PERFORMANCE OF GEOTEXTILE SEPARATORS

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16. ABSTRACT

This research involved field investigations and laboratory testing to evaluate the properties and overall performance of geotextile separators exhumed from the roadway at eight sites in eastern and central Washington (Phase I), and 14 sites in western Washington (Phase II). Both nonwoven and woven geotextile separators of different in-service ages were examined in detail, and specimens were tested in the laboratory for strength and hydraulic characteristics. The subgrade condition and geotechnical properties of the base course aggregate and subgrade soils were also evaluated.

Although all of the geotextile separators performed their intended separation function adequately, the geotextiles experienced very different levels of damage during construction. Base aggregate type, rather than initial aggregate lift thickness, appeared to have the most influence on the level of damage. All of the recovered geotextiles installed under an angular base aggregate sustained some damage, while geotextiles installed under sub-rounded to rounded aggregate experienced minor damage, if any. The woven slit-films and needle-punched nonwoven geotextiles experienced similar reductions in strength, and both survived the installation conditions reasonably well (except for one lightweight, needle-punched nonwoven, which was over stressed during installation and which may have been installed under an excessively thin pavement section). Although the heat-bonded nonwovens were heavily damaged during installation, they were installed under some of the more severe site survivability conditions.

Test results indicated that the permittivity of the woven slit-films and the needle-punched nonwovens both increased by similar percentages after being washed. The heat-bonded nonwovens had the highest percentage increases in permittivity after washing; this finding suggests that they clog more than other geotextiles. There was evidence that the woven slit-films experienced much more blinding than did the other geotextiles, and that iron staining and caking may also have affected their drainage performance adversely. Most woven slit-film geotextiles did not meet the filtration requirements set forth by Task Force 25 (1) and Christopher and Holtz (2) when they were placed on fine-grained subgrade soils.

The unwashed (i.e., "undisturbed") permittivity results also indicated that most woven slit-film geotextile permeabilities fell well below the Washington State Department of Transportation's (WSDOT) required value. The presence of caked fines on the upper surface of three woven slit-films could indicate that their pore openings were too large for the intended filtration function, and that they might be subject to fines migration. However, the evidence on this point was inconclusive. There was no other evidence of fines migration at any of the sites.

All of the pavements examined were in good condition, and damage to the geotextile separators did not appear to have had any negative impact on the pavements' long-term performance. Although one pavement surface showed signs of premature failure, this could not be attributed to the performance of the geotextile separator.

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Final Summary Report
Research Project T9233, Task 13
Geotextile Separators II

PERFORMANCE OF GEOTEXTILE SEPARATORS

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DISCLAIMER

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SUMMARY

This research involved field investigations and laboratory testing to evaluate the properties and overall performance of geotextile separators exhumed from the roadway at eight sites in eastern and central Washington (Phase I), and 14 sites in western Washington (Phase II). Both nonwoven and woven geotextile separators of different in-service ages were examined in detail, and specimens were tested in the laboratory for strength and hydraulic characteristics. The subgrade condition and geotechnical properties of the base course aggregate and subgrade soils were also evaluated.

Although all of the geotextile separators performed their intended separation function adequately, the geotextiles experienced very different levels of damage during construction. Base aggregate type, rather than initial aggregate lift thickness, appeared to have the most influence on the level of damage. All of the recovered geotextiles installed under an angular base aggregate sustained some damage, while geotextiles installed under sub-rounded to rounded aggregate experienced minor damage, if any. The woven slit-films and needle-punched nonwoven geotextiles experienced similar reductions in strength, and both survived the installation conditions reasonably well (except for one lightweight, needle-punched nonwoven, which was over stressed during installation and which may have been installed under an excessively thin pavement section). Although the heat-bonded nonwovens were heavily damaged during installation, they were installed under some of the more severe site survivability conditions.

Test results indicated that the permittivity of the woven slit-films and the needle-punched nonwovens both increased by similar percentages after being washed. The heat-bonded nonwovens had the highest percentage increases in permittivity after washing; this finding suggests that they clog more than other geotextiles. There was evidence that the woven slit-films experienced much more blinding than did the other geotextiles, and that iron staining and caking may also have affected their drainage performance

adversely. Most woven slit-film geotextiles did not meet the filtration requirements set forth by Task Force 25 (1) and Christopher and Holtz (2) when they were placed on fine-grained subgrade soils.

The unwashed (i.e., "undisturbed") permittivity results also indicated that most woven slit-film geotextile permeabilities fell well below the Washington State Department of Transportation's (WSDOT) required value. The presence of caked fines on the upper surface of three woven slit-films could indicate that their pore openings were too large for the intended filtration function, and that they might be subject to fines migration. However, the evidence on this point was inconclusive. There was no other evidence of fines migration at any of the sites.

All of the pavements examined were in good condition, and damage to the geotextile separators did not appear to have had any negative impact on the pavements' long-term performance. Although one pavement surface showed signs of premature failure, this could not be attributed to the performance of the geotextile separator.

CONCLUSIONS AND RECOMMENDATIONS

PHASE I (EASTERN WASHINGTON)

1. Damage observed in the geotextile from the SR 270 to Albion Road site suggested that a lightweight (120 g/m^2), nonwoven geotextile should not be used for separation applications—regardless of subgrade type, initial base course lift thickness, or survivability conditions.
2. Puncture holes were observed in many of the woven slit-film geotextiles from sites where gravel-sized particles were present on the subgrade surface. Several puncture holes were also observed in the 180 g/m^2 nonwoven geotextile from the Albion Road to Parvin Road site. No damage was observed in the 270 g/m^2 geotextile from the Colville Vicinity site, a "high survivability" installation. Therefore, a relatively heavy geotextile (say 270 g/m^2 or more) that meets the high survivability strength criteria and has a high grab elongation will help to minimize installation-related damage.
3. Because of the limited data obtained in this study, conclusions regarding geotextile clogging are difficult to draw. However, visual observation, supported by the results of permittivity tests, indicates that woven slit-film geotextiles tend toward blinding more readily than do nonwoven geotextiles when used over clayey silt subgrades. Woven slit-film permeability increased by an order of magnitude at the Fallon to Palouse site after the adhered clay and silt particles had been washed away. The nonwoven geotextiles had a permeability increase ranging from 4 percent to 70 percent after washing, depending on initial clogging levels.
4. In projects where the geotextile was used properly to separate weak subgrade soils from the initial aggregate lift, use of a geotextile separator expedited construction.

5. The existing roadway at all of the sites investigated in Phase I appeared to be performing quite well. No signs of premature failure were visible. Thus, there is no evidence that moderate construction damage or geotextile blinding/clogging significantly affected roadway performance.

PHASE II (WESTERN WASHINGTON)

1. Geotextiles installed between a soft subgrade and overlying base aggregate can prevent aggregate contamination and probably can enhance the pavement's long-term performance.
2. There was no evidence that even heavy damage to the geotextiles during installation affected roadway performance.
3. Base course aggregate type is very important in assessing geotextile survivability. If rounded to sub-rounded aggregate is placed according to WSDOT specifications, then even the lighter weight (136 g/m^2) geotextiles can survive construction reasonably well. However, lighter weight geotextiles will be severely damaged under high survivability construction conditions with angular base course aggregate. To limit potential damage to the separators, geotextiles with minimum weights of 240 g/m^2 should be used on sites with high survivability conditions.
4. Based on the seven WSDOT sites investigated in Phase II, WSDOT is using good construction practices for geotextile separator installation in western Washington. None of the geotextiles recovered from these sites had more than minor damage.
5. The pore openings for several of the woven slit-film geotextiles studied in this project failed to meet Task Force 25 (1) and FHWA (2) retention requirements for the fine-grained soils commonly found in western Washington. The results suggest that the maximum allowable AOS value should be under 0.3 mm for all geotextiles used over fine-grained soils in western Washington.

6. Blinding, caking, and possibly iron staining have a much greater effect on woven slit-film geotextiles than they do on nonwovens. The permittivity of woven slit-films often was less than 0.05 s^{-1}, even with minimal blinding. Therefore, woven slit-films should be avoided at sites with soft, silty soils where the separator may be subject to high groundwater conditions.
7. Woven slit-films and needle-punched nonwovens appeared to perform similarly as filters when the geotextile is not affected by high groundwater conditions. Many of the sites with soft subgrade soils benefited from geotextile use.
8. Finally, geotextile separators were needed over soft subgrade soils to expedite roadway construction. They appear to have enhanced long-term pavement performance for the roadways evaluated in this study.

RECOMMENDATIONS

When a woven slit-film geotextile is installed as a separator over a clayey silt subgrades, there is potential for blinding and clogging with subsequent buildup of pore pressures. Because nonwoven geotextiles tended to experience less blinding and clogging than woven slit-films, it is recommended that a nonwoven geotextile separator of appropriate strength be used with high groundwater conditions and where the subgrade consists of clayey silt or sandy silt.

Table 1 presents recommended survivability conditions as a function of aggregate type and initial lift thickness, based on findings from this study and modified from the Task Force 25 guidelines (shown in Table 2.) The geotextile strength properties required for the construction survivability conditions determined from Table 1 are those recommended by Task Force 25 and shown in Table 3. (1)

It is recommended that the WSDOT review their maximum allowable AOS values for geotextiles used in stabilization and separation applications. They may also want to review their current permeability requirements with respect to woven slit-film geotextiles.

Table 1. Recommended Construction Survivability Ratings Based on Aggregate Type[1]

Aggregate Type	Angular to Subangular			Rounded to Subrounded		
	Site Subgrade Soil[4] (CBR)					
Initial Lift Thickness[2,3] (cm)	<1	1-2	>2	<1	1-2	>2
15	NR	NR	NR	NR	NR	H
23	NR	NR	H	NR	H	M
30	NR	H	H	H	M	M
>45	H	M	M	M	M	M

H=High, M=Medium, NR=Not Recommended

[1] Based on equipment ground contact pressures greater than 350 kN/m^2 (50 psi)
[2] Maximum aggregate size not to exceed one half the compacted cover thickness
[3] Vibratory compaction not permitted on the initial lift
[4] Site subgrade to be relatively smooth and free of sharp or angular rocks

Table 2. Construction Survivability Ratings of Task Force 25 (1989)

Site Soil CBR at Installation			<1		1-2		>2	
Equipment Ground Contact Pressure		kN/m^2 (psi)	>350 (50)	<350 (50)	>350 (50)	<350 (50)	>350 (50)	<350 (50)
Cover Thickness[1] mm	(in.)	(Compacted)						
100[2,3]	(4)		NR	NR	H	H	M	M
150	(6)		NR	NR	H	H	M	M
300	(12)		NR	H	M	M	M	M
450	(18)		H	M	M	M	M	M

H=High, M=Medium, NR=Not Recommended

[1] Maximum aggregate size not to exceed one half the compacted cover thickness
[2] For low volume unpaved roads (ADT < 200 vehicles)
[3] The 100 mm minimum cover is limited to existing road bases and is not intended for use in new construction.

Table 3. Physical Property Requirements[1,2,3] of Task Force 25 (1989)

Survivability Level	Grab Strength ASTM D 4632 N	(lb)	Puncture Resistance ASTM D 4833 N	(lb)	Tear Strength ASTM D 4533 N	(lb)
Medium	800/510	(180/115)	310/180	(70/40)	310/180	(70/40)
High	1200/800	(270/180)	445/335	(100/75)	445/335	(100/75)

Additional Requirements	Test Methods
Apparent Opening Size	
1. < 50% soil passing a No. 200 US sieve, AOS < 0.6 mm	ASTM D 4751
2. > 50% soil passing a No. 200 US sieve, AOS < 0.3 mm	
Permeability	
k of the geotextile > k of the soil (permittivity times the nominal geotextile thickness)	ASTM D 4491
Ultraviolet Degradation	
At 150 hours exposure, 70% strength retained for all cases	ASTM D 4355
Geotextile Acceptance	ASTM D 4759

[1] Note, for the index properties, the first value of each set (N or lb) is for geotextiles which fail at less than 50% elongation, while the second value is for fabrics which fail at greater than 50% elongation. Elongation as determined by ASTM D 4632.

