1248

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Geosynthetics, Geomembranes, and Silt Curtains in Transportation Facilities

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Contents

Foreword

In recent years, there has been a nationwide increase in the use of geosynthetics, geomembranes, and silt curtains in transportation facilities. The six papers included in this Record are on the results of field implementation of these materials.

Peggs et al. report on the results of an investigation they conducted to determine the long-term effects of environment on a thermally bonded nonwoven polypropylene geotextile that was installed in the field. This geotextile showed minor degradation of its mechanical properties and had retained adequate survivability and durability characteristics.

Maurer and Malasheskie evaluated the effectiveness of four paving fabrics, one fiberized-asphalt, and one fiber-reinforced asphaltic concrete in retarding reflective cracking in asphaltic overlays. All the alternatives tested reduced the extent of cracking, but none completely eliminated the reflective cracking. They considered none of the alternatives to be cost-effective.

Button investigated the use of geotextiles to reduce or delay reflective cracking in asphalt concrete overlays. He reports that although none of the nine nonwoven polypropylene and polyester or the one woven polypropylene and polyester geotextile eliminated reflective cracking, all reduced or delayed reflective cracking.

Koerner and Hwu present a brief introduction to geomembranes, followed by a discussion of design philosophy and a review of the areas of geomembrane use in transportation systems.

Frobel reports on the use of geosynthetics to waterproof transportation tunnels. He describes methods of installation and inspection of geosynthetics.

Suits and Minnitti present the results of laboratory tests and a prototype installation of a turbidity curtain. The geotextile considered for use was tested for permittivity, soil retention, long-term flow, and strength. The data obtained in these tests were used as the basis for design recommendations for constructing a turbidity curtain.

Durability of a Polypropylene Geotextile in an Unpaved Road Structure

I. D. Peggs, L. G. Tisinger, and R. Bonaparte

This paper addresses select durability characteristics of a continuous-filament, nonwoven geotextile commonly used in transportation-related applications. Two samples of the geotextile were exhumed from the base of an unpaved road structure located at an industrial site in East Texas. The two samples had been in service for 12 and 13 years, respectively. The samples, together with an unused reference sample manufactured at the same time as the exhumed samples, were subjected to a series of destructive mechanical tests, structural analyses, and examinations via scanning electron microscopy. The mechanical tests included measurements of grab-tensile strength and elongation, burst strength, puncture strength, trapezoid-tearing strength, as well as individual fiber strength and elongation. The exhumed samples retained in excess of 70 percent of their initial strength and elongation properties. The microstructural analyses included differential scanning calorimetry and infrared spectroscopy. The results of these tests indicated that some polymer degradation had occurred such as might be caused by oxidation. The extent of the oxidation is not considered significant because scanning-electron microscopy does not show any circumferential cracking on the fiber surface, a feature that occurs when fiber oxidation is extensive. Scanning electron microscopy did show some mechanical damage on the surface of the fibers; however, this may be ascribed more to installation damage than to degradation during service.

To date, the majority of geosynthetic tests for civil or geotechnical engineering applications are used to determine whether the geosynthetic has properties appropriate for service only at the moment of installation. Be they geotextiles for highways, geogrids for embankment reinforcement, or geomembranes for landfill liners, little interest has been expressed in the long-term durability of the product. This is partially due to the fact that appropriate tests to evaluate durability are not routinely performed and standardized. However, recently, significant interest in the long-term degradation of geotextiles and the polymeric fibers from which they are manufactured has been expressed by the International Organization for Standardization, the American Society for Testing and Materials (*1*), the Strategic Highway Research Program, the Geosynthetic Research Institute (*2*), and others (*3–7*). The new test methods are mainly performed on the fibers that constitute the geotextile rather than on the geotextile itself and are employed to assess their long-term durability.

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BACKGROUND

The geotextile examined in this program was a continuous-filament, thermally bonded, nonwoven polypropylene material with a nominal mass per unit area of 136 g/m^2 (4 oz/yd^2). The individual fibers had linear densities of approximately 1.1 tex (10 denier) in both machine and cross directions.

Definitions

The geotextile for examination was exhumed from a site in East Texas. The site was chosen from one of seven sites used in a previous complementary study (*7*) of the survivability and durability characteristics of the same geotextile. In the previous study, survivability was defined as a geotextile's resistance to destruction during construction and initial operation. Durability was defined as the resistance of a buried geotextile to long-term degradation. These definitions are maintained in this paper. However, contrary to the previous study, which was concerned with geotextile survivability, this study is more concerned with geotextile durability and has been partially directed to compare the bulk geotextile properties with those of the individual fibers.

Site Description

The study site was previously described by Bonaparte et al. (*7*) as being located in a flat, wet, low-lying area near the Gulf Coast in East Texas. The site has poor drainage and a water table near the surface. The subgrade soil is a black organic, high-plasticity clay with undrained shear strengths in the range of 30 to 45 kPa (570 to 940 psf) in the first meter below the surface. Geotextiles were used to construct access roads and drill pads at the site in 1975 for oil and gas exploration and production.

The geotextile samples exhumed during the present study had been installed in an area where subgrade preparation prior to road construction was limited to the clearing of small trees and shrubs. The geotextiles were unrolled directly on the cleared, relatively flat subgrade. The fill material used to construct the roads and pads was a well-graded, crushed (angular) limestone aggregate with a maximum particle size of about 60 mm (2.5 in.), with about 15 to 20 percent fines (15 to 20 percent passing a No. 200 U.S. standard sieve). The fill was brought to the site in 225-kN (25-ton), 10-wheel dump trucks that back-dumped onto previously constructed portions of the road or pad. The fill was spread in a single lift using track-mounted Caterpillar D6 and Case 1450 bulldozers. Ground pressures exerted by the dump trucks were on the order of 500 kPa (5 tsf), whereas the bulldozers exerted ground pressures in the range of 70 kPa (1500 psf). Fill thicknesses ranged from about 225 mm (9 in.) to 300 mm (12 in.).

Test Specimens

In December 1986, a 0.5-m^2 (5-ft^2) sample of geotextile was retrieved from the Texas site. The sample had been in service approximately 12 years and is identified here as No. 12. The sample retrieval procedure has been described in detail by Bonaparte et al. (*7*), who also described the site, which has a moderate to high geotextile survivability rating based on the FHWA *Geotextile Engineering Manual* (*8*). At the Texas site, the geotextile was found to have performed adequately and to have been in good condition (*7*). On the basis of the observed good condition of the geotextile, it was concluded that the material had adequate physical and mechanical properties for use at a site with a moderate-to-high survivability rating.

The study by Bonaparte et al. (*7*) provided only limited information on geotextile durability. Therefore, in April 1988, a second 0.5-m^2 sample of geotextile was retrieved from the Texas site for the purpose of conducting additional durability studies. This second sample had been in service approximately 13 years and is identified here as No. 13. The remainder of this paper describes the additional studies carried out using geotextile samples 12 and 13.

LABORATORY EXAMINATION

After retrieval from the Texas site, the geotextile samples were delivered to the laboratory in tightly sealed polyethylene bags. After removal from the bags, the samples were gently shaken to remove loose dirt and cleaned of easily removed dirt by rinsing in deionized water. The samples were allowed to dry naturally in a standard laboratory atmosphere (temperature 21 ± 2°C, relative humidity 45 to 65 percent). The geotextile samples were then subjected to a series of tests as follows; however, both samples were not subjected to all the tests.

