When approved, this document should coincide with the findings of this NCHRP project and be readily available for general use and referencing.

Regarding the added cost of removal of the excavated soil, cost of replacement sand, and the cost of required water-puddling placement, a Kentucky contractor (*32*) estimates the increase to be $0.15 to $0.25 per linear foot. Even with the worst case figure, PGEDs should be significantly less expensive than other edge drain systems (by at least $1.00 per linear foot) without the incidence of soil retention and core clogging problems experienced during the field exhuming investigation of this study.

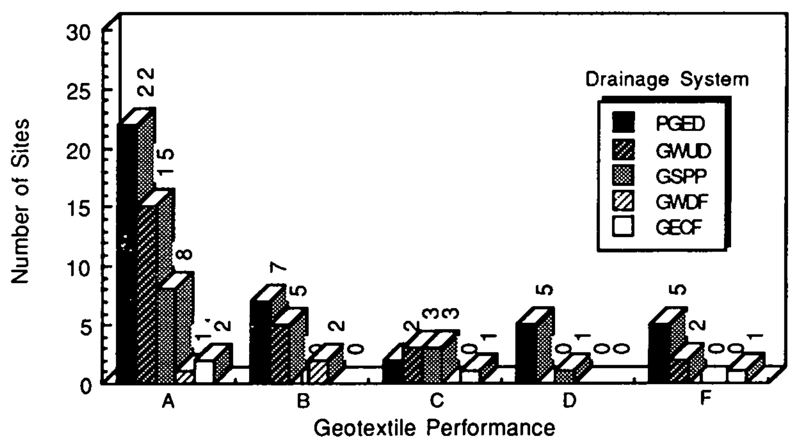
LABORATORY CONCLUSIONS

Three different types of laboratory tests on geotextile filters were conducted during this research project. The long-term flow (LTF) tests were instructive in understanding how fine silts in gap graded soils perform with different geotextiles. In general, the geotextiles allowed the silt to pass through them when of a low percentage, e.g., ≤ 5 percent. At high percentages of silt (e.g., ≥ 25 percent), the permeability of the silt becomes the



(a) Poor performance of different types of drainage systems

Note: Of the 10 PGED geotextile failures, 8 were due to initial lack of intimate contact and could be considered as construction related failures.



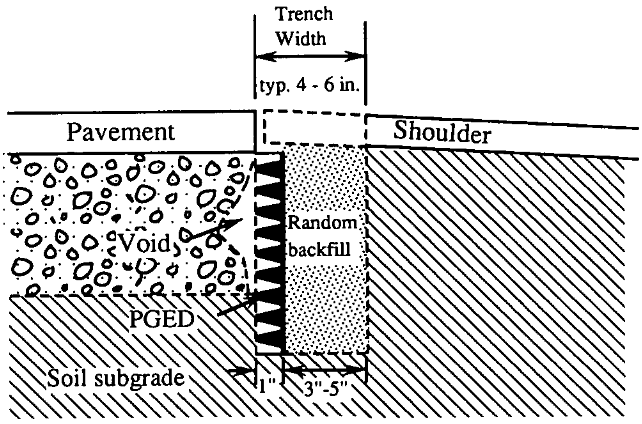
(b) Geotextile performance for the different types of drainage systems

Figure 22. Major results from field exhuming study.

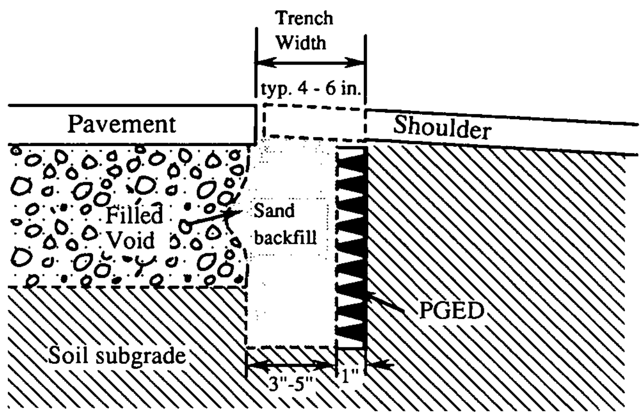
dominating factor and the flow rate is considerably decreased. The equilibrium flow rate in all instances must be compared to a site-specific flow rate to assess the adequacy of the situation. Intermediate situations of silt content must be laboratory modeled and evaluated if they are associated with a critical or severe application.

For permeating liquids with high turbidity and soils with zero or little silt, the turbid water decreased the permeability of the nonwoven geotextiles as the turbid particles were filtered from the water, or as they passed through the woven geotextile. Site-specific conditions will dictate if these situations are acceptable, or not.