[2] Values shown are minimum roll average values. Strength values are in the weakest principal direction.

[3] The values of the geotextile elongation do not imply the allowable consolidation properties of the subgrade soil. These must be determined by a separate investigation.

When slit-films are exposed to silty soils, they are susceptible to blinding and/or caking, even small amounts of which can dramatically reduce their permeability (or permittivity). A conservative permeability value is suggested for all geotextiles used in separation applications where high groundwater conditions exist, to account for possible decreases in permeability during service life.

Discussions with WSDOT district personnel and direct observation at a construction project near Pullman, Washington, make it apparent that geotextiles are sometimes being used solely to comply with contract specifications. It is recommended that contract specifications be written to allow the project engineer to evaluate subgrade conditions at the time of construction to determine whether the geotextile is actually needed as a separator. If the geotextile is not needed, then the contractor should not be forced to use it. The cost savings should be returned to WSDOT. An alternative would be to allow geotextile use only in the case of a change order, to be decided by the project engineer during construction.

At several of the study sites, the geotextile was installed after a layer of imported fill had been placed over weak subgrade soils. This type of installation is obviously incorrect. WSDOT inspectors and project engineers should be instructed as to proper geotextile installation methods. Furthermore, inspectors should treat the geotextile as they would any other engineering material such as ACP, concrete, or steel. They should be required to keep accurate records of the installation, including geotextile type, subgrade condition, initial lift thickness, method of compaction, and any damage observed or other problems.

Some additional research on geotextile separators is also recommended. Most of the sites should be investigated again in 5 or 10 years in order to continue monitoring pavement performance and the long-term strength, filtration and drainage characteristics of the geotextiles. In order to better understand the long-term filtration and drainage performance of separator geotextiles, well instrumented laboratory experiments under carefully controlled conditions should be conducted using typical problem subgrade soils and common separator geotextiles. Among other things, the effect of increasing the maximum allowable AOS should be investigated.

INTRODUCTION

Geotextiles are often used as separators at the base/subgrade interface for roadway construction over soft, low-strength soils. Although this is one of the oldest applications of geotextiles, there are few well-documented studies on short- and long-term field performance. The properties that enable geotextiles to survive normal construction operations (short-term performance) are not well established, nor is there much documentation of geotextile separator performance over the design life (the long-term) of highway projects.

Highway pavements constructed on soft soils are prone to premature failure. One of the major causes of such failure is the intermixture of the base-subbase aggregate with the finer grained subgrade soils; this intermixture reduces the effective thickness of aggregate. Problem subgrade soils are saturated fine-grained (silt and/or clay) soils with water contents at or above the plastic limit. Highly compressible peat deposits are also problematic. Intermixture of the base/subbase materials and subgrade soils occurs as a result of (1) intrusion of the fine-grained subgrade soils into the aggregate because of pumping or subgrade weakening (due to excess pore water pressure), and/or (2) aggregate penetration into the subgrade (due to localized bearing capacity failures caused by high wheel load stresses).

The primary purpose of a geotextile separator is to prevent the mixture of aggregate and subgrade materials. If the geotextile is to be an effective separator throughout the pavement's life, it is generally recognized that the geotextile must also carry out secondary functions at the soil-geotextile interface, such as filtration, drainage, and to some extent, reinforcement. Both strength and hydraulic properties are required to make the geotextile effective as a separator. Strength is required to resist the stresses induced by aggregate penetration into the subgrade, and hydraulic properties prevent subgrade fines from migrating up into the aggregate as excess pore water pressures dissipate. Geotextiles are effective separators because they help maintain the design aggregate thickness, reduce the need for over-excavation and/or stabilization aggregate, and expedite construction.

In order for the geotextile to function as a separator, it must be strong enough to tolerate the installation procedures and construction operations such as aggregate placement and compaction (construction "survivability"). Survivability is governed by initial site conditions, subgrade strength, construction equipment, aggregate type, and initial lift thickness. The geotextile experiences the highest mechanical stresses during initial roadway construction. Thus, if a geotextile survives the stress of construction, then it can usually survive in-service stresses.

Although geotextiles have been used for separation for many years, only recently have state and federal agencies attempted to specify guidelines for their use. The American Society of Testing and Materials (ASTM) has developed standardized tests to obtain appropriate geotextile properties. Guidelines and property requirements allow designers to write specifications for geotextile strength, drainage and filtration, and durability. Many states, including Washington, base their specifications for geotextile separators on the recommendations of Task Force 25 of the American Association of State Highway and Transportation Officials, the Associated General Contractors, and the American Road and Transportation Builders Association contained in "Guide specification for geotextiles in separation applications." (1) These recommendations have led to extensive use of woven slit-film geotextiles because (1) they meet construction survivability requirements, (2) they are generally less expensive than nonwoven geotextiles of similar weight, and (3) the original (1983) Task Force 25 recommendations did not mention filtration and drainage properties. Although woven slit-film geotextiles may have the required strength for short-term performance; they usually do not meet filtration and drainage requirements for long-term performance, and they may be subject to blinding or clogging.

Table 2 (page 6) presents the current Task Force 25 survivability rating system. Minimum strength values can be selected from Table 3 (page 6) on the basis of required survivability values from Table 2. The validity of these strength values is somewhat questionable because they are not based on any systematic research. Rather, they are based on properties of separator geotextiles that had performed satisfactorily in temporary roads and other similar applications. Also included in Table 3 are additional requirements for filtration, durability (ultraviolet degradation), and geotextile acceptance criteria. It is the survivability and filtration requirements that are the primary focus of this research.

OBJECTIVES

The research objective was to evaluate the performance of geotextiles used as separators in Washington highways. The principal issues included the following:

- Survivability—Assess the impact of construction on the geotextile separator by means of visual observation and laboratory strength tests. Variables included the initial subgrade condition, climate, construction equipment, base course material, initial lift thickness, and geotextile type.
- Long-term geotextile performance—Assess possible clogging/blinding via visual observations and laboratory permittivity analyses. Variables included subgrade material, groundwater conditions, chemical and biological conditions, traffic, and geotextile type.
- Long-term pavement performance—Correlate, if possible, long-term roadway and pavement performance with the information gathered from the as-built conditions, site investigations and laboratory analyses.

SCOPE

To accomplish the research objective, the project was divided into six tasks:

1. preliminary research and site selection
2. final site selection
3. site investigations
4. laboratory investigations
5. analysis of field and laboratory data
6. final report

In Task 1, WSDOT project records involving geotextile separators were reviewed and ranked according to the following criteria: how well the sites were documented, the age of the sites, the availability of WSDOT laboratory test results, and probable site conditions.

In Task 2, project engineers and inspectors present during geotextile installation were contacted. Preliminary site visits were also made to verify the geotextiles' existence and/or installation conditions. The sites were then re-ranked, and final sites were selected primarily on the basis of the age of the site, geotextile type, verified existence, traffic control considerations, and probable excavation costs. A good mix of geotextile types (woven and nonwoven) as well as different ages and weights was desired.

Task 3 involved falling weight deflectometer (FWD) tests; testpit excavations; observations of the base, geotextile, and subgrade; and detailed documentation of each site. Samples of the geotextile separator, base aggregate, and subgrade soil were retrieved from each site. Page (3) and Metcalfe (4) contain additional details on the site investigations.

In Task 4, grab tensile and wide width strength tests, as well as permittivity tests, on random specimens of the geotextile samples retrieved from each site were conducted. In addition, soil classification and moisture content tests were performed on representative soil samples from each site. Geotextile strength tests were carried out at the WSDOT Materials Laboratory in Phase I (3); all other Phase I tests were done at the

University of Washington's Geotechnical Laboratories. All Phase II testing was done at the University of Washington's Geotechnical and Geosynthetics Laboratories.

The field and laboratory data were analyzed in Task 5, and findings, conclusions, and recommendations are presented in Page (3), Metcalfe (4), and this report, Task 6.

REVIEW OF PAST WORK

This review of past work addresses the following functions and properties of geotextile separators: survivability; filtration and drainage; durability; and pavement performance. It is a brief summary of the extensive literature reviews prepared by Page (3) and Metcalfe (4). Many studies, both field and laboratory, have been performed to assess the short- and long-term performance of geotextile separators. These studies have included short- and long-term field and laboratory performance analyses to evaluate survivability, filtration/drainage, and durability of geotextiles. Laboratory studies have also been performed to assess the above issues under dynamic loading conditions. Although the results of many of these studies are very different, inconclusive, and even conflicting, a few trends emerge.

The studies of separator survivability are inconclusive, probably due to the different conditions under which the geotextiles were installed. Some researchers found that lightweight geotextiles (<135 g/m^2) survived installation quite satisfactorily. Others, however, found that these geotextiles experienced considerable damage during construction, but the amount of damage depended on the backfill type, placement techniques, and degree of compaction. Thus, survivability is more an issue of construction practice rather than geotextile type. End-dumping aggregate or operating equipment directly on the geotextile increased damage, as did very thin initial lifts, although there is no general agreement as to an adequate initial lift thickness. The trend under normal construction conditions is to recommend 270 g/m^2 geotextiles because they are expected to survive normal construction operations.

Although it is generally recognized that filtration and drainage of geotextile separators is important, the requirements have not been adequately established. Several researchers have found that fines migrate through virtually all types of geotextiles under laboratory dynamic loading conditions. Laboratory tests also indicated that geotextiles will blind and clog (see Fig. 1 for definitions of these terms) under repeated loads, although in some cases the decrease in permeabilities may not have been detrimental when compared to the subgrade soil permeability. On the other hand, several field studies have showed no migration of fines up through the geotextiles, although a few found some indications of subgrade fines migration through woven slit-films. Thicker geotextiles may be more capable of preventing subgrade fines migrations, and although there is some evidence of clogging and blinding of geotextiles in the field, no negative effects on the pavement system have been reported.

Durability is generally not considered a significant problem for the separator application; see Metcalfe (4) for additional details.

Finally, although qualitative pavement performance data indicate that geotextile separators are being used successfully, very little *quantitative* data exist regarding the geotextile separators' influence on long-term pavement performance. However, the little that has been published indicates that the separators improve pavement performance.