Mechanical Property Tests

Mechanical property testing included the following standard geotextile index tests:

- Mullen burst strength (ASTM D 3786),
- Puncture strength (ASTM D 3787),
- Grab-tensile strength (ASTM D 1682), and
- Trapezoid-tearing strength (ASTM D 4533).

Sample 13 was subjected to the Mullen burst-strength test only, because the emphasis of testing on this sample was to be the individual fiber and analyses of the fiber structure.

Hydraulic Property Test

Sample 12 was subjected to permittivity testing according to ASTM D 4491 at a hydraulic head of 50 mm (2 in.). Because permittivity data were not available in 1975, reference data were obtained from 1987 literature for the equivalent product.

Fiber Linear Density and Strength Tests

Individual fibers were carefully removed from sample 13 and the 1975 reference material. Fiber tests were not performed on sample 12. Each fiber was gently pulled out of the geotextile with the assistance of a stereomicroscope. The linear density of the fibers was measured on a Vibromat tester according to ASTM D 1577. The peak tensile strength (tenacity) and strain at rupture were determined using specimens with a 25-mm (1-in.) long gage length at an elongation rate of 25 mm/min (1 in./min) according to ASTM D 3822.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to examine the outside surfaces and fracture surfaces of individual geotextile fibers in both samples 12 and 13. In an attempt to detect whether the fibers had become more or less brittle during exposure, small samples of the geotextile were pulled in tension so that the microscopic features of the fiber fracture faces could be examined. One of the prime objectives of the SEM analysis was to identify any circumferential cracking, which, if present, is evidence of the degradation of the surface layers of the polypropylene. Reference data were generated by examining 1975 reference samples that had been stored indoors.

Chemical Structural Analyses

Both samples 12 and 13 were subjected to two types of analytical tests: differential scanning calorimetry (DSC) and infrared spectroscopy (IR). Reference data were generated by performing the same tests on the 1975 archive samples.

The analytical tests were used to assess the effects of long-term environmental exposure on the microstructure of the geotextile. The degrees of crystallinity and oxidative induction temperatures were measured using DSC. Structural characteristics were evaluated using IR.

Differential Scanning Calorimetry

A DSC analysis involves monitoring of the thermal energy required to maintain a test specimen at the same temperature as a reference specimen heated at a constant rate of increasing temperature. This energy is exhibited as a function of the reference temperature in a thermogram. The thermogram may display endotherms (Figure 1), corresponding to energy absorbed in the specimen, and exotherms (Figure 2), corresponding to energy emitted. From endotherms, melting point ranges and degree of crystallinity may be derived. Exotherms provide data for the assessment of the oxidative stability of

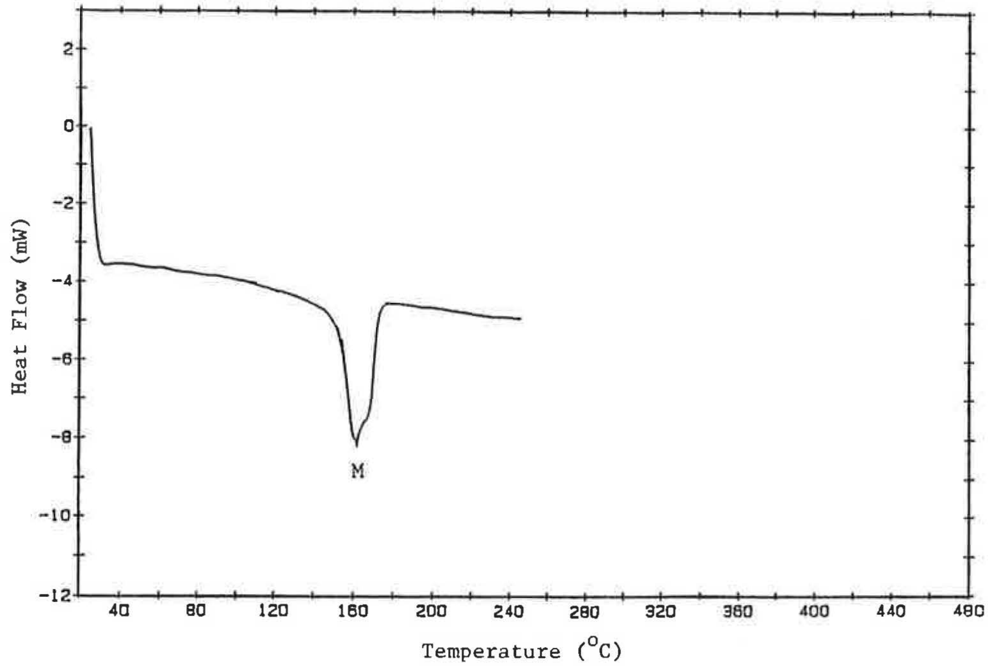


FIGURE 1 Melting endotherm (*M*) for archive polypropylene geotextile.

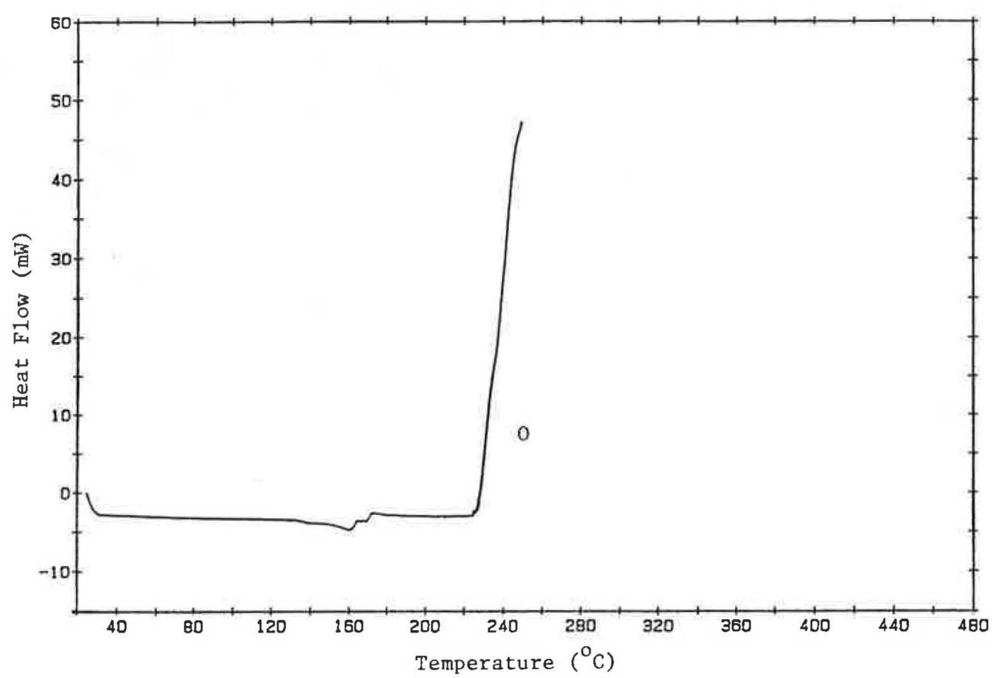


FIGURE 2 Oxidation exotherm (*O*) for archive polypropylene geotextile.

the material based on either the oxidative induction time or oxidative induction temperature, which is the time or temperature at which the specimen is completely degraded. The oxidative induction temperature tests were conducted in an air atmosphere at a heating rate of 20°C/min. The degree-of-crystallinity tests were performed in a nitrogen atmosphere at a heating rate of 20°C/min.