The quest for an accelerated test method to predict the type of behavior just described was not successful. Two tests using the fine fraction of the upstream soil were developed and investigated. One used slurried increments of the fines under quasi-static conditions (the F^3 test) and the other used dynamic conditions (the D-F^3 test). Both tests could illustrate the difference between excessive soil loss and clogging of the geotextile, but neither could distinguish between field sites that performed acceptably from those that performed nonacceptably. Thus these two tests are not recommended for use as precursor or index tests to predict field behavior of geotextile filters.



(a) Existing location of PGED's by current placement methods



(b) Recommended location of PGED's for future placement methods

Figure 23. Existing and recommended installation methods for prefabricated geocomposite edge drains (PGEDs).

DESIGN CONCLUSIONS

The current status of design insofar as the *drain* component of a highway drainage system is quite good. Only 6 nonacceptable drains were observed and they were unusual situations (e.g., no holes in a pipe), or could be remedied by moving PGED products to the shoulder side of the excavation as shown in Figure 23b. Detailed information on the design of polymeric drainage cores of PGEDs is given in reference 34.

The current status of design insofar as the geotextile *filter* component of a highway drainage system is also good. As seen in Table 7 for permeability criteria, a number of techniques are reasonable with the FHWA (noncritical/nonsevere) criterion being among the best. As seen in Table 10 for soil retention criteria, an even larger number of techniques are again reasonable with the FHWA (steady state) criterion being among the best. As seen in Table 12 for excessive soil clogging criteria, the FHWA criterion is again the best; however, for mixed soils in the 13 to 49 percent passing the #200 sieve range, agreement is poor. When viewing the disagreement further, it is seen that all but two of these sites were actually acceptable in the field. Thus the criteria are relatively conservative. This suggests that the two nonacceptable field sites not properly predicted should be put into a severe category, which requires separate laboratory testing. While FHWA recommends the gradient ratio test, the LTF test as described in Appendix C is favored.

Other than this relatively minor detail in the overall context of geotextile filter design, the current FHWA guidelines as they appear in reference *29* are very suitable and perform well against the field-exhumed findings.