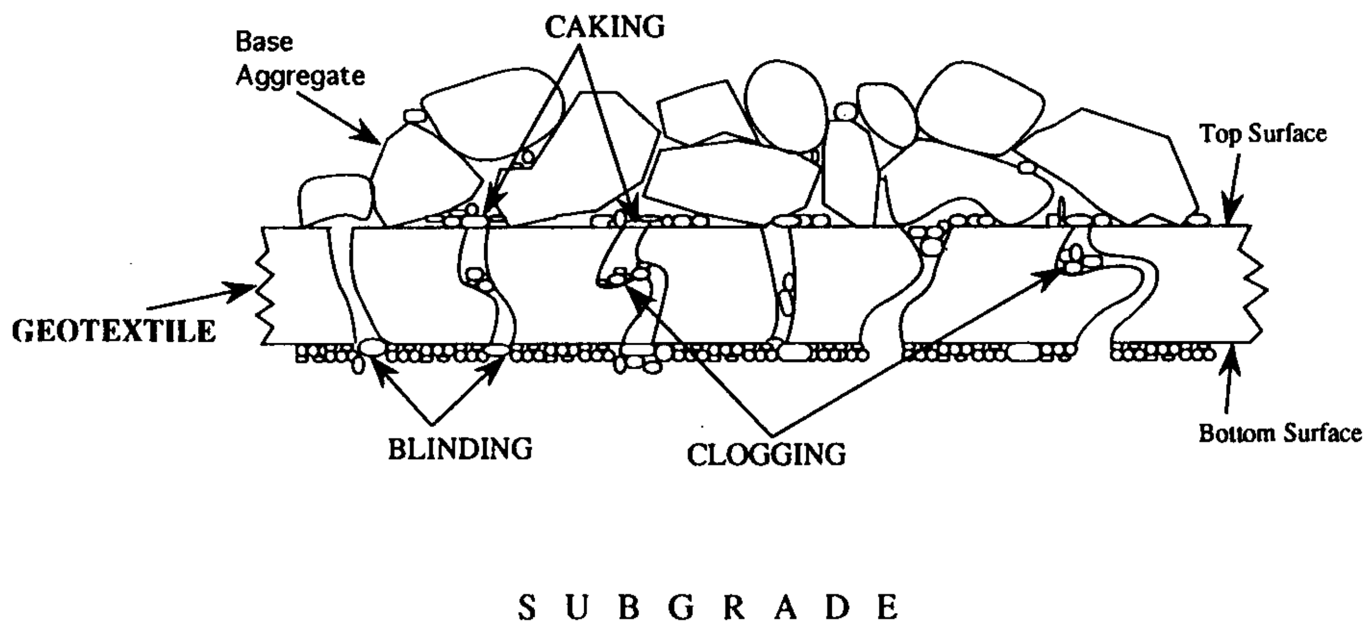


Figure 1. Illustration of Blinding, Clogging, and Caking

SITE SELECTION AND FIELD INVESTIGATION PROCEDURES

SITE SELECTION

Preliminary Site Selection

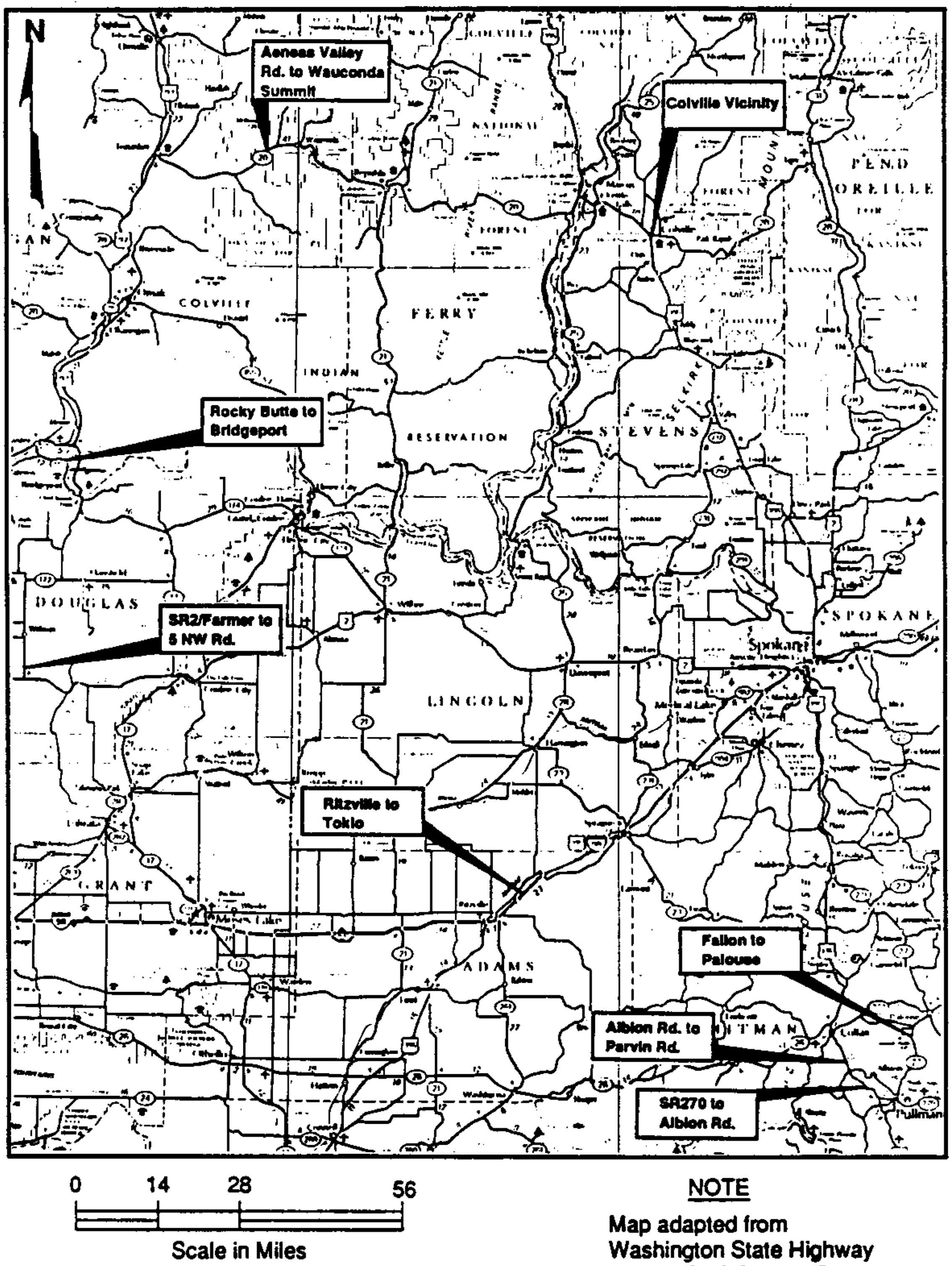
The first step in selecting research sites was to identify WSDOT projects in which geotextiles had been used as separators. Mr. Tony Allen, of the WSDOT, supplied a preliminary list of 18 such projects in eastern Washington and 19 in western Washington. Searches of WSDOT records produced additional candidate sites. The WSDOT database encompassing conformance tests, change orders, and requests for approval of the geotextiles was the best information source. Contacts with district personnel revealed more sites, some involving city and county roadways. The preliminary site selection process ultimately produced more than 80 candidate sites which were evaluated and ranked as "good," "fair," or "poor."

Final Site Selection

Final site selection followed the preliminary stage. Some site visits were conducted in an attempt to verify the existence of the geotextile separators and to check the subgrade soil conditions. When possible, inspectors who had observed the geotextile installation were contacted for further information.

Final site selection was based on (1) geotextile type and age; (2) verified installation location and condition wherever possible; (3) subgrade soil type; (4) base aggregate type; (5) consideration of safety and traffic control; (6) excavation costs; and (7) the likely cooperation of relevant maintenance districts and local agencies. A wide variety of geotextile types, weights, and ages was desirable.

Eight sites were ultimately selected for Phase I field investigations (Fig. 2). Their route numbers, geotextiles, WSDOT project names, and contract numbers are listed in Table 4.



NOTE
Map adapted from Washington State Highway Map, WSDOT, 1989 Edition.

Figure 2. Site Location Map (Eastern Washington)

Table 4. List of Investigated Sites in Phase I

Priority Ranking	State Route	Geotextile Type and Weight g/m^2 (oz/yd^2)	WSDOT Project Name or Location	WSDOT Contract No.
1	SR 395	Needle-punched NW (Supac 8NPUV) 143 (80)	Colville Vicinity	C-3331
2	SR 27	Woven Slit-film (Mirafi 500X) 136 (4)	Fallon to Palouse	C-2364
3	SR 195	Heat-bonded NW (- -) 118 (3.5)	SR 270 to Albion Road	C-2550
4	SR 195	Needle-punched NW (Supac 5NP) 180 (5.3)	Albion Road to Parvin Road	C-2290
5	I-90	Woven Slit-film (Mirafi 500X) 136 (4)	Ritzville to Tokio and Weigh Stations	C-3503
6	SR 20	Woven Slit-film (Amoco 2002) 153 (4.5)	Aeneas Valley to Wauconda Summit	C-3582
7	SR 173	Woven Slit-film (Mirafi 500X) 136 (4)	Rocky Butte to Bridgeport Bar	C-3057
8	SR 172	Woven Slit-film (Mirafi 500X) 136 (4)	SR 2/Farmer to 5NW Road	C-3369

Investigations began in April, 1990 at the Colville Vicinity site. Concern that base course and subgrade soils might still be frozen from the previous winter prevented researchers from beginning the project earlier in the year. However, no frozen soils were found in April, which indicated that the site investigations could have begun earlier.

Table 5 lists the sites selected and investigated in Phase II (see Fig. 3). Two sites were selected on Columbia Heights Road in Cowlitz County (Fig. 4), because this roadway was showing signs of premature failure in the form of localized fatigue cracking and minor rutting. One site (1a) was selected for investigation on the basis of its distressed pavement; the other site (1), was located in an adjacent area, but its pavement condition appeared to be good. Three sites were assigned priority rankings (5, 12, and 15), but were not investigated, therefore, they have been left out of Table 5. Site 5 was not excavated due to a lack of cooperation on the part of a local agency, and the subgrade soils under the separators at sites 12 and 15 consisted of imported rock backfill.

SITE INVESTIGATION PROCEDURES

Although the chief purpose of the site investigation was retrieval of the geotextile separator, the conditions of the pavement, base course, subgrade, and especially the geotextile, were also documented, in detail. The research team took field notes, made sketches, and took many photographs of each testpit, both before and during the investigation.

Phase II site investigation was based primarily on the procedures developed by Page (3) during Phase I; however, some modifications were made by Metcalfe (4) to expedite excavation and to obtain better information.

Researchers visited each site one day early to meet with maintenance personnel and to determine the best possible testpit location. In addition to traffic control and safety considerations, all testpits were located in the right-hand wheel path nearest the roadway shoulder. They were in or as close as possible to areas with a low subgrade modulus as determined by the FWD analyses or where very poor subgrade conditions were pointed

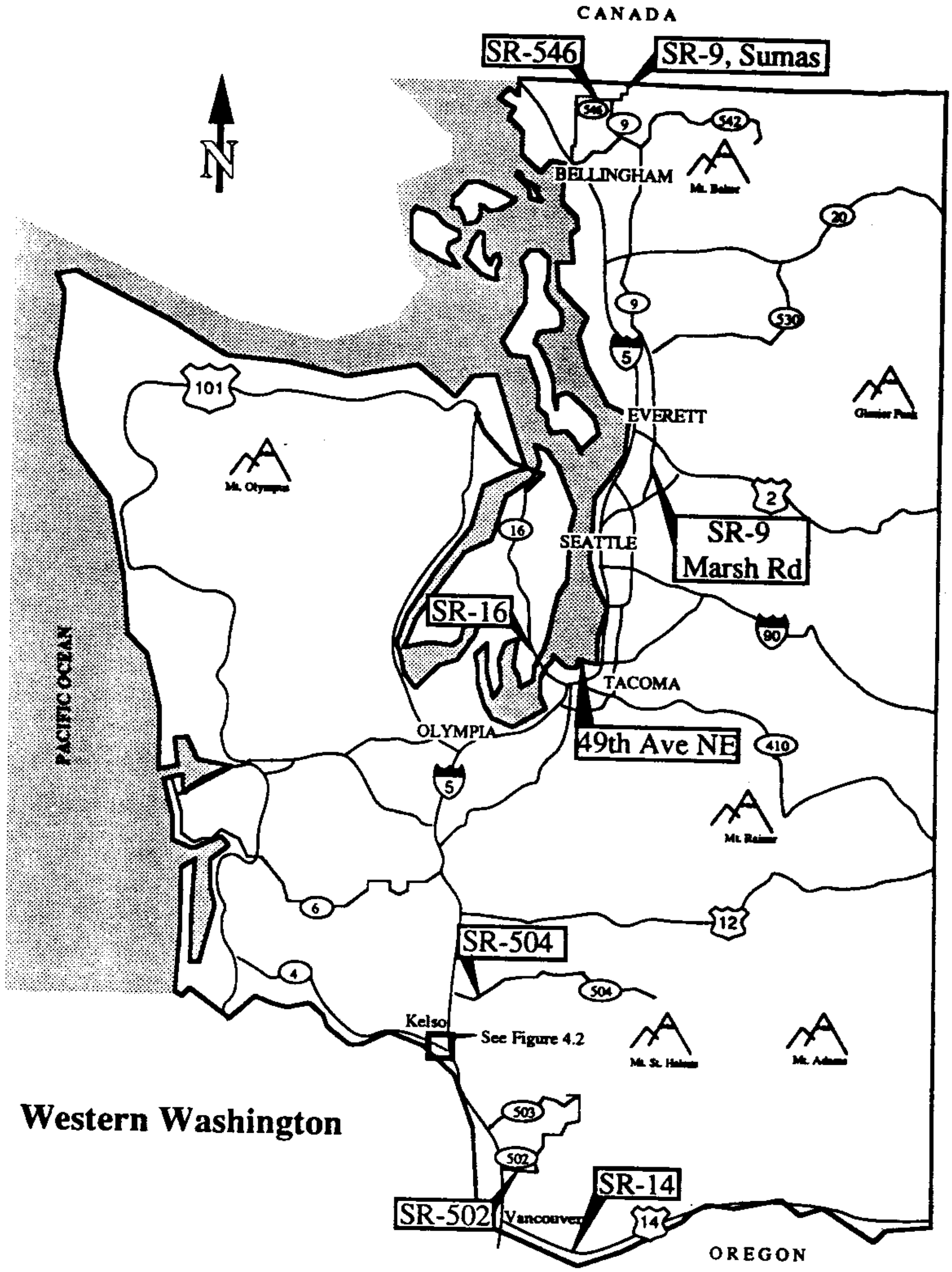


Figure 3. Site Location Map (Western Washington)