Polypropylene is a semicrystalline polymer. By comparing the area within the melting endotherm (the heat of fusion) to the heat of fusion of a fully crystalline material such as indium, the degree of crystallinity of the microstructure can be determined.

The oxidative induction temperature is the temperature at which reaction of a material with oxygen occurs. The DSC analysis is conducted with the specimen in a reactive atmosphere (air or oxygen), and the oxidative induction temperature value is the temperature at the onset of the exotherm, approximately 232°C in Figure 2. This parameter gives an indication of the oxidative stability of a material (i.e., the effectiveness of the antioxidant package).

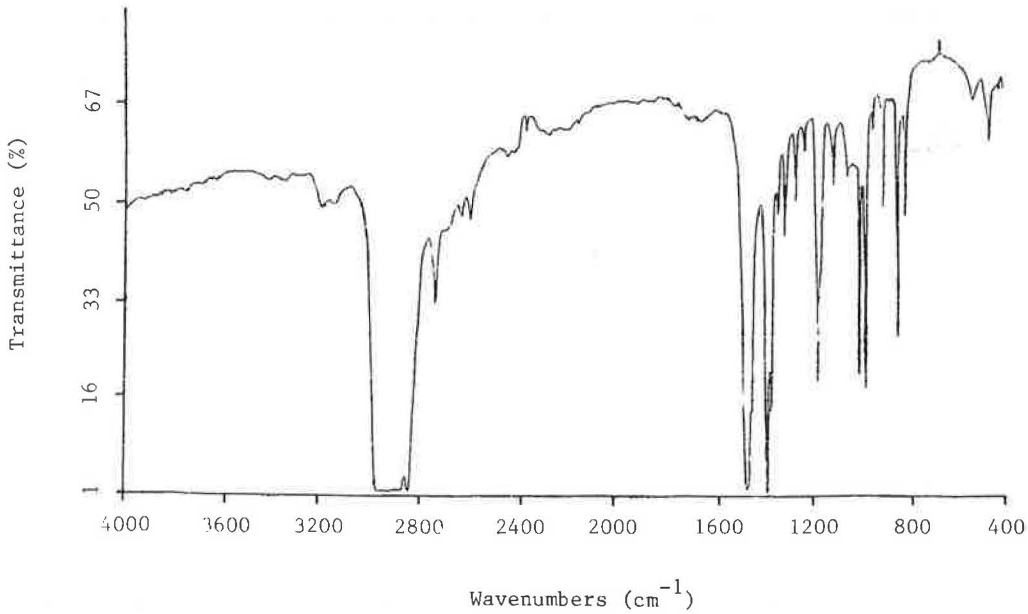


FIGURE 3 Typical IR spectrum for polypropylene geotextile.

Infrared Spectrometry

IR spectra provide information on the structural characteristics of a material. This analytical technique involves exposing the material to infrared radiation at decreasing frequencies. This radiation scan generates a spectrum of bands (Figure 3), each corresponding to a particular frequency or range of frequencies in which infrared radiation is absorbed by the specimen. The molecular components of any given material display a characteristic "spectrum of bands," thus allowing correlations or comparisons with spectra from other materials.

IR can be used to identify a specific degradative process in a geotextile through the identification of new spectral bands generated by the products of the degradative process.

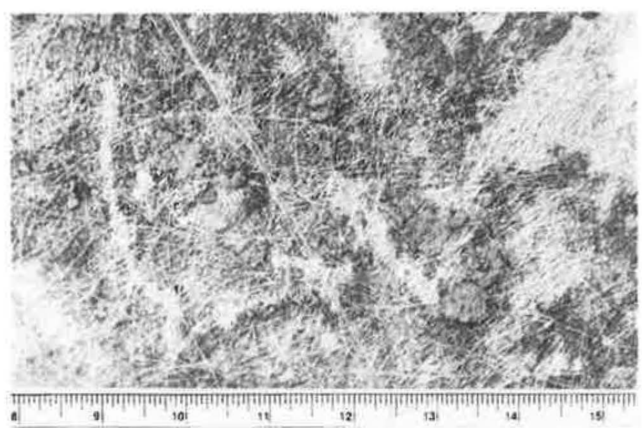


FIGURE 4 Close-up view of the surface of the as-received sample.

TEST RESULTS

Before any laboratory tests were performed, the as-received samples were examined carefully. Sample 13 contained only one hole, which had been caused by the pickaxe when the soil cover was being removed during field exhumation. The condition of sample 12 appeared to be undamaged. Sample 13 showed no signs of severe distress, although deformations and indentations from the limestone aggregate base that covered the geotextile were evident. A close-up view of a typical area of the sample is shown in Figure 4. The geotextile has retained its original morphology without significant evidence of "fraying" or loosened fibers.

Figure 5 shows a direct comparison of the exhumed sample 13 and the 1975 reference sample. Except for the dirt in the exhumed sample, there is very little difference in the appearance of the two materials.

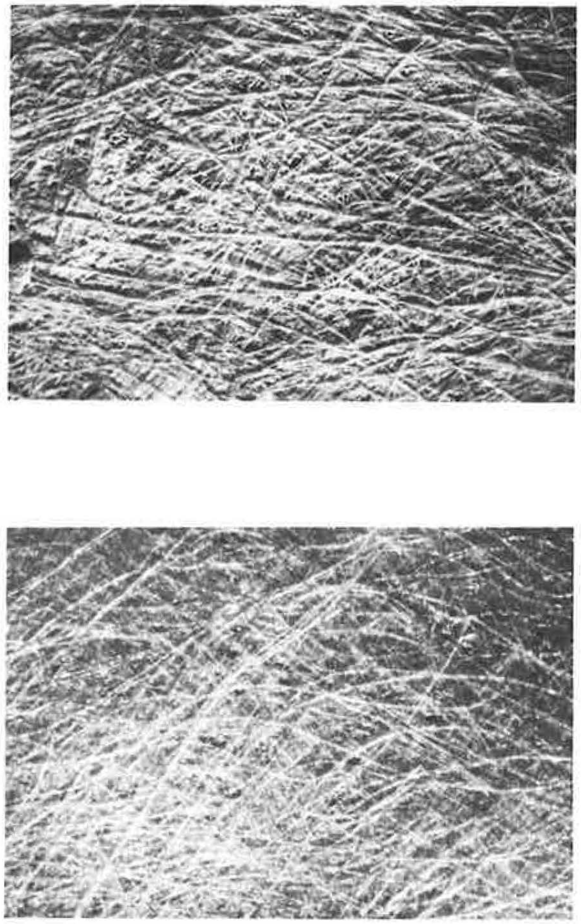
In general, the exhumed sample 13 does not appear to have suffered significant degradation on a macro scale.

Mechanical Property Test Results

The mechanical property test results, including those from sample 12, are shown in Table 1. Because it was difficult to identify the machine and cross directions of the samples removed from the field, the reference parameter is presented as the arithmetic mean of the two (machine and cross direction) values published in the 1975 product brochure.