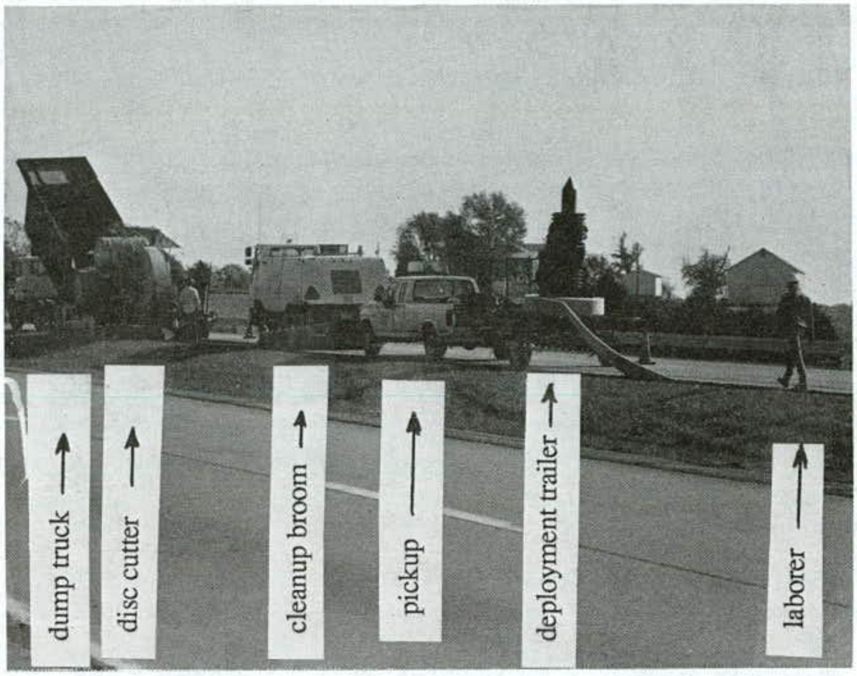
RECOMMENDATIONS

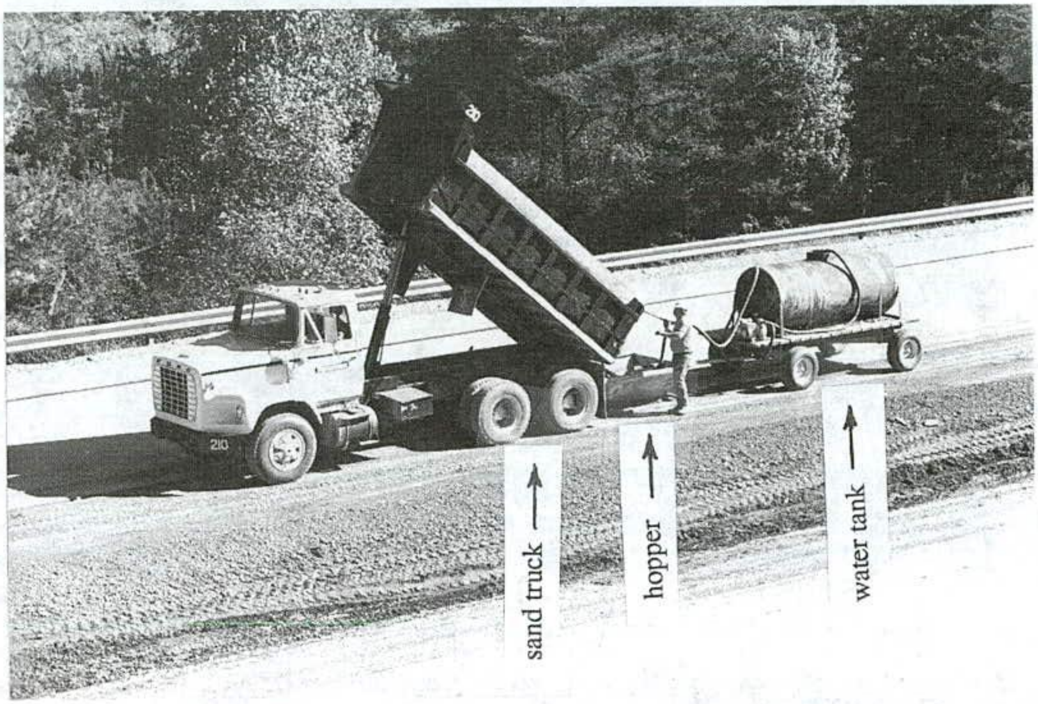
Quite clearly, excessive soil loss through PGED geotextile filters was the most commonly encountered field problem. The recommendation for solution to this situation is shown in the schematic diagrams of Figure 23. In addition to hopefully solving the soil retention problem (and subsequent clogging of the drainage core), this subtle change will possibly handle a few other problems with respect to PGEDs. Core bending and buckling might be lessened, as well as the possibility of avoiding excessive clogging of the geotextile—the reason being that sand is now the upstream backfilling material and geotextiles can be designed with confidence in this regard.

Regarding design methods, the currently practiced FHWA design models for permeability, soil retention, and nonexcessive clogging of geotextile filters should continue to be used. They are particularly appropriate for filtration using granular soils.

Regarding design models for fine-grained soils, the FHWA procedures can be continued for noncritical/nonsevere applications. For critical/severe installations, laboratory tests are recommended. This study pursued LTF testing, but other tests might also be investigated. The hydraulic conductivity ratio test is one that has recently been proposed in this regard (*35*).

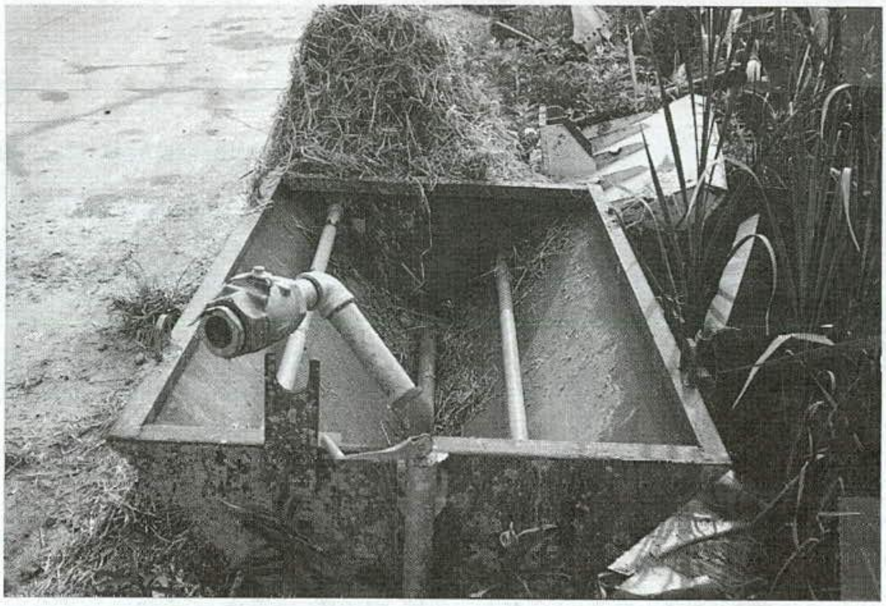
Other than these recommendations, it can be concluded that within the context of this study the status of geosynthetic use in long-term highway drainage applications is quite good. This statement is made on the basis that the field-exhuming task actively solicited failures and it was no surprise that some were discovered. Understanding and eliminating the PGED failures from the nonacceptable sites by virtue of a modified installation method, brings the "Ds" and "Fs" to a very low number. Further elimination of foolish construction/maintenance problems brings the number of nonacceptable sites down still further. In fact, by eliminating these two situations there are only 4 nonacceptable sites that are encountered. Out of a total of 91 field-exhumed sites, this is felt to be an excellent performance record. It is the type of confidence that a state DOT expects. It is felt that this type of performance speaks very well for the long-term performance of geosynthetics in transportation related drainage applications.