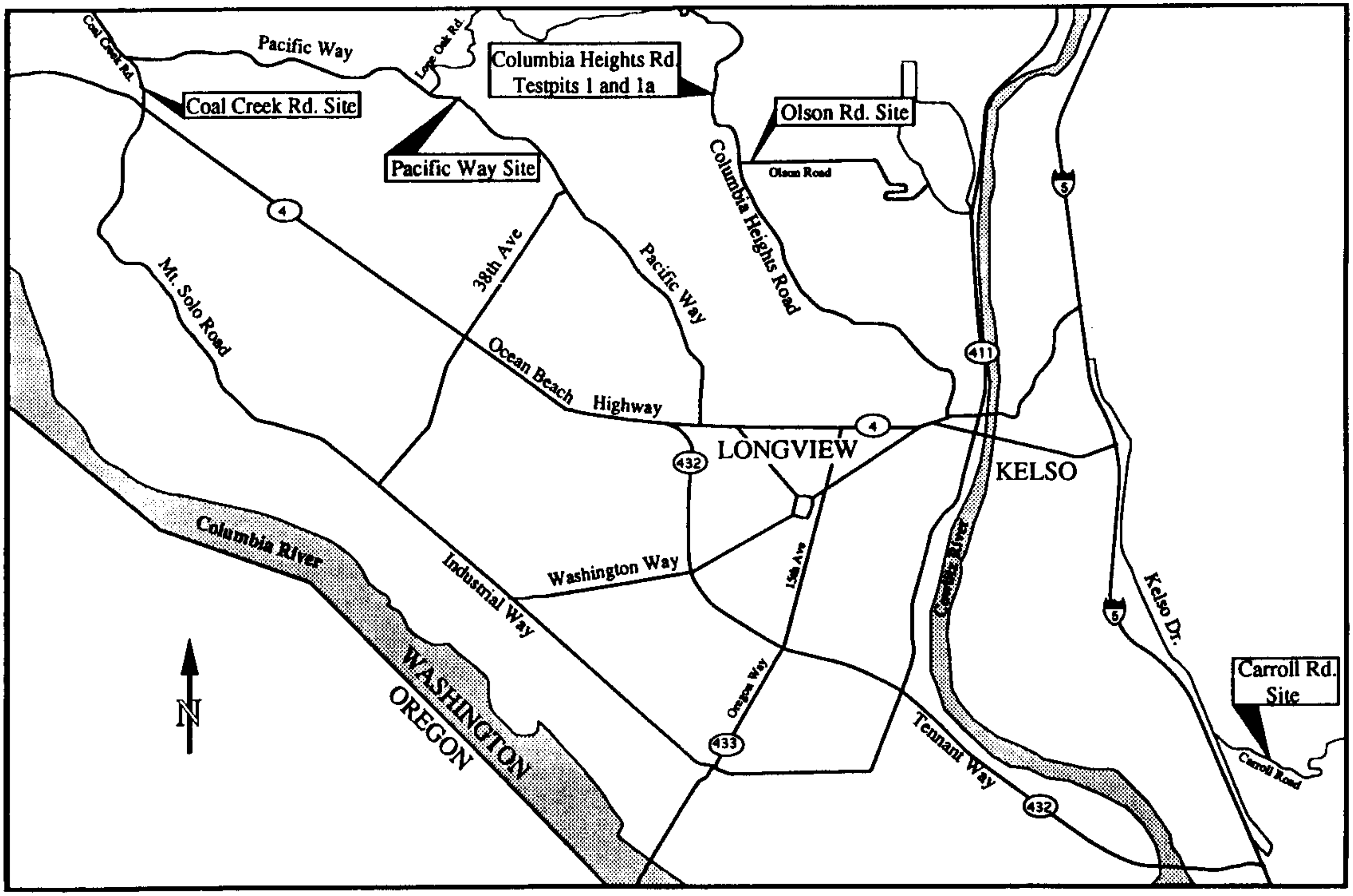


Figure 4. Cowlitz County and City of Kelso Site Locations

Table 5. List of Investigated Sites in Phase II

Priority Ranking	State Route or Roadway Name	Geotextile Type and Weight g/m^2 (oz/yd^2)	WSDOT Project Name or City/County Location	WSDOT Contract No.
1a	Columbia Heights Rd. (distressed pavement)	Needle-punched NW (Trevira 1114) 143 (4.2)	Cowlitz County	—
1	Columbia Heights Rd. (good pavement)	Needle-punched NW (Trevira 1114) 143 (4.2)	Cowlitz County	—
2	Coal Creek Rd.	Heat-bonded NW (Typar 3401) 136 (4.0)	Cowlitz County	—
3	Pacific Way	Needle-punched NW (Trevira 1115) 153 (4.5)	Cowlitz County	—
4	SR 14	Woven Slit-film (Exxon GTF 300) 231 (6.8)	SR 500 to Top of Steigerwald Hill	C-3821
6	SR 9 (Marsh Rd.)	Woven Slit-film (Permeatex 2350) 163 (4.8)	Lowell/Larimer Road to Snohomish River Bridge	C-3523
7	SR 546	Woven Slit-film (Propex 2002) 149 (4.4)	SR 539 to SR 9	C-3661
8	Carroll Rd.	Heat-bonded NW (Typar 3401) 136 (4.0)	City of Kelso	—
9	SR 504	Needle-punched NW (Trevira 1125) 251 (7.4)	Paine Road to Morgan Park	C-3279
10	49th Ave. NE	Woven Slit-film (Permeatex 2300) 153 (4.5)	City of Tacoma	—
11	SR 16	Woven Slit-film (Propex 2002) 149 (4.4)	Gig Harbor Olympic Interchange	C-3336
13	SR 502	Needle-punched NW (Trevira 1115) 153 (4.5)	NE 72nd Avenue Intersection	C-3062
14	Olson Rd.	Needle-punched NW (Trevira 1120) 204 (6.0)	Cowlitz County	—
16	SR 9 (Sumas)	Woven Slit-film (Permeatex 2200) 122 (3.6)	Bridge 9/360 to International Boundary	C-3254

out by the inspectors; in a few cases, very localized uses of the geotextile separator dictated testpit location. Once the best testpit location had been identified, white spray paint was used to mark the testpit's boundaries. Each testpit was rectangular, measuring approximately 1.2 m by 1.8 m.

After the first four sites in Phase I had been dug with the aid of a backhoe, Page (3) discovered that pneumatic or electric jack-hammers and hand shovels could excavate the testpits more quickly, precisely, and cheaply. Thus, the last five sites were excavated this way. However, where a meter or more of ballast had been placed and compacted over a geotextile in an over-excavation (as at the Rocky Butte site), a backhoe would have greatly expedited operations.

In Phase II, a few days before the excavation, maintenance personnel saw-cut along the marked limits of each testpit. (Maintenance supervisors, in every case, preferred saw-cuts to jack-hammer cuts in asphalt concrete pavements (ACP) because saw-cuts make for better patches.) On excavation day, a jack-hammer was used to break the saw-cut pavement up into manageable chunks for hand removal. Once the pavement had been removed, shovel excavation could be performed. The jack-hammer was also used to loosen densely compacted, angular, base courses which overlay some of the geotextile separators. Shovels alone worked best where the backfill consisted primarily of sandy materials.

At the Phase II sites in Cowlitz County, maintenance personnel suggested a different, and, as it turned out, much more effective way to excavate the base course materials. After removing the ACP and the top course at the Coal Creek Road site (Fig. 4), a very thick ballast material, up to 90 cm thick and consisting of 50 to 100 mm crushed angular basalt, was found over the geotextile. It would have been very difficult and time consuming to remove this material with normal excavation procedures because shovels were ineffective. The county maintenance supervisor opted to use an Elgin "Vac-all" to remove this material. Normally used to clean gutters and storm drains, this equipment consists of a large (about 250 mm diameter) semi-flexible suction tube connected to a truck-mounted container into which material is deposited. The Vac-all removed the backfill material very easily and rapidly. It was important to take care when operating the suction tube immediately above the geotextile to avoid damaging the geotextile and the possibility of sucking clogged subgrade material from between the yarns of the geotextile.

After the necessary tests had been performed and information gathered for the site, the maintenance crew backfilled the excavation by dumping the rock directly from the Vac-all back into the testpit. The Vac-all was again used at the Pacific Way and Olson Road sites (Fig. 4).

Because the geotextile was located approximately 1.1 m below the pavement surface at the SR 9 (Marsh Rd.) site (Fig. 3), the maintenance crew brought in a backhoe to remove the sandy base material.

Additional details on the site investigation procedures can be found in Page (3) and Metcalfe (4).

Summary of Phase I Site Investigation

Nine sites in eastern Washington were visited, and geotextile separators were found at eight. Of these eight sites, five were selected for study because the geotextile was placed directly over soft subgrade soil. At three sites where the geotextile was not placed directly on the subgrade soils, some information on construction damage, survivability, and retained strength was obtained. Table 6 contains a summary of the site conditions, based on both first-hand observations and on a review of construction records.

With the exception of the 118 g/m^2 product at the SR 270 to Albion Road site, all of the geotextiles performed well with regard to construction survivability. The 270 g/m^2 nonwoven needle-punched geotextile from the Colville Vicinity site survived remarkably well considering the very high survivability conditions under which it was installed. Minor puncture damage was observed in the following cases: in the 180 g/m^2 nonwoven

Table 6. Summary of Phase I Site Investigations

SR and Site Name	Installation Date	Geotextile Type and Weight g/m^2 (oz/yd^2)	Subgrade Material	Base Material	Initial Lift Thickness (cm)	Survivability Rating	Degree of Damage	Degree of Blinding or Clogging
SR 395 Colville Vicinity	10/87	Supac 8NPUV NP-NW 270 (8)	Sandy gravel fill	Crushed rock ballast	30-46	Very high	None	None
SR 27 Fallon to Palouse	9/83	Mirafi 500X W-SF 136 (4)	Clayey silt w/ trace gravel	CSBC	15	?	None	Severe
SR 195 SR 270 to Albion Rd.	10/83	Heat-bonded non-woven 118 (3.5)	Crushed rock fill	Crushed rock ballast	13-15	High	Severe	Minimal
SR 195 Albion Rd. to Parvin Rd.	9/85	Supac 5NP NP-NW 180 (5.3)	Clayey silt w/ occasional gravel	Crushed rock ballast	23	High	Moderate	Minimal
SR 90 Ritzville to Tokio	7/89	Mirafi 500X W-SF 136 (4)	Crushed rock fill	CSTC	15	Very high	Minimal	None
SR 20 Aeneas Valley to Wauconda Summit	6/89	Amoco 2002 W-SF 153 (4.5)	Silty sand	Crushed rock ballast	33	Moderate to High	Moderate	Minimal
SR 173 Rocky Butte to Bridgeport Bar	4/86	Mirafi 500X W-SF 136 (4)	Silty sand	Pit-run gravel	91	Moderate	None	Minimal
SR 172 SR2/Farmer to 5NW Road	7/88	Mirafi 500X W-SF 136 (4)	Sandy silt	CSTC	10	High	Minimal	Moderate

NP-NW = Needle-punched non-woven
W-SF = Woven slit-film

geotextile from the Albion Road to Parvin Road site, in the 153 g/m^2 woven geotextile from the Aeneas Valley site, and in the 136 g/m^2 geotextiles from the Ritzville to Tokio and SR 2 (Farmer to 5NW Road) sites. This minor damage appeared to be due to puncture by small stones, which were present in the subgrade. This damage did not appear to have significantly affected the geotextile's performance as a separator. As mentioned previously, the geotextile at the Ritzville to Tokio site was not functioning as a separator because it lay on a layer of crushed rock.