Although some general loss-of-strength properties are indicated in Table 1 for sample 13, it is notable that at the 95 percent confidence limits (approximately two standard deviations), the data for the exhumed samples overlap the ranges of values for the 1975 reference samples. The Mullen burst strength for sample 13 shows virtually no loss when compared with the reference data.

(a)



(b)

FIGURE 5 Comparison of the surfaces of (a) sample 13 and (b) the 1975 reference sample (×3).

The residual property values after exposure of the geotextile to the environment are of major interest to geotechnical and transportation engineers. These data are given in Table 2.

The exhumed geotextile has retained in excess of 70 percent of its original mechanical properties after construction and 12 to 13 years of burial. It appears in addition that the strength retention could be dependent upon the location of the specimen within the exhumed sample as shown in sample 13 (exposed for the longer period), which has a higher burst strength than sample 12. This suggests that a major contributor to the loss could be mechanical damage incurred during installation rather than the overall degradation of the geotextile during service. A similar conclusion was reached by Bonaparte et al. in the previous study (7) of this geotextile.

Hydraulic Property Test Results

The results of the permittivity testing are as follows: field sample 12, 0.48 s^{-1}; brochure reference (1987), 0.55 s^{-1}. The geotextile has retained 87 percent of its original permittivity. However, this loss is not due to aging processes but primarily to the retention of soil particles within the pore structure of the geotextile. All of the soil particles were not removed by the preparatory wash in deionized water. The geotextile clearly had not become clogged with soil and still allowed passage of water.

Fiber Linear Density and Strength Test Results

The individual fiber test results are summarized in Table 3. Nine fibers from the 1975 reference sample and six sample 13 fibers were tested. The exhumed fibers show a 5 percent loss in linear density and an equivalent loss in peak tensile

TABLE 1 MECHANICAL PROPERTY TEST DATA

Parameter	Field Sample #12	Field Sample #13	Brochure Reference (1975) (Mean of MD and XD)
Grab Strength (N)	481 ± 62[a]	-	614 ± 40[a]
Grab Elongation (%)	53	-	74
Burst Strength (kPa)	837 ± 186[a]	1200 ± 15[a]	1200 ± 140[a]
Puncture Strength (N)	209 ± 22[a]	-	220 ± 18[a]
Tear Strength (N)	245 ± 62[a]	-	310 ± 45[a]

[a] Standard deviation

MD = Machine direction

XD = Cross-machine direction

TABLE 2 RESIDUAL MECHANICAL PROPERTIES

Parameter	Brochure Reference Value	Residual Value Field Sample #12 (%)	Residual Value Field Sample #13 (%)
Grab Strength (N)	614	78	-
Grab Elongation (%)	74	71	-
Burst Strength (kPa)	1200	70	100
Puncture Strength (N)	220	94	-
Tear Strength (N)	310	79	-

TABLE 3 FIBER TEST RESULTS

Parameter	Field Sample #12	Field Sample #13	Reference Fibers (1975)
Linear Density (D)	-	10.1 (95)[a]	10.6
Tenacity (g/D)	-	3.2 (94)[a]	3.4
Break Strain (%)	-	123 (86)[a]	143

[a] Residual Value

strength or tenacity. To produce a decrease in linear density, material must be lost from the surfaces of the fibers. The scanning electron microscopy results that follow show that the loss may be due to scraping or gouging of the fibers during the construction operation. This process produces stress-concentrating notch defects on the surface of the fiber, which cause a reduction in tenacity and strain at rupture. Similar observations have been noted in polyethylene geomembranes (*9*, *10*) in which break strength may be reduced by approximately 50 percent and break elongation by approximately 95 percent due to surface defects. In comparison with these reductions for polyethylene, the polypropylene fibers have suffered relatively little loss of mechanical properties.

In sample 13 fibers, there were two specimens of average linear density that did in fact show low peak-tenacity values of 2.44 and 2.91 g/D and rupture strains of 42 and 90 percent, both well below the average reference values. These individual specimens had apparently suffered major surface damage. However, two of the reference geotextile fiber specimens also showed similar mechanical characteristics: peak tenacities of only 2.64 and 3.02 g/D and rupture strains of 47 and 93 percent. It therefore appears that some of the as-manufactured fibers contain surface features that affect the mechanical properties of the fibers. Therefore, excessive damage may not have occurred during installation.

The test data from sample 13 indicate that little degradation of the geotextile fibers has occurred over the 13-year period that the geotextile has been in service.

SEM Test Results

The original as-manufactured geotextile (the 1975 reference sample) and the individual fiber surfaces (from sample 13) are shown in Figure 6. The individual fibers (occasionally a few are bonded together in a parallel fashion) are distributed more or less randomly to produce a planar isotropic structure. The surfaces of the individual fibers are generally very smooth,

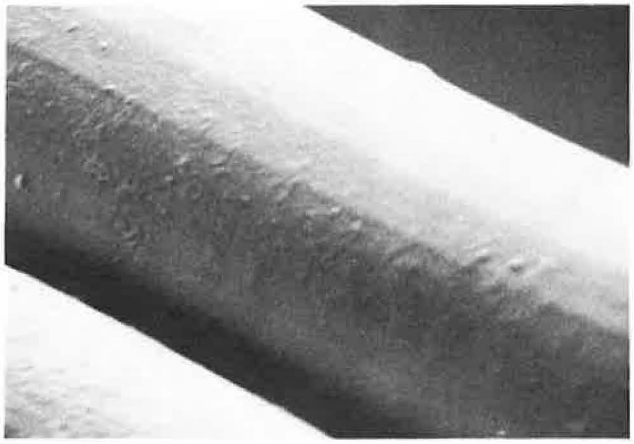


FIGURE 6 Surface of reference geotextile fiber (×975).

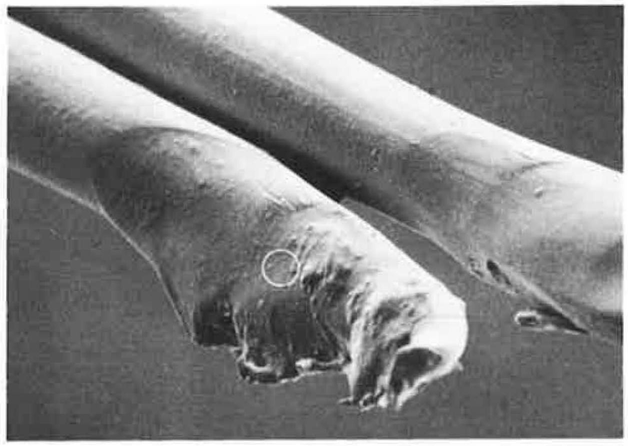


FIGURE 8 End of fractured reference geotextile fiber (×325).

with only occasional surface blemishes (Figure 7). These blemishes, particularly those with the geometrical profile of a notch, were probably responsible for the few low tenacity and rupture strain values obtained in the fiber-testing component of the program.

Fibers that had failed in tension showed a significant amount of elongation with a characteristically ductile final fracture. The surface of the fiber adjacent to the final fracture region was smooth, as seen in Figures 8 and 9.

In comparison, Figure 10 shows the surfaces of fibers removed from samples 12 and 13. In general, the fibers from sample 12 are more severely damaged than those from either the sample 13 fibers or the reference sample. The damage appears to be more of a ductile "smearing" than a brittle chipping. In other words, the fiber material is not lost but is just redistributed, probably as a result of spreading of the limestone aggregate over the geotextile during installation.