(b) Sand installation and backfilling equipment at end of equipment train according to Figure 23(b)

Figure 24. Method of installation of prefabricated geocomposite edge drains (PGEDs) using sand backfill upstream of the product as installation in Figure 23b.



(a) Water connection being made to sand hopper for puddling delivery of backfilling sand

(b) Perforated pipe system used for providing a uniform supply of water for puddling backfill sand

Figure 25. Photographs of a sand hopper used in the installation of prefabricated geocomposite edge drains (PGEDs).

TABLE 15. Recommended sieve size of sand backfill upstream of a PGED to prevent soil loss through the geotextile and clogging of the drainage core, after Raymond and Bathurst (*33*)

U.S. Std. Sieve Size	Opening Size (mm)	Amount Passing (%)
3/8 in.	9.5	100
No. 4	4.75	100-95
No. 8	2.36	100-80
No. 16	1.18	85-50
No. 30	0.60	60-25
No. 50	0.30	30-10
No. 100	0.15	10-2
No. 200	0.075	2-0

REFERENCES

1. CEDERGREN, H. R., *Seepage, Drainage and Flow Nets,* J. Wiley and Sons, Inc., NY (1967).
2. KOERNER, R. M., *Designing with Geosynthetics,* 3rd Ed., Prentice Hall, Englewood Cliffs, NJ (1994).
3. KOERNER, R. M., and KO, F. K., "Laboratory Studies on Long-Term Drainage Capability of Geotextiles," *Proceedings 2nd Intl. Conf. Geotextiles,* Las Vegas, NV, Industrial Fabrics Association International (Aug. 1–6, 1982), pp. 91–95.
4. GRI Test Method GT1, "Clogging Potential via Long Term Flow Rate," Geosynthetic Research Institute, Drexel University, Philadelphia, PA.
5. WAYNE, M. H. and KOERNER, R. M., "Correlation Between Long-Term Flow Testing and Current Geotextile Filtration Design Practice," *Proceedings Geosynthetics '93,* Vancouver, B.C., Canada, Industrial Fabrics Association International (1993), pp. 501–518.
6. HOOVER, T. P., "Laboratory Testing of Geotextile Filter Fabrics," *Proceedings 2nd Intl. Conf. Geotextiles,* Las Vegas, NV, International Fabrics Association International (1982), pp. 839–843.
7. LEGGE, K. R., "A New Approach to Geotextile Selection," *Proceedings 4th Intl. Conf. Geotextiles,* The Hague, Netherlands (1990), pp. 269–272.
8. GRI Test Method GT8, "Fine Fraction Filtration Using Geotextile Filters," Geosynthetic Research Institute, Drexel University, Philadelphia, PA.
9. SANSONE, L. J. and KOERNER, R. M., "Fine Fraction Filtration Test to Assess Geotextile Filter Performance," *J. Geotextiles Geomembranes,* Vol. 11, Nos. 4–6, Elsevier (1992), pp. 371–394.
10. NAREJO, D. B. and KOERNER, R. M., "A Dynamic Filtration Test for Geotextile Filters," *J. Geotextiles Geomembranes,* Vol. 11, Nos. 4–6, Elsevier (1992), pp. 395–400.
11. CHRISTOPHER, B. R. and FISCHER, G. R., "Geotextile Filtration Principles, Practices and Problems," *J. Geotextiles Geomembranes,* Vol. 11, Nos. 4–6, Elsevier (1992), pp. 337–354.
12. GIROUD, J. P., "Filter Criteria for Geotextiles," *Proceedings 2nd Intl. Conf. Geotextiles,* Las Vegas, NV (1982), pp. 103–108.
13. CALHOUN, C. C., "Development of Design Criteria and Acceptance of Specifications for Plastic Filter Cloth," *Technical Report 5-72-7,* U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS (1972).
14. SCHOBER, W. and TEINDL, H., "Filter Criteria for Geotextiles," *Proc. 7th European Conf. Soil Mechanics and Foundation Engineering,* Brighton, Vol. 2 (1979), pp. 123–129.