In terms of drainage and filtration, the woven geotextiles exhibited some blinding at the openings between filaments by silt and clay subgrade soils. This was most notable in the geotextile from the Fallon to Palouse site. The nonwoven geotextile from the Albion Road to Parvin Road site also showed signs of clogging; however, this geotextile still appeared to be draining adequately.

Summary of Phase II Site Investigations

Metcalfe (4) investigated 13 sites and excavated 14 testpits. Geotextile separators were recovered in all the testpits. The 14 geotextile separators retrieved consisted of six woven slit-films (122 g/m^2 to 231 g/m^2), six needle-punched nonwovens (143 g/m^2 to 251 g/m^2), and two heat-bonded nonwovens (136 g/m^2). Table 7 summarizes the geotextile types, their observed conditions, and installation conditions. This information is based on construction records and personal communications with relevant inspectors.

Seven of the 14 sites, summarized in Table 8, had subgrade conditions that were not ideal for an evaluation of long-term filtration characteristics. The geotextile separator at the site on SR 14, for example, was installed over a gravel and sand embankment fill; consequently, evaluations of filtration and drainage are not useful. Base material was mixed in with the subgrade soils at the sites on SR 546 and Carroll Road, and coarse gravel was found below part of the geotextile separator at the Olson Road site. At the site on SR 9 (Marsh Road), the geotextile was installed directly over native vegetation. Although this is normally good construction practice, it was not useful for long-term

Table 7. Summary of Phase II Geotextile Separator Installation Conditions and Observations

Site Name	Date Installed	Geotextile and Weight g/m^2 (oz/yd^2)	Subgrade Material	Basecourse Material	Initial Lift Thickness (cm)	Geotextile Damage
Columbia Hts. Rd. 1 and 1a	1990	NP-NW 143 (4.2)	Lean clay	CSBC	23	Moderate to Heavy (1a) Severe (1)
Coal Creek Rd.	1984	HB-NW 136 (4.0)	Wood debris and silt	Angular coarse gravel/cobbles	50 to 60	Heavy
Pacific Way	1982	NP-NW 153 (4.5)	Clayey sand	CSBC	33	Minor
SR 14	8/1990	W-SF 231 (6.8)	Gravel with sand	CSBC	15 to 18	Minor
SR 9 (Marsh Rd.)	8/1989	W-SF 163 (4.8)	Organics over silt	Sand with gravel	60	None
SR 546	9/1989	W-SF 149 (4.4)	Gravel with silt and sand	Sand with gravel	30	Minimal
Carroll Rd.	1978/79	HB-NW 136 (4.0)	Gravel with clay and sand	Angular coarse gravel/cobbles	23 to 33	Severe
SR 504	6/1988	NP-NW 251 (7.4)	Silt	Sand with gravel/cobbles	60	None
49th Ave. NE	11/1988	W-SF 153 (4.5)	Sandy silt	Sandy gravel	23 to 25	Moderate
SR 16	5/1988	W-SF 149 (4.4)	Lean clay	Sandy gravel	30	None
SR 502	6/1986	NP-NW 153 (4.5)	Lean clay	Sand with some gravel	30	None
Olson Rd.	1991	NP-NW 204 (6.0)	Silty sand	CSBC	23	Moderate
SR 9 (Sumas)	1987	W-SF 122 (3.6)	Silt and sand	Sand and gravel	18 to 20	Minor

NP-NW = Needle-punched non-woven
HB-NW = Heat-bonded non-woven
W-SF = Woven slit-film

Table 8. Sites With Unfavorable Subgrade Conditions

Site	Subgrade Condition
Coal Creek Road	Wood debris in the silt subgrade
SR 14	Sand and gravel
SR 9 (Marsh Rd.)	Vegetation matted down above the silt subgrade
SR 546	Base material intermixed in the subgrade
Carroll Road	Base material intermixed in the subgrade
49th Ave. NE	Utility trench sand backfill south half of excavation
Olson Road	Imported crushed rock below approximately 1/3 of geotextile

filtration evaluations, because of possible filtering effects of the vegetation. The recovered geotextile on Coal Creek Road was installed over an old timber holding area, and the large amount of wood debris found between the silt subgrade and the geotextile separator interfered with the long-term performance evaluations. Approximately one-half of the testpit at the 49th Ave NE site contained imported sandy backfill for a utility trench below the geotextile. Although the subgrade conditions for long-term filtration and drainage evaluations at all these sites were less than favorable, they are useful for assessing construction damage as a function of the subgrade, the base course, and construction practices.

All 14 sites were useful for studying the construction damage for each type of geotextile. The retained strength of the geotextiles could also be determined at all sites, except for Columbia Heights Road, where damage to the geotextile was so severe that it was impossible to collect an adequate number of test specimens for the grab and wide width tests. Geotextile separators at the four following sites showed no signs of construction damage: SR 9 (Marsh Road), SR 504, SR 16, and SR 502. Minimal or minor geotextile damage was observed at Pacific Way, SR 14, SR 546, and SR 9 (Sumas). Two geotextiles had moderate damage: 49th Avenue NE and Olson Road. The four remaining sites sustained the most damage, ranging from the moderate-to-heavy damage at Columbia Heights Road (testpit 1a) and at Coal Creek Road, to severe damage at Columbia Heights Road (testpit 1) and Carroll Road. Although the heat-bonded, nonwoven geotextiles experienced heavy damage, it should be remembered that they were installed under the highest survivability conditions.

Metcalfe (4) also examined the geotextiles for possible blinding/clogging and iron staining. He did not observe any heavy blinding on the woven geotextiles, although several were moderately blinded. The nonwoven geotextiles showed varying degrees of clogging, some of which appeared to be heavy-to-severe (Columbia Heights and Carroll Road). Several geotextile had moderate-to-heavy iron oxide deposits; those at the Columbia Heights Road sites were the heaviest. Geotextiles at three sites (SR 14, 49th Ave NE, and SR 16) showed signs of significant caking (see Fig. 1); fine-grained soil particles covered their upper surfaces.

Page (3) and Metcalfe (4) show color photographs of the site investigations, testpits, geotextile samples, and subgrades. Detailed descriptions of their field and laboratory observations and test data are also included.

DISCUSSION

ANALYSIS OF PHASE I RESULTS

Geotextile separators from eight sites in eastern and central Washington were evaluated as part of the Phase I study. (3) The resulting data yielded information on retained strength, retained permittivity, and survivability, as well as general observations on the performance of the geotextiles. The geotextile separators were installed directly over imported gravel fills at three of the sites; thus, these sites were useful only for evaluating survivability conditions and construction damage. Table 6 summarizes the Phase I sites, installation conditions, and damage and clogging estimates.

All of the pavement surfaces studied appeared to be in good condition, with no signs of premature failure. All of the geotextiles apparently performed the separation function adequately, even though three of them had not been installed properly. All appeared to have survived construction reasonably well, although several had minor-to-moderate damage, mainly in the form of punctures. Page (3) noted that "there is no evidence that the presence of moderate construction damage to the geotextile separator significantly affected the performance of the roadway."

Based on the severe damage sustained by the 118 g/m^2 heat-bonded nonwoven geotextile from the SR-270 to Albion Rd. site, Page (3) concluded that a lightweight, nonwoven geotextile should not be used in any separator application, regardless of the subgrade material or the initial base course lift thickness. He also stated that the use of a relatively heavy geotextile, 270 g/m^2 or more, which meets the high survivability strength criteria with a high grab elongation will help minimize damage to the geotextile that may occur during construction. The results of the Phase I laboratory strength tests are summarized in Table 9.

Table 9. Summary of the Phase I Index Strength Test Results

Site Name	Grab Tensile %	Trapezoidal Tear %	Puncture %	Burst %	Average % Retained Strength
Colville Vicinity	80	99	100	99	95
Fallon to Palouse	87	61	100	81	82
SR 270 to Albion		Severe damage — no tests performed			
Albion to Parvin	100	100	100	66	92
Ritzville to Tokio	76	41	100	67	72
Aeneas Valley	38	29	73	41	45
Rocky Butte	100	96	100	99	99
SR2/Farmer	62	61	100	63	72

Most of the sites that Page evaluated showed only small increases in the fines content of the base material immediately above the geotextile separator. Fines migration up through the geotextiles was probably not a significant problem at the eastern Washington sites.

Page (3) also evaluated the geotextile separators with respect to blinding or clogging, concluding that woven slit-film geotextiles "would be adequate for separation applications over most subgrade soils; however, they tend to become blinded more readily than nonwovens when used over clayey silt subgrades." This conclusion was based on the results from one site, Fallon to Palouse, and it was the only woven slit-film installed over a clayey silt subgrade. Page conducted no permittivity tests on three of the woven slit-films because the "geotextile was clean in-situ." The woven slit-film from the Fallon to Palouse site had many iron-oxide deposits adhering to it; these deposits acted as a binder that held the clay and silt particles together and to the geotextile. This was interpreted as clogging.

Page (3) compared his washed permittivity values to the manufacturers' values and reported the percentage of permittivity retained. All of the geotextiles retained more than 67 percent of their published permittivity values. But when the unwashed test results were compared with the washed results, the Fallon to Palouse site showed a 1,950 percent increase in permittivity. All of the other sites had washed permittivity increases of less than 70 percent. Subsequent runs in the unwashed tests from the woven slit-film geotextile from the Aeneas Valley to Wauconda Summit site also showed permittivity increases of 71 and 153 percent. Page concluded that "for the woven slit-film geotextiles, only a small amount of contamination of the material by fine-grained soil particles is required to cause a significant drop in permittivity." However, even blinding or clogging during the separation process were not shown to diminish the pavement performance.

Table 10 summarizes Phase I permittivity test results. The table is based on unwashed and washed test results, which were used to determine percentage increases in permittivity (manufacturers' and WSDOT values were not used). The permittivity of each successive run tended to increase in the case of the unwashed tests; this was due to the cleansing of the geotextile. Therefore, in Table 10, unwashed first test runs are compared with the corresponding averaged washed test results.

Because of the susceptibility of some geotextiles to blinding and/or clogging by fine-grained soil particles, the potential decrease in geotextile permeability should be considered. Provided they were not severely damaged during construction, all separators seemed to be adequately performing their intended function, even though some had sustained varying degrees of damage. The pavements were performing well at all of the sites investigated in Phase I.