The fracture features of fibers in sample 12 (Figures 11 and 12) show more brittle characteristics in that there is little reduction in the cross section of the fibers. However, the nature of the fracture face itself shows the rounded, coarse surface features of a progressive ductile failure.

The fiber fracture in sample 13, shown in Figures 13 and 14, is essentially a replicate of the fiber fracture in the reference material shown in Figures 8 and 9. The only difference is the presence of the soil particles that have contributed to the roughness of the polypropylene surface adjacent to the fracture.

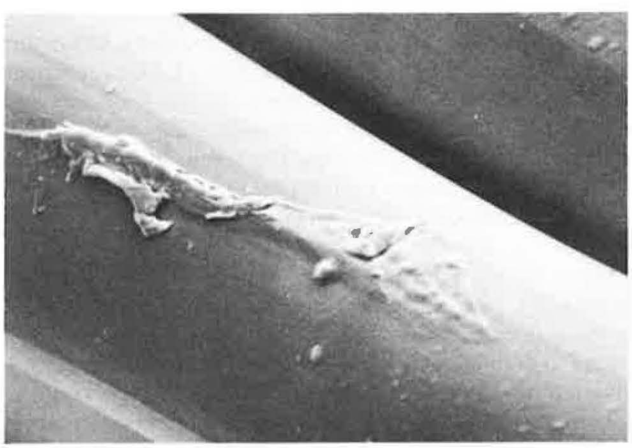


FIGURE 7 Blemish on surface of reference geotextile fiber (×975).

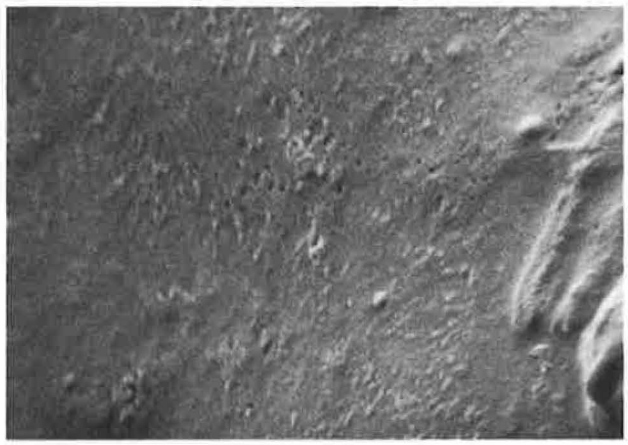


FIGURE 9 Surface of fiber in area circled in Figure 8 (×1950).

It appears that the fibers from sample 12 have been damaged more severely than those from sample 13. In fact, the fibers from sample 13 appear to have received very little damage or not to have suffered any damage at all. This may explain the observation that the Mullen burst strength of the geotextile in sample 13 shows no loss when compared with the reference data, whereas the burst strength of sample 12 does.

Many fibers were examined in the electron microscope for this project and the project reported earlier (*7*), but at no time was any evidence of circumferential surface cracking found. Such cracking occurs in highly oriented fibers when they degrade because of oxidation initiated by ultraviolet radiation. An example of degradation after 3 months of exposure to sunlight in a geotextile manufactured from a polypropylene resin similar to the one used in the present study is shown in Figure 15. Quite clearly, the individual fibers of the geotextile break up into short lengths at points where they are stressed.

The circumferential nature of the cracking in the oxidized fibers is clearly shown in Figure 16.

(a)

(b)

(c)

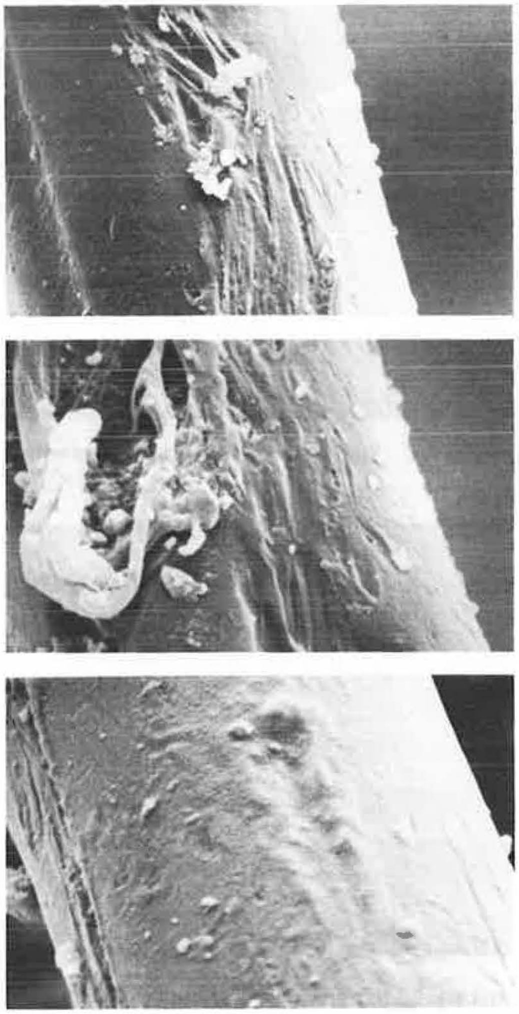


FIGURE 10 Surfaces of fibers from (a,b) sample 12 and (c) sample 13 (×975).

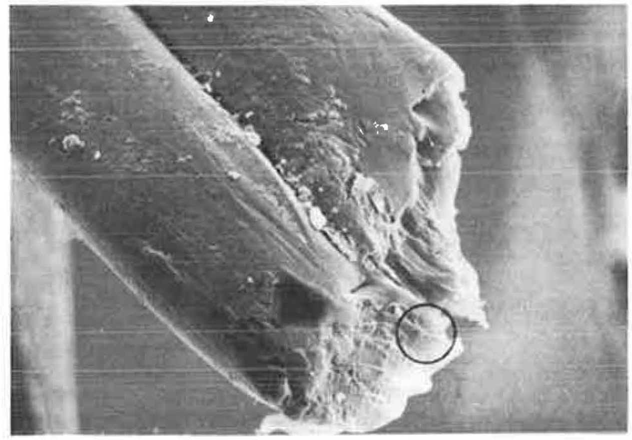


FIGURE 11 Fracture characteristics of fibers in sample 12 (×423).

FIGURE 12 Fracture characteristics of fibers in area circled in Figure 11 (×1950).

Chemical Structural Analytical Test Results

The data from both DSC and IR studies indicate that only minor amounts of polypropylene chemical structural degradation have occurred since 1975.

Degree of Crystallinity

The crystallinity values and melting ranges of the reference geotextile and the exposed sample 13 geotextile are shown in Table 4. Five specimens from different areas of each were analyzed to take into account material variability.

The results are consistent, as indicated by the low standard deviations. The degree-of-crystallinity values for the exhumed samples are lower than for the reference samples, although the magnitude of the difference is not significant (within one standard deviation of the reference value). The average melting range for the exhumed material is lower and wider than the corresponding reference melting range. This is not unexpected, because retention of minute quantities of impurities within the polypropylene microstructure may have occurred in the exhumed sample. (Impurities lower and widen melting ranges through modification of the cohesive forces.)