15. WATES, J. A., "Filtration: An Application of a Statistical Approach to Filters and Filter Fabrics," *Proc. 7th Regional Conf. for Africa on Soil Mechanics and Foundation Engineering,* A. A. Balkema, Rotterdam, The Netherlands (1980), pp. 433–440.
16. CARROLL, R. G., "Geotextile Filter Criteria," *Transportation Research Record No. 916,* TRB, National Research Council, Washington, DC (1983), pp. 46–53.
17. HALIBURTON, T. A., LAWMASTER, J. D., and MCGUFFEY, V. E., "Use of Engineering Fabric in Transportation Related Applications," *FHWA Training Manual*—FHWA Contract No. DTTFH-80-C-00094 (1982).
18. CHRISTOPHER, B. R. and HOLTZ, R. D., "Geotextile Engineering Manual," *Report No. FHWA-TS-86/203,* U.S. Federal Highway Administration, Washington, DC (1989).
19. FRENCH COMMITTEE of GEOTEXTILES and GEOMEMBRANES, "Recommendations for the Use of Geotextiles in Drainage and Filtration Systems," Institut Textile de France, Boulogne-Billancourt, France (1986).
20. AASHTO, Geotextile Specifications prepared by joint committee of AASHTO-AGC-ARTBA Task Force 25, Washington, DC (1986).
21. ZITSCHER, F. F., "Recommendations for the Use of Plastics in Soil and Hydraulic Engineering," *Die Bautechnik,* Vol. 52, No. 12 (1974), pp. 397–402.
22. OGINK, H. J. M., "Investigations on the Hydraulic Characteristics of Synthetic Fabrics," Delft Hydraulics Laboratory, *Publication No. 146,* Delft, The Netherlands (1975).
23. SWEETLAND, D. B., "The Performance of Non-Woven Fabrics as Drainage Screens in Subdrains, M. thesis, University of Strathclyde, Glasgow, UK (1977).
24. RANKILOR, P. R., *Membranes in Ground Engineering,* John Wiley, Chichester, UK (1981).
25. FISCHER, G. R., CHRISTOPHER, B. R., and HOLTZ, R. D., "Filter Criteria Based on Pore Size Distributions," *Proc. 4th Intl. Conf. on Geotextiles,* The Hague, Netherlands, Vol. 1 (1990), pp. 289–294.
26. LUETTICH, S. M., GIROUD, J.-P., and BACHUS, R. C., "Geotextile Filter Design Guide," *J. Geotextiles Geomembranes,* Vol. 11, Nos. 4–6, Elsevier (1992), pp. 355–370.
27. HALIBURTON, T. A. and WOOD, P. D., "Evaluation of the U.S. Army Corps of Engineers Gradient Ratio Test for Geotextile Performance," *Proc. of the 2nd Intl. Conf. on Geotextiles,* Las Vegas, IFAI, St. Paul, MN (1982), pp. 97–102.
28. KOERNER, R. M., HSUAN, Y., and LORD, A. E., Jr., "Remaining Technical Barriers to Obtaining General Acceptance of Geosynthetics," *J. Geotextiles and Geomembranes,* Vol. 12, No. 1 (1993), pp. 1–52.
29. CHRISTOPHER, B. R., and HOLTZ, R. D., "Geotextile Design and Construction Guidelines," U.S. Dept. of Transportation, Federal Highway Administration, *Publ. No. FHWA-HI-90-001,* National Highway Institute, Washington, DC (April 1992).
30. ALLEN, D. L. and FLECKENSTEIN, L. J., "Field and Laboratory Comparison of Pavement Edge Drains in Kentucky," University of Kentucky, Kentucky Transportation Center, *Paper No. 93609, Transportation Research Record No. 1425,* TRB, National Research Council, Washington, DC (January 1993).
31. FLECKENSTEIN, L. J., "Vertical Compression Test Method for Geocomposite Panel Drains," proposed Test Method to ASTM Committee D-35 (August 18, 1992).
32. Personal communication, Doug Brossart and Jack Sanders,

Spartan Underground Construction, Inc., Burlington, Kentucky.