ANALYSIS OF PHASE II RESULTS

In Phase II, 14 geotextile separators were recovered from testpits at 13 sites in western Washington. The geotextiles consisted of six woven slit-films (122 to 231 g/m^2), six needle-punched nonwovens (143 to 251 g/m^2), and two heat-bonded nonwovens (136 g/m^2). Tables 5 and 7 summarize the geotextile types and installation conditions. Information on survivability, filtration, and drainage was obtained, as described in detail by Metcalfe (4). Although the study focused on the separators' short-term (survivability)

Table 10. Summary of Phase I Permittivity Test Results

SR and Site Name	Geotextile Type and Weight g/m² (oz/yd²)	Sample	Unwashed Permittivity Ψ 1st Run	Average Washed Permittivity Ψ	Permittivity Increase %
SR 395 Colville Vicinity	Supac 8NPUV NP-NW 270 g/m² (8 oz/yd²)	1	1.07	***0.96***	***0***
		2	0.93	-	-
		3	1.31	***1.13***	***0***
SR 27 Fallon to Palouse	Mirafi 500X W-SF (4 oz/yd²)	1	0.030	0.67	2133
		2	0.021	0.10	376
		3	0.0089	0.45	4956
SR 195 SR 270 to Albion Rd.	Heat-bonded non-woven (3.5 oz/yd²)	Severe damage — no tests performed			
SR 195 Albion Rd. to Parvin Rd.	Supac 5NP NP-NW (5.3 oz/yd²)	1	0.310	damaged	-
		2	0.4319	0.872	102
		3	0.4576	0.618	35
SR 90 Ritzville to Tokio	Mirafi 500X W-SF (4 oz/yd²)	1	0.589	***0.743***	***26***
		2	0.665	***0.778***	***17***
		3	0.638	***0.585***	***0***
SR 20 Aeneas Valley to Wauconda Summit	Amoco 2002 W-SF (4.5 oz/yd²)	1	0.313	***0.344***	***10***
		2	0.013	***0.033***	***154***
		3	0.021	***0.036***	***71***
SR 173 Rocky Butte to Bridgeport Bar	Mirafi 500X W-SF (4 oz/yd²)	1	0.1004	***0.1088***	***8***
		2	0.0791	***0.0861***	***9***
		3	0.0507	***0.0504***	***0***
SR 172 SR2/Farmer to 5NW Rd.	Mirafi 500X W-SF (4 oz/yd²)	1	0.0968	0.136	41
		2	0.0652	0.095	46
		3	0.0744	0.096	29

Italic = Indicates no washed tests were performed because samples appeared to be clean.
The indicated values are from the ***last recorded unwashed run*** for each test.

NP-NW = Needle-punched non-woven

W-SF = Woven slit-film

and long-term (filtration/drainage) performance and their effects on long-term pavement performance, subgrade conditions and geotextile durability are also discussed.

Subgrade Conditions

The subgrades at all the sites except SR 502 were supposed to consist of soft silts and clays. The SR 502 site reportedly had silty soils, but no unusually bad conditions during construction. Although all the subgrades consisting of silt and/or clay were soft during construction, they were well consolidated at the time of the site investigations. No high water table levels were encountered in any of the testpits.

Some sites had subgrade conditions that were less than ideal for evaluating long-term geotextile performance (Table 8). For example, the subgrade in testpit 1, on Columbia Heights Road, was obviously soft during construction. Large ruts in the subgrade and "mushroomed" clay intrusions into the base course through rips in the geotextile suggested that poor subgrade conditions existed during construction (see Figs. 5.10 through 5.13 in Metcalfe (4)). However, the subgrade had consolidated with time, so that three years after construction, the subgrade unconfined strength (according to a pocket penetrometer) was generally greater than 400 kPa.

Although base material was mixed in with the subgrade soil at Carroll Road, this site had a history of poor performance prior to installation of the geotextile separator. Apparently, the additional aggregate that had been added to the unpaved roadway became contaminated with fines from the subgrade. This situation persisted until the separator was installed and the roadway paved. The separator may have aided in the consolidation of the subgrade, while preventing further subgrade soil intrusion into the base material. Paving the surface would reduce any adverse climatic effects such as rainfall or humidity. Similar conditions were encountered at the SR 546 site.

The consolidated condition of the subgrades may have been due to (1) the time of year at which they were excavated (a dry period), (2) the overburden pressure from the roadway, (3) surface water drainage away from the roadway, (4) decreased rainfall infiltration due to the paved surface, or (5) any combination of these reasons.

Survivability

The subgrade, base, initial lift thickness, and construction equipment used (if known) for all the sites in Phase II are summarized in Table 7. Task Force 25 guidelines (1) were used to assess the survivability conditions at each site at the time of construction (Table 1). The estimated survivability levels are shown in Table 11, along with most of the construction information from Table 7.

As shown in Table 11, the only site with a survivability level rated "not recommended" was the one on Carroll Road. There was angular crushed rock in the subgrade at this site; a relatively thin vibratory compacted initial lift was used; and trucks dumped large angular base material directly onto the geotextile. While placing the initial lift, trucks were allowed to drive directly on top of the geotextile without any protective cover. The contractor at the Coal Creek Road site (estimated high survivability rating) also end-dumped large crushed rock directly onto the geotextile, but very thick initial lifts were used, and the subgrade consisted of organic debris. The other sites with high estimated survivability ratings were the Columbia Heights Road, SR 14, and Olson Road sites. The Columbia Heights Road site might actually have had a very high, or "not recommended," survivability condition because of the rutting found in testpit 1 and relatively thin compacted initial lifts. All the other sites were rated at medium survivability because of their thick initial lifts, rounded backfill material, and/or higher initial subgrade strengths.

Damage

Although the various separators sustained widely divergent degrees of damage, there were no real surprises when the survivability conditions were taken into account. A damage survey was performed on each of the recovered geotextiles; Metcalfe described the results in detail. (4) Punctures constituted most of the damage to the geotextiles; they

Table 11. Summary of Survivability Levels (Task Force 25, 1989), Installation Conditions, and Geotextile Damage

Site Name	Geotextile and Weight g/m^2 (oz/yd^2)	Subgrade Material	Basecourse Material	Initial Lift Thickness (cm)	Geotextile Damage	Estimated Survivability Level
Columbia Hts. Rd. (testpit 1a)	NP-NW 143 (4.2)	Lean clay	CSBC	23	Moderate to Heavy	High
Columbia Hts. Rd. (testpit 1)	NP-NW 143 (4.2)	Lean clay	CSBC	23	Severe	High
Coal Creek Rd.	HB-NW 136 (4.0)	Wood debris and silt	Angular coarse gravel/cobbles	50 to 60	Heavy	High
Pacific Way	NP-NW 153 (4.5)	Clayey sand	CSBC	33	Minor	Medium
SR 14	W-SF 231 (6.8)	Gravel with sand	CSBC	15 to 18	Minor	High
SR 9 (Marsh Rd.)	W-SF 163 (4.8)	Organics over silt	Sand with gravel	60	None	Medium
SR 546	W-SF 149 (4.4)	Gravel with silt and sand	Sand with gravel	30	Minimal	Medium
Carroll Rd.	HB-NW 136 (4.0)	Gravel with clay and sand	Angular coarse gravel/cobbles	23 to 33	Severe	Not Recommended
SR 504	NP-NW 251 (7.4)	Silt	Sand with gravel/cobbles	60	None	Medium
49th Ave. NE	W-SF 153 (4.5)	Sandy silt	Sandy gravel	23 to 25	Moderate	Medium
SR 16	W-SF 149 (4.4)	Lean clay	Sandy gravel	30	None	Medium
SR 502	NP-NW 153 (4.5)	Lean clay	Sand with some gravel	30	None	Medium
Olson Rd.	NP-NW 204 (6.0)	Silty sand	CSBC	23	Moderate	High
SR 9 (Sumas)	W-SF 122 (3.6)	Silt and sand	Sand and gravel	18 to 20	Minor	Medium

NP-NW = Needle punched non-woven
HB-NW = Heat-bonded non-woven
W-SF = Woven slit-film

were due to base aggregate penetration into the subgrade, and/or to the penetration of angular gravels in the subgrade up into the base material.

The only heavier weight separators (>200 g/m^2) installed under high survivability conditions were at the SR 14 (231 g/m^2 woven slit-film) and Olson Road (204 g/m^2 needle-punched nonwoven) sites. The separator at SR 14 sustained minor damage; the Olson Road site sustained moderate damage. The four lighter weight geotextiles (<150 g/m^2), installed under high and "not recommended" survivability conditions, sustained moderate to severe damage. This finding suggests that (1) separators with weights under 240 g/m^2 installed under high survivability conditions will sustain some damage, and (2) that separators with weights of under 200 g/m^2 should not be used at all in high survivability conditions.

Retained Strength

Figure 5 shows the percentage of retained grab tensile strength as a function of the percentage of hole area for the 13 geotextiles tested. As expected, the retained strength decreased as damage increased. Because the data were plotted on a semi-log graph, the zero percent hole area was assigned to the 0.001 logarithmic value for presentation purposes.

The results in Figure 5 are similar to those of Koerner and Koerner (6, 7), although they plotted their results as a function of the number of holes greater than 6 mm, rather than as the percentage of hole area. Thus, a hole 30 mm in diameter would have the same credit as a hole 6 mm in diameter. It is more meaningful to plot the percentage of retained strength as a function of the percentage of hole area of each geotextile.

It is interesting to note that, of the four geotextiles that did not sustain any damage, the two woven geotextiles had higher percentages of retained strengths than the two needle-punched nonwoven geotextiles. Although the heat-bonded nonwovens had the highest percentage of hole areas, the geotextile from the Coal Creek Road site had a reasonable retained strength. This finding could be due in part to the fact that most of the

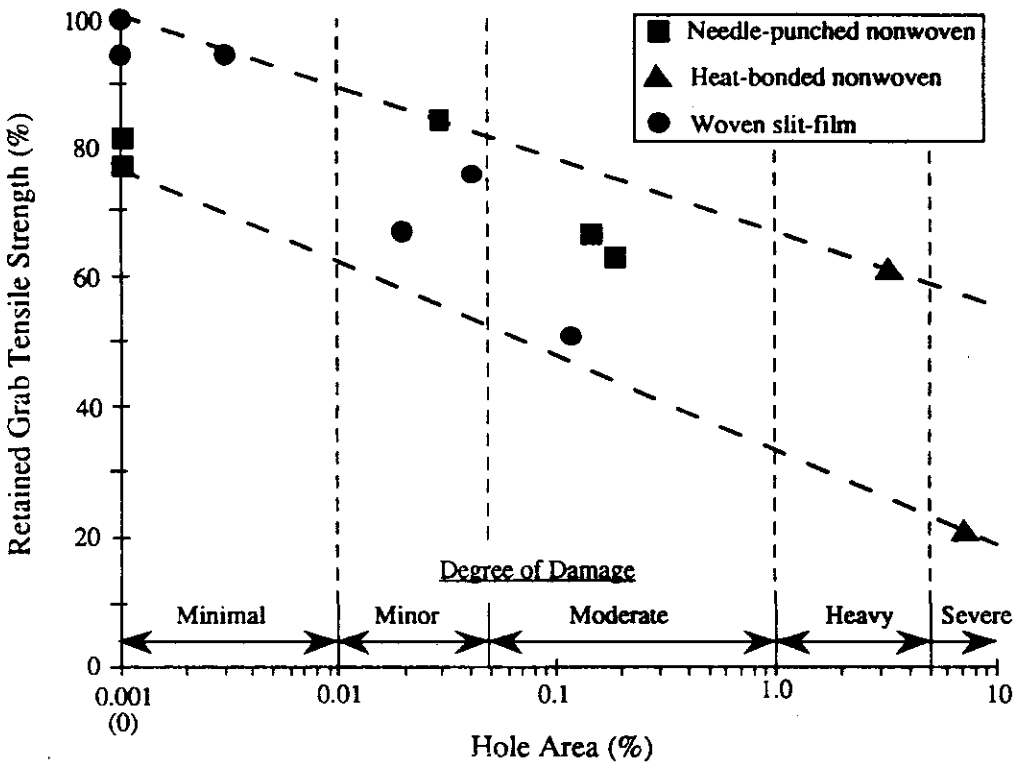


Figure 5. Percent Retained Strength vs. Percent Hole Area

holes in the geotextile were quite large, and tensile test specimens were not taken in those areas. The geotextile from the Carroll Road site had numerous, very uniform holes, and its retained strength values are quite indicative of its present condition.

The average percentage of retained strength for each geotextile was also plotted as a function of geotextile type (see Fig. 6). Although the retained strength values for the needle-punched nonwovens and the woven slit-films are somewhat similar, the woven geotextiles had the three highest retained strengths. Also shown are the two low retained strength values for the heat-bonded geotextiles. Estimated survivability levels for each site at the time of installation (Table 11) must also be taken into account when the short-term performance of the geotextiles are assessed.

Of the seven geotextiles with retained strengths in excess of 70 percent, six were installed under rounded to sub-rounded base materials. The only exception was the geotextile recovered from the Pacific Way site. Even the geotextiles from SR 546 (which had gravel in the subgrade) and from SR 9 at Sumas (which had a thin initial lift) still retained a relatively high percentage of their strength. However, all the sites that had angular aggregate placed on the geotextile also had the thinner initial lifts. In any event, this suggests that although base aggregate type is more important than initial lift thickness, both properties must be taken into account. Paulson's conclusions (8) are similar.