Oxidative Induction Temperature

Table 5 presents oxidative induction temperature values for the reference sample and exhumed sample 13. Five specimens were measured from different areas of the reference and exhumed samples. The tests were conducted in an air atmosphere at a scan rate of 20°C/min. The results of the oxidative induction temperature analysis for the reference and exhumed samples are consistent, as shown by the low standard deviation for both sets of data.

The oxidative induction temperature of the exhumed sample was 20°C lower than the oxidative induction temperature for the reference sample, which is consistent with a reduction in oxidative stability. Such a reduction in oxidative induction temperature demonstrates the decreased effectiveness of the stabilizer package after long-term environmental exposure, through consumption or some other factor. Partial consumption of the stabilizer package may have occurred during initial installation of the geotextile. Buried geotextiles would not

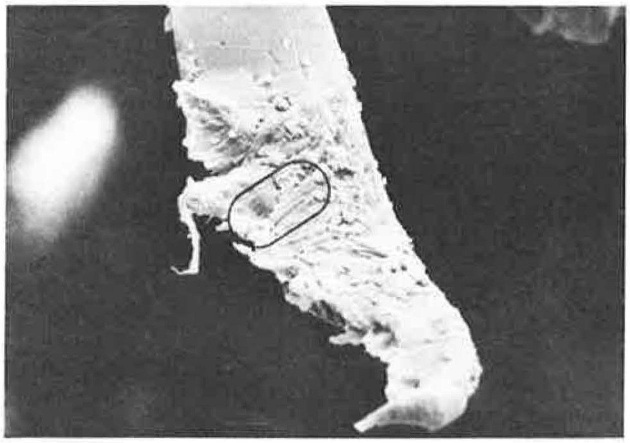


FIGURE 13 Fracture characteristics of fibers in sample 13 (× 325).

FIGURE 14 Fracture characteristics of fibers in area circled in Figure 13 (× 1950).

likely encounter sufficient quantities of heat or ultraviolet radiation to initiate significant degradation. Also, the initial concentration of the stabilizer package in the exhumed geotextile may have been lower than that in the reference sample because of variability in processing. The 20°C reduction in oxidative induction temperature appears significant. However, the effect of such a reduction on the overall durability of the geotextiles is difficult to quantify.

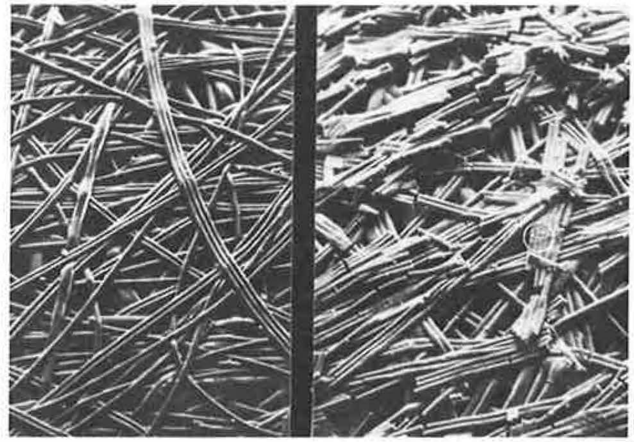


FIGURE 15 Comparison of a polypropylene geotextile structure (a) before and (b) after exposure to natural weather conditions for 3 months (× 18).

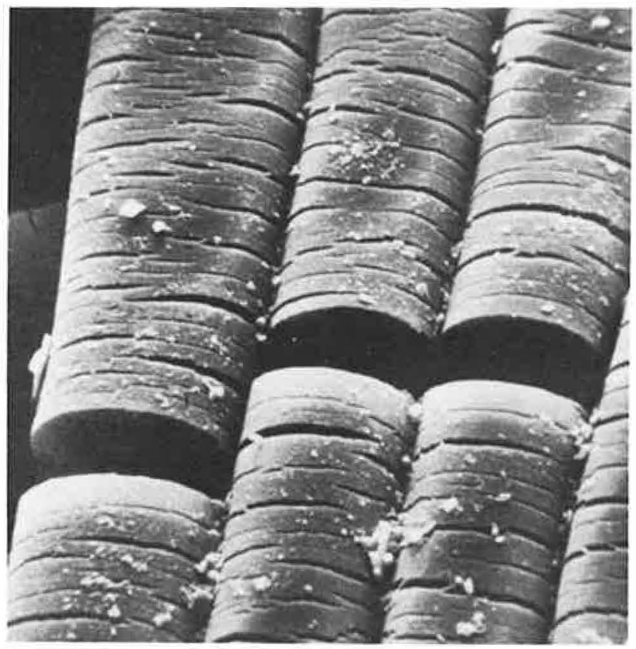


FIGURE 16 Area circled in Figure 15: circumferential cracking after 3 months of exposure to the weather could initiate fiber fracture at any stressed location (× 455)

Infrared Spectrometry

Table 6 lists the characteristic spectral bands of the reference sample and exhumed sample 13 obtained from the IR analysis. Figures 17 and 18 show infrared spectra for the reference and exhumed geotextiles, respectively. Five specimens from each of the reference and exhumed samples were analyzed.

Each spectrum displays bands at 3000 to 2780 cm^{-1} and 1480 to 800 cm^{-1}, which are those bands attributable to polypropylene. The absence of bands in the 1775- to 1750 cm^{-1} region for the exhumed geotextile sample indicates that oxidative attack on the polymer molecules was minimal. Bands appearing in this region are typically observed when oxidation has occurred in polypropylene. Additional IR spectra were obtained for both the reference sample and sample 12 by Bonaparte et al. (*7*).

DISCUSSION OF RESULTS

The data generated by this study and the related earlier one (*7*) indicate that residual strength values exceeding 70 percent have been achieved by the polypropylene geotextile in this unpaved road application, which according to the FHWA *Geotextile Engineering Manual* (*8*), required use of "moderate-to-high" survivability materials. Bonaparte et al. (*7*)

TABLE 4 DEGREE OF CRYSTALLINITY AND MELTING RANGE

Sample Number	Reference		Exhumed Sample #13	
	Crystallinity (%)	Melting Range (°C)	Crystallinity (%)	Melting Range (°C)
1	28.58	127.30-180.81	22.99	119.13-182.89
2	24.31	119.12-179.96	29.27	119.50-190.67
3	25.71	122.83-182.33	20.48	128.48-180.81
4	27.22	133.95-178.29	33.00	129.82-181.59
5	26.06	125.35-176.91	21.82	119.50-186.97
Average	26.38	125.71-179.66	23.51	123.29-184.59
$\sigma_{n^{-1}}$[a]	1.61	5.53- 2.12	5.37	5.38- 4.15

[a] Standard deviation is $\sigma_{n^{-1}}$

TABLE 5 OXIDATIVE INDUCTION TEMPERATURE

Sample Number	Reference Sample	Exhumed Sample #13
1	240.97°C	228.87°C
2	238.84°C	202.86°C
3	238.97°C	227.94°C
4	237.09°C	208.42°C
5	239.52°C	231.29°C
Average	239.10°C	219.88°C
$\sigma_{n^{-1}}$[a]	1.40°C	13.20°C

[a] Standard deviation is $\sigma_{n^{-1}}$

examined similar polypropylene geotextiles from other sites and found that residual strength values may decrease to approximately 50 percent in sites with a material survivability rating that is "very high."