33. RAYMOND, G. P. and BATHURST, R. J., "Premanufactured Drainage System Effectiveness on Ontario Highway 402 Near Strathroy," Report to Ministry of Transportation of Ontario, Canada (Jan. 1993), 30 pp.
34. KOERNER, R. M. and HWU, B.-L., "Prefabricated Highway Edge Drains," *Transportation Research Record No. 1329,* TRB, National Research Council, Washington, DC (1991), pp. 14–20.
35. WILLIAMS, N. D. and ABOUZAKHM, M. A., "Evaluation of Geotextile/Soil Filtration Characteristics Using the Hydraulic Conductivity Ratio Analysis," *J. Geotextiles Geomembranes,* Vol. 8, No. 1 (1989), pp. 1–26.

APPENDIX A

Summary table for field study of the 91 exhumed sites and their respective performance levels.

Site No.	Date of Exhuming	Location (City, State)	FHwA Region	Highway Designation	Drain Type	Age in Years	Overall Perf. Level	Const./Maint. Condition	Drain (Stone, Core, or Pipe) Condition	Geotextile Filter Condition
1	4/16/90	Claysville, PA	3	I-70	PGED	5	0%	D (spacing)	A	F (retention)
2	4/17/90	Washington, PA	3	I-70	PGED	5	15%	D (spacing)	A	F (retention)
3	5/15/90	Luray, OH	5	I-70	PGED	5	99%	A	A	A
4	5/17/90	Zainesvile, OH	5	I-70	GWUD	1.5	80%	F (in shoulder)	A	A
5	5/18/90	Hopewell, OH	5	I-70	PGED	2	95%	B (in pavement)	B (J'ing)	A
6	5/18/90	Hopewell, OH	5	I-70	PGED	2	100%	A	A	A
7	7/24/90	Bald Knob, AR	6	RT 167	PGED	3.5	60%	A	B (col. orientation)	D (retention)
8	7/24/90	Bald Knob, AR	6	RT 167	PGED	3.5	70%	A	B (J'ing)	C (retention)
9	7/25/90	Ozark, AR	6	I-40	GWUD	7	5%	A	A	F (clogging)
10	7/25/90	Ozark, AR	6	I-40	PGED	7	65%	B (settlement)	B (col. orienation)	D (retention)
11	7/31/90	Checotah, OK	6	RT 69	PGED	4.5	0%	A	A	F (retention)
12	7/31/90	Summit, OK	6	RT 69	PGED	4	100%	A	A	A
13	8/1/90	Oktaha, OK	6	RT 69	GWUD	4.5	75%	A	A	C (retention)
14	8/1/90	Wainwright, OK	6	RT 69	GWUD	4	100%	A	A	A
15	8/14/90	Holland, NY	1	RT 16	GWUD	9	95%	C (in shoulder)	A	B (slag precip.)
16	8/14/90	Hamlet, NY	1	RT 75	GWUD	8.5	99%	A	A	B (slag precip.)
17	8/20/90	Goreville, IL	5	I-24	GWUD	15	99%	A	A	B (clogging)
18	8/22/90	Galesburg, IL	5	RT 34	PGED	5	98%	A	B (col. orientation)	A
19	8/23/90	Cameron, IL	5	RT 34	GECF	4	99%	A	n/a	A
20	8/23/90	Monmouth, IL	5	RT 34	GSPP	5	0%	F (too high)	A	C (clogging)
21	8/24/90	Oilfield, IL	5	RT 49	GECF	4	95%	B (design)	n/a	A
22	8/27/90	Moline, IL	5	RT 92	GWDF	2	95%	C (no GT cover)	A	A
23	8/28/90	Montrose, IL	5	I-70	PGED	4	99%	A	A	A
24	8/28/90	Montrose, IL	5	I-70	GSPP	7	90%	B (backfill)	A	C (clogging)
25	8/29/90	Monroe, IL	5	I-39	GSPP	5	n/a	F (no outlet)	A	F (clogging)