Filtration/Drainage

Washed Permittivity Test Results

Laboratory permittivity tests were conducted to assess the general blinding/ clogging characteristics of the recovered geotextiles. Figure 7 shows the results of the permittivity tests as a percentage of permittivity increase after washing according to geotextile type. The needle-punched nonwovens and the woven slit-films performed similarly. The two needle-punched nonwovens with the greatest increases in washed permittivity were from the SR 502 and Olson Road sites. The SR 502 geotextile was

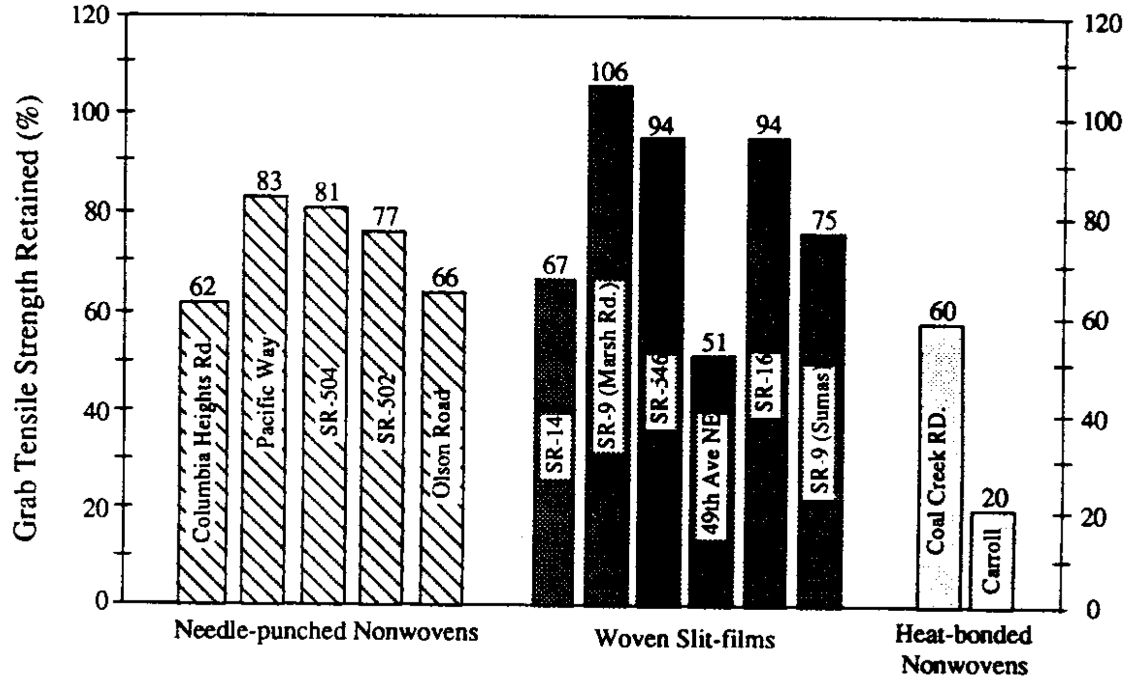


Figure 6. Percent Strength Retained vs. Geotextile Type

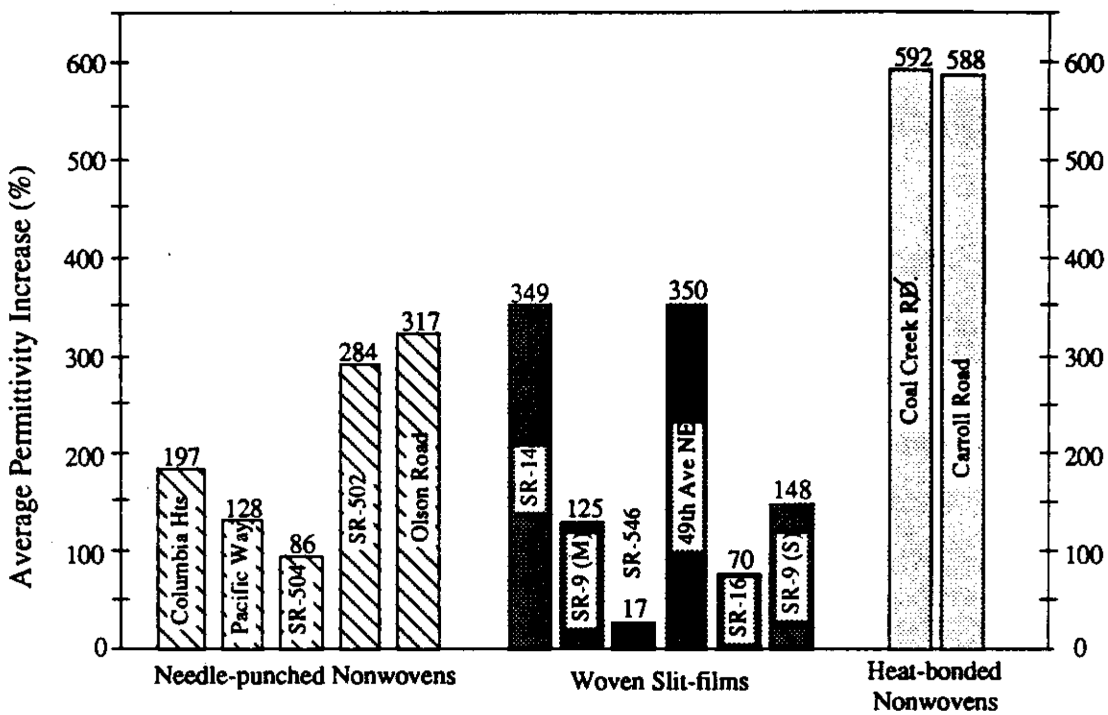


Figure 7. Average Percentage Permittivity Increase (after washing) vs. GeotextileType

installed over a lean clay subgrade. The geotextile at the Olson Road site was installed over a silty sand subgrade. The woven geotextiles with the greatest washed permittivity increases experienced significant caking. Both of the heat-bonded nonwovens showed the highest increases in washed permittivity. Even the heat-bonded geotextiles overlying the organic debris at Coal Creek Road had a high increase in washed permittivity. This indicates that the heat-bonded nonwovens are more susceptible to clogging than are other geotextiles.

Blinding/Clogging

Although the woven slit-films and needle-punched nonwoven geotextiles had similar average percentage increases (see Fig. 7), the wovens had smaller increases because they had been disturbed the most prior to testing. Observations indicated that the wovens were most susceptible to blinding. However, after the wovens had been exhumed, but prior to testing, a good portion of the blinded particles (generally silt) fell off the geotextile, especially after even a small amount of drying. Additionally, the mere act of removing the woven slit-films from the subgrade probably stripped many of the blinded particles away from the geotextile. As for clogging, the needle-punched nonwovens were the most susceptible. Little material was lost while handling these geotextiles, because the soil particles were embedded within the geotextile fibers. Thus, the permittivity values of the needle-punched nonwovens were probably good indicators of their undisturbed hydraulic characteristics. On the other hand, the permittivity values for the woven slit-films were only indicative of the material that remained on the geotextile after sampling and handling. Thus, small pore-space reductions (by blinding, clogging, or caking) can significantly decrease the permeability of the woven slit-film geotextiles to a value well below WSDOT's required minimum of 0.04 cm/s.

Page's Phase I conclusions (3) with respect to woven slit-film blinding are similar. One woven slit-film (Fallon to Palouse) was severely blinded with fine soil particles (see Table 9). This geotextile had washed permittivity increases approaching 5,000 percent, and the average washed permittivity increase for the three tests was close to 2,000 percent.

Generally, the nonwoven geotextiles clogged, rather than blinded. Some of the needle-punched geotextiles appeared to be moderately to severely clogged (e.g., Columbia Heights Road, Carroll Road, SR 504, and Olson Road). However, the needle-punched nonwovens had washed permittivity increases of around 300 percent or less, and the permeabilities of the geotextiles were still quite high. The two heat-bonded nonwovens appeared to be the most susceptible to detrimental clogging because of the higher washed permittivity increases (almost 600 percent), and the fact that their permeabilities were lower to begin with.

Geotextile clogging occurred at the contact points of the base aggregate and the subgrade at the Carroll Road and Olson Road sites. In several instances there were clean or relatively clean spots on the geotextile between the aggregate and soil contact points. At the Olson Road site, the clean spots occurred where the geotextile bridged across some of the large rocks on the subgrade surface, thus preventing contact with the subgrade soils.

Caking

Caking on the upper surface of woven slit-film geotextiles was significant at three sites: SR 14, 49th Ave NE, and SR 16. Laboratory observations revealed the blinding and caking results shown in Table 12.

Table 12. Blinding and Caking Results

Site	Blinding (%)	Caking (%)
SR 14	10 to 30	50 to 75
49th Avenue NE	25 to 50	40 to 50
SR 16	0 to 10	25 to 50

The permittivity results indicated that caking also prevented water flow through the pores. This occurred despite the fact that the geotextiles were placed in the permeater so as to simulate upward flow from the subgrade through the geotextile. Test results indicated that both blinding (as well as clogging) and caking can diminish woven slit-film permittivity.

The grain size analyses did not indicate conclusively that subgrade fines had migrated up through the geotextile separators at any of the sites. However, the grain size analyses for four of the sites did indicate small increases in the fines content in the base material immediately above the geotextile. Although significant caking was discovered on the surface of three woven slit-film geotextiles, there was no conclusive evidence that migration of subgrade fines had caused the caking. Two of the sites that had significant caking, SR 14 and SR 16, also had higher fines content in the base material immediately above the separator. The fines may have been deposited on the geotextile surface during construction. Rathmayer (9) also noted fines on top of geotextiles during field investigations. Laier and Brau (10) and Tsai et al. (11) found evidence of fines migration up through woven slit-film geotextiles in their studies. Although there was no conclusive evidence, the possibility that the caking observed on the woven slit-films was due to subgrade fines migration up through the woven geotextiles (due to their larger pore openings) cannot be ruled out.

Although the subgrade soils at the SR 14 site consisted of gravel with sands, it was gap-graded, with 13 percent passing the No. 200 sieve. Carroll (12) found that gap-graded soils are susceptible to piping, which can lead to geotextile clogging. However, the pores in woven slit-films may be too large to prevent soils from passing through them as piping occurs. The fines could then be deposited on the geotextile surface.

Iron Staining

Iron staining was prevalent at several of the sites, as indicated by Metcalfe. (4) It was most obvious and more widespread on the needle-punched geotextiles (e.g., at Columbia Heights Road, Pacific Way, and SR 502). Although the needle-punched geotextiles may appear to suffer greater reductions in permittivity because of widespread staining, they probably do not. This is because the needle-punched nonwoven geotextiles have more pore spaces in their three-dimensional structure—the iron stains appear to be just "decoloration" on and within the geotextiles—they do not indicate significant pore volume reduction. However, the iron stains on the woven slit-film geotextile (SR 9 at Marsh Road and SR 9 in Sumas) were actually iron deposits, which could generally be found around or even covering the pore openings. Although the impact of iron staining on geotextile permeability was not assessed in this study, observations indicate that woven slit-films would be the most heavily impacted.

Task Force 25 (1) and FHWA (2, 5) Filter Design Criteria

Table 13 is a summary of subgrade and geotextile data collected from all 22 sites, as well as an evaluation of how well the geotextile used met Task Force 25 (1) and FHWA (2, 5) filter design criteria. (The two Columbia Heights sites are combined in this table.) The AOS values in Table 13 were obtained from WSDOT compliance test results, if available. The remaining few were obtained from manufacturers' published data.

Four sites, all with woven slit-films, failed the TF25 AOS (retention) criteria, while an additional three sites failed the FHWA AOS criteria. One of these latter sites had a heat bonded and two used needle-punched nonwovens. The permeability criteria was satisfactory in all but three cases, and these three were on coarse granular subgrades using two slit-films and one heat-bonded geotextile.