Thus, there is an expected relationship between the survivability rating of a site and the damage sustained by the geotextile during its installation. It might, in turn, be expected that the extent of damage to the geotextile during its installation is reflected in its durability, or its performance characteristics over the period of intended service. Despite the fact that both samples 12 and 13 show different degrees of installation damage, they appear to have performed their designed separation function as intended. There are no signs of accelerated aging processes that might have been initiated at the areas of surface damage on the fibers in sample 12 over the 12-year service period. Such effects can be of major importance in polyolefin products, as shown by the slow-crack-growth, brittle-fracture phenomenon initiated at surface defects in natural gas distribution pipe manufactured from different polyethylene resins (*11–13*). In these products, fractures have occurred after as little as 2 years of service. Apparently, the polypropylene geotextile examined in this project is not subject to these phenomena and appears to be, thus far, quite durable.

There are two components to the durability (and survivability) of geotextiles that have been compared in this examination. The first is the durability and aging performance of the polypropylene fiber. The second is the performance of the composite geotextile, which is mostly related to the geometric way in which the individual fibers are oriented and the chemical and mechanical ways in which they interact at their crossover points.

If the fibers are degraded, the geotextile will lose its durability, as shown by the circumferential cracking fractures. However, if the fibers are durable, it does not automatically follow that the geotextile will also be durable. If the chemical and mechanical bonding between fibers is destroyed with time, the geotextile may not be considered durable. Therefore, in order to assess whether a geotextile is durable in a specific environment, a two-step approach is necessary. Specifically, the two steps are to

TABLE 6 INFRARED ANALYSIS DATA

Spectral Bands	Reference Sample					Exhumed Sample #13				
	1	2	3	4	5	1	2	3	4	5
3000 - 2780 cm^{-1}	+	+	+	+	+	+	+	+	+	+
1480 - 800 cm^{-1}	+	+	+	+	+	+	+	+	+	+
New Bands	o	o	o	o	o	o	o	o	o	o

+ = Bands appearing in same region

o = No band(s) appearing

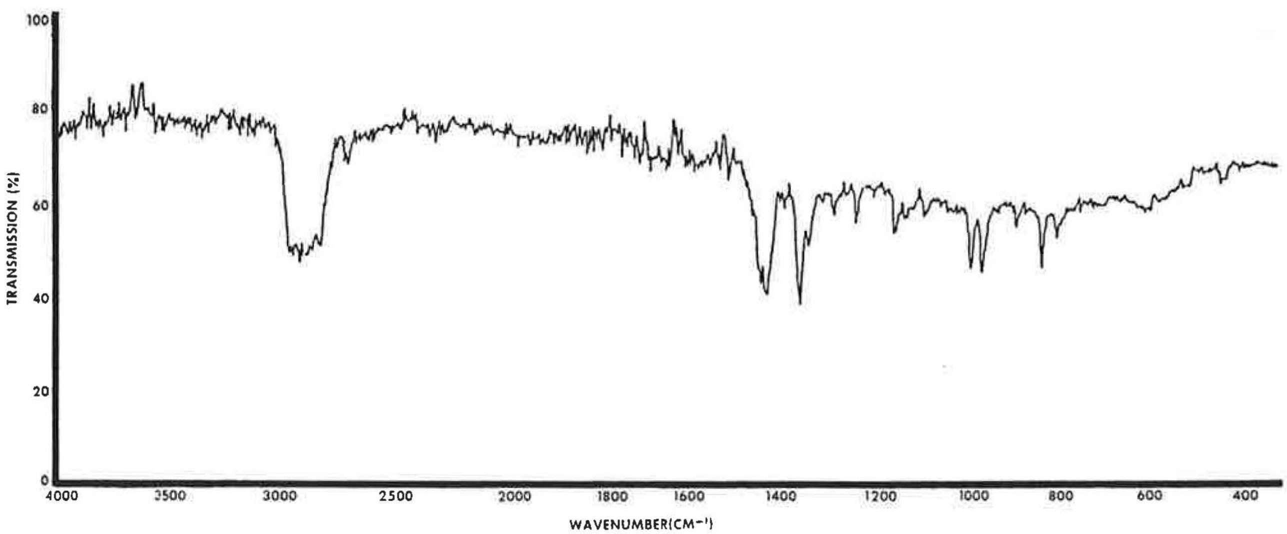


FIGURE 17 IR spectrum for the reference polypropylene geotextile.

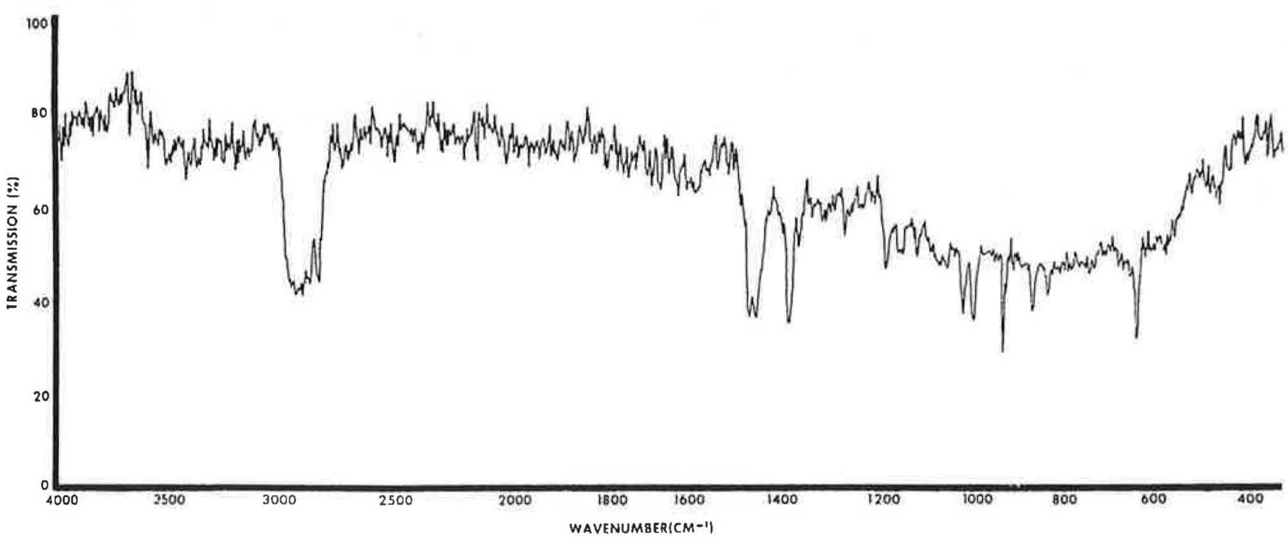


FIGURE 18 IR spectrum for the exposed polypropylene geotextile.

- Assess the degradation of the fibers from which the geotextile is manufactured. Structural analytical tests will constitute the key component in this examination. If the fiber degrades, no further steps are necessary. If the fiber does not degrade, it will be necessary to proceed to the next step.
- Assess a property of the composite geotextile related to the intended service function. This step will determine whether the integrity of the composite geotextile has been compromised.

In examining a relatively new technological field, like the durability of geosynthetics, which is not yet thoroughly understood, there is yet another overriding caution. A material or product may show some degradation or some lack of chemical compatibility, but if critical design parameters are not exceeded, the degradation may be immaterial. A product need not be discarded just because it is degraded. For instance, as discussed by Bonaparte et al. (*7*), specific minimum criteria have been established for the survivability ratings of geotextiles in specific applications. The purpose is to provide adequate survivability so that when the product is installed it will function continuously as designed. There are, however, exceptions. Some materials that do not meet the survivability ratings and have suffered some damage during installation may still provide adequate service when installed and continue to provide adequate service. Moreover, some materials that meet the survivability criteria and consequently receive very little damage during installation may not provide adequate survivability because of damage of a type that seriously reduces the durability of the product.