Site No.	Date of Exhuming	Location (City, State)	FHwA Region	Highway Designation	Drain Type	Age in Years	Overall Perf. Level	Const./Maint. Condition	Drain (Stone, Core, or Pipe) Condition	Geotextile Filter Condition
26	8/29/90	Freeport, IL	5	RT 20	PGED	3	99%	A	A	A
27	10/4/90	Blewett, WA	10	RT 97	GWUD	6	99%	A	A	A
28	10/4/90	Wenatchee, WA	10	RT 2	GWUD	6	99%	A	A	A
29	10/5/90	Monroe, WA	10	RT 2	GWUD	10	20%	A	A	F (retention)
30	10/8/90	Labam, WA	10	RT 6	GWUD	12	75%	F (no GT cover)	A	A
31	10/9/90	Kelso, WA	10	RT 5	GWUD	9	99%	B (inst. damage)	A	B (lightweight)
32	10/10/90	Coupeville, WA	10	FN RD	GWUD	5	0%	F (no outlet)	B	C (clogging)
33	10/16/90	Willmar, MN	5	RT 71	GSPP	9	99%	A	A	A
34	10/16/90	Marshall, MN	5	RT 19	GSPP	5	98%	A	A	A
35	10/16/90	Marshall, MN	5	RT 19	PGED	5	99%	A	A	A
36	10/17/90	Jackson, MN	5	RT 71	GSPP	4	96%	B (poor placement)	A	A
37	10/17/90	Northrop, MN	5	RT 15	GSPP	3	99%	A	A	A
38	10/17/90	Truman, MN	5	RT 15	GWUD	5	95%	A	A	A
39	10/18/90	Albert Lea, MN	5	RT 35	GSPP	4	97%	B (too deep)	A	A
40	10/18/90	Austin, MN	5	I 90	GWUD	4	96%	B (no top filter)	A	A
41	10/18/90	Oronco, MN	5	RT 52	PGED	3	95%	A	A	B (retention)
42	10/18/90	Oronco, MN	4	RT 52	PGED	3	95%	A	A	B (retention)
43	12/15/90	W. Alexander, PA	3	I-70	PGED	5	85%	A	A	C (slag clogging)
44	7/1/91	Rock Hill, SC	4	I-77	PGED	2	100%	A	A	A
45	7/8/91	High Point, NC	4	I-85	PGED	4	95%	B (poor placement)	B (J'ing)	B (retention)
46	7/9/91	Lexington, NC	4	I-85	GWUD	7	80%	B (poor placement)	A	C (clogging)
47	7/22/91	Stanwood, MI	5	RT-131	GECF	10	85%	C (workmanship)	n/a	C (placement)
48	7/26/91	Paris, MI	5	RT-131	GSPP	6	95%	A	A	C (retention)
49	7/26/91	Paris, MI	5	RT-131	GECF	6	50%	F (workmanship)	n/a	F (UV degrad.)
50	7/23/91	Farnwell, MI	5	RT-115	PGED	9	40%	A	F (compressed)	A
51	7/23/91	Farnwell, MI	5	RT-115	PGED	9	98%	A	B (core deflective)	A

Site No.	Date of Exhuming	Location (City, State)	FHwA Region	Highway Designation	Drain Type	Age in Years	Overall Perf. Level	Const./Maint. Condition	Drain (Stone, Core, or Pipe) Condition	Geotextile Filter Condition
52	7/25/91	Lansing, MI	5	I-69	GWUD	3	70%	F (mobile cement)	A	A
53	7/24/91	Portland, MI	5	I-96	GSPP	5	90%	C (high outlet)	A	A
54	7/30/91	Linden, MI	5	RT-23	GSPP	9	75%	C (poor placement)	C (deformed pipe)	A
55	7/29/91	New Boston, MI	5	I-275	GSPP	9	65%	A	A	D (retention)
56	7/31/91	Battle Creek, MI	5	I-94	PGED	3	95%	A	A	A
57	8/11/91	Wheatland, WY	8	I-25	GWUD	4	95%	B (poor compaction)	A	A
58	8/12/91	McFadden, WY	8	I-80	PGED	2	30%	A	A	F (clogged)
59	8/12/91	Rawlins, WY	8	I-80	GWUD	1	99%	A	A	A
60	8/14/91	Point of Rocks, WY	8	I-80	PGED	2	70%	A	A	D (retention)
61	8/14/91	Evanston, WY	8	I-80	GWUD	2	60%	D (poor placement)	A	A
62	8/16/91	Glendo, WY	8	I-25	PGED	4	99%	A	B (col orientation)	A
63	8/16/91	Glendo, WY	8	I-25	GWUD	3	99%	A	A	A
64	9/5/91	Rozet, WY	8	I-90	PGED	2	98%	A	A	B (retention)
65	9/5/91	Sundance, WY	8	I-90	PGED	3	99%	A	A	A
66	9/6/91	Aladdin, WY	8	I-90	PGED	3	99%	A	A	A
67	9/9/91	Elborn, IA	7	RT-21	PPUD	16	100%	A	A	n/a
68	9/9/91	Guernsy, IA	7	I-80	PPUD	10	85%	A	B (retention)	n/a
69	9/10/91	Moville, IA	7	RT-20	PGED	9	99%	A	A	A
70	9/10/91	Des Moines, IA	7	I-80	PPUD	12	90%	A	B (retention)	n/a
71	9/11/91	Williams, IA	7	I-35	PPUD	13	99%	A	A	n/a
72	9/11/91	Decatur City, IA	7	I-35	PPUD	3	99%	A	A	n/a
73	9/12/91	Guttenberg, IA	7	RT-52	PGED	6	97%	A	A	B (clogging)
74	9/13/91	Davenport, IA	7	I-80	PPUD	10	0%	F (shallow)	F (filled with fines)	n/a
75	9/16/91	Stanton, KY	4	RT-402	PGED	3	70%	C (crack and seat)	B (compressed)	D (retention)
76	9/16/91	Clay City, KY	4	Rt-402	PGED	3	75%	C (crack and seat)	A	D (retention)
77	9/17/91	Forest Grove, KY	4	I-75	PGED	3	95%	C (trench settlement)	A	A