There is some question as to whether the maximum allowable AOS value for fine grained soils could be increased. After all, even though several geotextiles failed the TF 25 and FHWA criteria, the geotextiles worked well as filters and separators--there was no

Table 13. Subgrade and Geotextile Characteristics vs. Filtration Design Criteria

SR and Site Name	Installation Date	Geotextile Type and Weight g/m^2 (oz/yd^2)	Subgrade Material	Percent Pass No. 200	D_{85} (mm)	Est. k (cm/s)	AOS (mm)	Required AOS TF 25	Required AOS FHWA	$k_{geotextile}$
SR 395 Colville Vicinity	10/87	NP-NW 270 (8)	Sandy gravel fill	7	11	10^{-2}	0.22	<0.6 OK	<11 OK	10^{-1} OK
SR 27 Fallon to Palouse	9/83	W-SF 136 (4)	Clayey silt w/trace gravel	85	0.08	$<10^{-7}$	0.35	<0.3 NG	<0.08 NG	10^{-3} OK
SR 195 SR 270 to Albion Rd.	10/83	HP-NW 118 (3.5)	Crushed rock fill	9	8	10^{-2}	0.25	<0.6 OK	<8 OK	10^{-2} OK
SR 195 Albion Rd. to Parvin Rd.	9/85	NP-NW 180 (5.3)	Clayey silt w/ occasional gravel	41	12	10^{-6}	0.20	<0.6 OK	<12 OK	10^{-1} OK
SR 90 Ritzville to Tokio	7/89	W-SF 136 (4)	Crushed rock fill	12	2	10^{-5}	0.42	<0.6 OK	<2 OK	10^{-3} OK
SR 20 Aeneas Valley to Wauconda Summit	6/89	W-SF 153 (4.5)	Silty sand	29	5.5	10^{-5}	0.20	<0.6 OK	<5.5 OK	10^{-3} OK
SR 173 Rocky Butte to Bridgeport Bar	4/86	W-SF 136 (4)	Silty sand	20	0.33	$<10^{-4}$	0.42	<0.6 OK	<0.4 ~OK	10^{-3} OK
SR 172 SR2/Farmer to 5NW Road	7/88	W-SF 136 (4)	Sandy silt	63	0.8	$<10^{-6}$	0.40	<0.3 NG	<0.3 NG	10^{-3} OK
Columbia Hts Rd. 1 and 1a	1990	NP-NW 143 (4.2)	Lean clay	95	0.05	$<10^{-7}$	0.3	<0.3 ~OK	<0.09 NG	10^{-1} OK
Coal Creek Rd.	1984	HB-NW 136 (4.0)	Wood debris and silt	84	0.08	10^{-5}	0.21	<0.3 OK	<0.14 NG	10^{-2} OK

NP-NW = Needle-punched nonwoven
HB-NW=Heat-bonded nonwoven
W-SF = Woven slit-film

Table 13. Subgrade and Geotextile Characteristics vs. Filtration Design Criteria (continued)

SR and Site Name	Installation Date	Geotextile Type and Weight g/m^2 (oz/yd^2)	Subgrade Material	Percent Pass No. 200	D_{85} (mm)	Est. k (cm/s)	AOS (mm)	Required AOS: TF 25	Required AOS: FHWA	$k_{geotextile}$
Pacific Way	1982	NP-NW 153 (4.5)	Clayey sand	49	0.2	10^{-5}	0.21	<0.6 OK	<0.2 ~OK	10^{-1} OK
SR 14	8/1990	W-SF 231 (6.8)	Gravel with sand	13	38	$<10^{-2}$	0.4	<0.6 OK	<38 OK	10^{-3} ?
SR 9 (Marsh Rd.)	8/1989	W-SF 163 (4.8)	Organics over silt	56	0.3	10^{-5}	0.33	<0.3 ~OK	<0.3 ~OK	10^{-3} OK
SR 546	9/1989	W-SF 149 (4.4)	Gravel with silt and sand	10	38	10^{-2}	0.41	<0.6 OK	<38 OK	10^{-3} NG
Carroll Rd.	1978/79	HB-NW 136 (4.0)	Gravel with clay and sand	8	38	10^{-2}	0.21	<0.6 OK	<38 OK	10^{-2} ?
SR 504	6/1988	NP-NW 251 (7.4)	Silt	96	0.054	$<10^{-5}$	0.21	<0.3 OK	<0.1 NG	10^{-1} OK
49th Ave. NE	11/1988	W-SF 153 (4.5)	Sandy silt	56	0.85	10^{-5}	0.26	<0.3 OK	<0.3 OK	10^{-3} OK
SR 16	5/1988	W-SF 149 (4.4)	Lean clay	98	0.04	$<10^{-7}$	0.6	<0.3 NG	<0.04 NG	10^{-3} OK
SR 502	6/1986	NP-NW 153 (4.5)	Lean clay	65	0.21	10^{-7}	0.21	<0.3 OK	<0.3 OK	10^{-1} OK
Olson Rd.	1991	NP-NW 204 (6.0)	Silty sand	26	10	10^{-4}	0.21	<0.6 OK	<10 OK	10^{-1} OK
SR 9 (Sumas)	1987	W-SF 122 (3.6)	Silt and sand	59	0.14	10^{-5}	0.85	<0.3 NG	<0.14 NG	10^{-3} OK

NP-NW = Needle-punched nonwoven
HB-NW=Heat-bonded nonwoven
W-SF = Woven slit-film

evidence of significant fines migration into the base course. Thus, the geotextile filter retention criterion for fine grained subgrades is possibly too restrictive and could be relaxed (i.e., the AOS increased) somewhat. On the other hand, increasing the AOS too much could lead to increased base course contamination and pavement failures. As noted in the Conclusions for Phase II, Metcalfe (4) believes that the maximum allowable AOS should be kept at 0.3 mm for all geotextiles on fine grained subgrades in western Washington. This point requires further consideration and study.

Durability

Although assessment of geotextile durability was not a study objective, the research team made a few observations on the durability of the recovered geotextiles. In general, all the geotextiles appeared to have performed well, with no indications of chemical or biological degradation. The iron staining on several of the geotextiles did not appear to have affected their strength. However, it would be difficult to distinguish these effects from mechanical damage.

The two undamaged needle-punched nonwovens (SR 504 and SR 502) had significantly lower retained strength values than did the two undamaged woven slit-films (Figs. 5 and 6). The two needle-punched nonwovens were composed of polyester fibers; the two woven geotextiles had polypropylene slit tapes. Hydrolysis may have lowered the retained strength values for the two nonwoven polyester geotextiles. Although there was no standing water on the subgrade surface in the testpit, the geotextile from the SE 504 site was very wet when uncovered. The SR 502 site was moist, but not wet. The geotextile from the SR 502 site had significant iron staining on the bottom surface, while the iron staining on the geotextile from the SR 504 site was negligible. On the other hand, the two woven slit-film polypropylene geotextiles had significantly lower retained elongations at break, which may indicate potential brittle behavior with film.

Separation

All of the recovered geotextiles appeared to have performed their intended separation function well. With the possible exception of the three woven slit-films, which had significant upper surface caking, no subgrade fines migration was found at any of the sites. Even the most heavily damaged geotextiles (e.g., Columbia Heights Road and Carroll Road) still separated the subgrade fines from the overlying base aggregate.

The clay intrusions found in testpit I on Columbia Heights Road were the result of subgrade soils pumping up through large tears in the needle-punched nonwoven geotextile. These intrusions were not caused by fines migration through the geotextile or through geotextile punctures. During construction, rutting overstressed the geotextile to the point at which the deformations exceeded its elongation potential. Therefore, it ripped in several areas. The clayey subgrade soils were then able to penetrate up through the tears under the pumping action caused by the wheels of the construction equipment. The clay intrusions then consolidated on top of the separator. There was no evidence of fines migration in the areas between tears.

Although the heat-bonded nonwoven geotextile from the Carroll Road site was severely damaged, it nonetheless separated the subgrade soils from the base aggregate. This site had a history of bad performance prior to separator installation.

Evidence from this study shows that damaged geotextiles are still able to perform the required separator function. The geotextile was used at most of the sites as a construction aide. However, it seemed that once the subgrade had gained strength through consolidation, then the need for the separator became less critical because subgrade intrusion was less of a problem. If the sites had been subject to fluctuating groundwater conditions, then the more heavily damaged geotextiles may not have performed as well, especially in the long-term.

Pavement Performance

All of the pavements except for those at Columbia Heights Road were in good condition at the time of the Phase II site investigations.

The pavement surface at the Columbia Heights Road site showed signs of premature failure in the form of fatigue cracking and minor rutting in several areas. The asphalt concrete pavement (ACP) in this area was only 35 mm thick (it was to receive an additional asphalt concrete overlay shortly after this site investigation), and the base material was approximately 30 to 35 cm thick. Given the soft subgrade conditions at the time of construction, the roadway section in this area was probably not adequate to support its traffic loads without premature failure.

Findings from the two testpits on Columbia Heights Road support the conclusion that the thin pavement section on the soft subgrade, rather than the damaged geotextiles, was the cause of the premature failure. The fact that the intact geotextile separator was under the fatigue-cracked pavement area, while the severely damaged separator was under the pavement surface which was in good condition, is counter-intuitive. However, it indicates that, in this case, the severely damaged separator was not the root of the problem.

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REFERENCES

1. Task Force 25 of the AASHTO-AGC-ARTBA Joint Committee (1989). "Guide specification for geotextiles in separation applications," March 1989, revised.

2. Christopher, B.R. and Holtz, R.D. (1985). *Geotextile Engineering Manual*, U.S. Federal Highway Administration, Washington D.C., Report FHWA-TS-86/203, 1044 pp.

3. Page, M.W. (1990). "Performances of geotextile separators," Master's Thesis, University of Washington, Seattle, Washington, 136 pp. Also published as Holtz, R.D. and Page, M.W. (1991). "Performance of geotextile separators - Phase I," Washington State Department of Transportation, Final Technical Report No. WA-RD 280.1, 136 pp.

4. Metcalfe, R.C. (1993). "Performance of Geotextile Separators in Western Washington," MSCE thesis, University of Washington, 262 pp. Also published as Metcalfe, R.C., and Holtz, R.D. (1994). "Performance of Geotextile Separators in Western Washington," Washington State Department of Transportation, Final Technical Report No. WA-RD 321.1, 265 pp.

5. Christopher, B.R. and Holtz, R.D. (1989). *Geotextile Design and Construction Guidelines*, National Highway Institute, U.S. Federal Highway Administration, Washington D.C., Report FHWA-HI-90-001, 305 pp.

6. Koerner, R.M. and Koerner, G.R. (1988). "A qualification and assessment of installation damage to geotextiles," *Geosynthetic Research Institute*, Report No. 2, Drexel University, 56 pp.

7. Koerner, G.R. and Koerner, R.M. (1990). "The installation survivability of geotextiles and geogrids," *Proceedings of the 4th International Conference on Geotextiles, Geomembranes and Related Products*, The Hague, Vol. 2, pp. 597-602.

8. Paulson, J.N. (1990). "Summary and evaluation of construction related damage to geotextiles in reinforcing applications," *Proceedings of the 4th International Conference on Geotextiles, Geomembranes and Related Products*, The Hague, Vol. 2, pp. 615-619.

9. Rathmayer, H. (1980). "Long-term behavior of geotextiles installed in road constructions in Finland since 1973," Väg-och vattenbyggaren, Vol. 26, No. 7-8, pp. 33-36.

10. Laier, H. and Brau, G. (1986). "The use of geotextiles in road constructions under intensive dynamic loading," *Proceedings of the 3rd International Conference on Geotextiles*, Vienna, Vol. 4, pp. 995-1000.

11. Tsai, W.-S., Savage, B.M., Holtz, R.D., Christopher, B.R. and Allen, T. (1993). "Evaluation of geotextiles as separators in a full scale road test," Proceedings of the Geosynthetics '93 Conference, Vancouver, B.C., (In publication).

12. Carroll, R.G. (1983). "Geotextile filter criteria," *Transportation Research Record 916*, Transportation Research Board, pp. 46-53.