Site No.	Date of Exhuming	Location (City, State)	FHwA Region	Highway Designation	Drain Type	Age in Years	Overall Perf. Level	Const./Maint. Condition	Drain (Stone, Core, or Pipe) Condition	Geotextile Filter Condition
78	9/17/91	Lisletown, KY	4	I-75	PGED	2	40%	F (trench settlement)	C (sharp top edge)	F (puncture)
79	9/17/91	Frankfort, KY	4	I-65	PGED	8	99%	A	A	A
80	9/18/91	Franklin, KY	4	I-65	PGED	4	60%	C (alignment)	D (column collapsed)	B (clogging)
81	9/18/91	Franklin, KY	4	I-65	PGED	4	50%	F (folding)	D (core folded)	B (clogging)
82	10/8/91	Springfield, PA	3	RT-1	GWDF	11	65%	C (soil behind GT)	n/a	B
83	10/8/91	Springfield, PA	3	RT-1	GWDF	11	65%	C (soil behind GT)	n/a	B
84	2/3/92	San Juan, NM	6	I-40	PGED	4	99%	A	A	A
85	2/3/92	Glen Rio, NM	6	I-40	PGED	4	95%	A	A	A
86	2/5/92	Amorillo, TX	6	FH 335	GWUD	2	80%	D (pipe too high)	B (no outlet works)	A
87	2/19/92	Lufkin, TX	6	US 59	GWUD	1,5	95%	A	A	A
88	2/19/92	Diboll, TX	6	US 59	PGED	2	95%	A	A	A
89	2/20/92	Pleasanton, TX	6	I-37	PGED	4	75%	D (PED outside of shoulder)	A	A
90	2/24/92	Chipley, FL	4	I-10	GWUD	4	25%	C (asphalt treated paper pipe)	F (no holes in pipe)	A
91	2/24/92	Marianna, FL	4	I-10	GWUD	3	80%	B (drain crete not v/perm)	B (low permeable aggregate inside drain)	B (precipi-tate on drain)

*where
PGED = prefabricated geocomposite edge drain
GWUD = geotextile wrapped underdrain (stone and perforated pipe)
PPUD = perforated pipe underdrain (no geotextile filter)
GSPP = geotextile socked perforated pipe
GWDF = geotextile wall drain filter
GECF = geotextile erosion control filter

**also
A = all three components (system, drain and filter) functioning as intended
B = one component of above showing less than ideal performance
C = more than one compound of above showing less than ideal performance
D = one component of above showing poor performance
F = more than one component showing poor performance, or one component showing failure

APPENDIXES B, C, AND D

UNPUBLISHED MATERIAL

Appendixes B, C, and D as contained in the research agency's final report are not published herein, but complete copies of that report, titled "Long-Term Performance of Geosynthetics in Drainage Applications," may be obtained on loan or for purchase ($20.00) by writing to the Transportation Research Board, Business Office, Box 289, Washington, DC 20055. The available appendixes are titled as follows: Appendix B, "Summary Table for Hydraulic Properties of Geotextiles and Physical Properties of Site Soils Found in Subgrade Beneath or Around Drain, and Soil Inside Drain"; Appendix C, "Standard Test Method for 'Geotextile Filter Performance Via Long-Term Flow (LTF) Tests' "; and Appendix D, "Complete Documentary of 91 Field Sites."

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 8970

000021-02
Materials Engineer
Idaho DOT
P O Box 7129
Boise ID 83707-1129