CONCLUSIONS

This examination of a thermally bonded, nonwoven polypropylene geotextile exhumed after 12 and 13 years of service in an unpaved road structure indicates that although a minor amount of oxidation has occurred in the polypropylene fibers, there has been little apparent degradation of the mechanical properties of the geotextile since its installation. The microstructural changes identified in the individual fibers are reflected by the mechanical property changes in the bulk geotextile, thus confirming the appropriateness of the fiber tests.

The properties of the exhumed geotextile are predominantly determined by the amount of local mechanical damage suffered by the fiber and the geotextile during installation.

The geotextile examined has adequate survivability and durability characteristics to perform satisfactorily in its intended role at the site investigated in this study.

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Field Performance of Fabrics and Fibers to Retard Reflective Cracking

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The purpose of this project was to determine whether any, or various, uses of geotechnical fabrics and fibers will significantly retard reflective cracking in an asphaltic concrete overlay. Four paving fabrics, one fiberized-asphalt membrane, and one fiber-reinforced asphaltic concrete were the treatment alternatives being evaluated. All treatments were compared with each other and with untreated control sections to determine relative performance. Considerations in making these comparisons were construction and maintenance costs, ease of placement, and the ability to prevent or retard reflective cracking. Performance data are presented for surveys conducted at 8 months, 26 months, and 44 months after construction. All treatments retarded cracks over the evaluation period, although the amount and rate of reduction varied. One paving fabric and fiber-reinforced asphalt concrete had the highest crack reduction ratios after the 44-month evaluation. On the basis of all factors considered in the evaluation—cost, ease of construction, and performance relative to distress treated—the fiber-reinforced concrete provided superior performance relative to the treatment alternatives. However, on the basis of the extent of cracking evident after the 44-month survey, and considering current and proposed crack sealing costs in addition to the documented construction costs, none of the treatments used on this project was found to be cost-effective or recommended for use.

Reflective crack formation in asphalt concrete pavement has confronted highway engineers for many years. Since the first flexible overlay was placed, there has been a need to restrict underlying deficiencies or weaknesses or prevent them from reflecting through the new surface. The primary cause of the cracking phenomenon has been recognized for some time—differential movement of the pavement layers occurs because of stresses produced by traffic and the environment (moisture and thermal-induced). The preventive treatments that have been, and are being, attempted vary in material composition and application method. Most treatments, though different in some respect, share common design aspects. In general, an interlayer is formed that is intended to both separate old and new pavement with a waterproof membrane and reinforce and bond the entire layered system.

The experience of the Pennsylvania Department of Transportation (PennDOT) includes several research projects that field evaluate either the use of construction fabrics or stress-absorbing membrane interlayers (SAMIs). Research Project 73-20 considered the effects of placing a full-width, nonwoven polypropylene fabric (Petromat) over alligator-cracked, flexible-base roads before overlaying in 1973 and 1976. The final report issued in 1981 stated that although cracking was retarded, use of the fabric was not recommended because the benefits were insufficient to justify the additional cost (*1*). Research Project 79-6, the evaluation of which was completed in August 1985, considered fabric as a strip treatment over rigid base joints and cracks. Final report conclusions indicate that significant crack reduction occurred due to treatment (*2*). However, Research Project 79-2, which is a continuing evaluation of SAMIs, appears to be inconclusive. Two projects constructed in 1980 currently indicate that the untreated pavement sections are performing equal to or better than the treated sections (*3*). Other states with similar evaluations have reported similar results (*4*).

PLAN OF STUDY

In the summer of 1982, PennDOT Engineering District 4-0 (Northeast Pennsylvania) expressed interest in placing paving fabrics on a scheduled overlay project and requested guidance to set up a research project, because such usage is not standard practice in Pennsylvania.

One conclusion from Research Project 73-20, documented by other work (*5*), was significant in the selection of the proposed District 4-0 site. It was determined that fabric was more effective in retarding transverse cracking (in asphalt concrete) associated with thermal changes than cracking associated with structural inadequacies. Because the site was characterized as a mostly stable base with predominant surface, block-type cracking, fabric treatment represented a potentially effective benefit. The characterization of this type of cracking and its association with low distress levels would later prove to be invalid on the basis of actual posttreatment evaluation. However, at the time of planning, the consensus was that this condition could be successfully treated in the manner proposed based on the available technical literature.

Four fabrics or geotextiles and one SAMI-type, fibrous-membrane application were selected for evaluation. Before actual field placement, fiber-reinforced asphalt concrete was included in the study at the request of the District. Because fiber-reinforced concrete is a simpler application with lower overall cost relative to the other treatments, its consideration in the comparison was desirable. Table 1 summarizes the treatments compared.

OBJECTIVES

The primary objective of this study was to determine whether any of various treatments would significantly retard reflective crack formation in the asphalt concrete overlay. All treat-

Pennsylvania Department of Transportation, 1118 State Street, Harrisburg, Pa. 17120.

TABLE 1 TREATMENT DESCRIPTION

	Treatment Identify	Product Description & Application
(1)	Control	No treatment - 1-1/2" ID-2 Wearing Overlay Existing Pavement.
(2)	Reepav T-376 Fabric Interlayer	Nonwoven, spunbonded, heatbonded polyester; rolled and tacked on existing pavement with asphalt cement prior to 1-1/2" ID-2 Wearing Overlay.
(3)	Amopave Fabric Interlayer	Nonwoven, needle punched, polypropylene; rolled and tacked on existing pavement with asphalt cement prior to 1-1/2" ID-2 Wearing Overlay.
(4)	Trevira 1115 Fabric Interlayer	Nonwoven, spunbonded, needle punched polyester; rolled and tacked on existing pavement with asphalt cement prior to 1-1/2" ID-2 Wearing Overlay.
(5)	Mirafi Fabric Interlayer	Nonwoven, needle punched, some heatbonding, polypropylene; rolled and tacked on existing pavement with asphalt cement prior to 1-1/2" ID-2 Wearing Overlay.
(6)	Fiber Pave 3010 Fiber-Reinforced Asphalt Interlayer	Asphalt cement (AC-20) composed of min. of 6% fine denier, short length polypropylene fiber; cast in place with specially designed mixing kettle/applicator prior to 1-1/2" ID-2 Wearing Overlay.
(7)	Bonifibers B Fiber-Reinforced Asphalt Overlay	Addition of 0.3% (by wt. of mix) fine denier, short length polyester fiber to ID-2 wearing at mixing plant; 1-1/2" Modified ID-2 Wearing Overlay of existing pavement.

ments involved the use of synthetic fabric or fibers and were compared with control pavement sections in which only a conventional hot-mix overlay was placed. As a secondary objective all treatments were compared with each other to determine relative performance, considering cost, ease of placement or adaptability to normal overlay practice, and effective length of time in resisting reflective cracking. The pavement sections were monitored in the field for approximately 4 years to determine overall and relative performance of each treatment.

PROJECT SITE

Roadway Location and Description

The project site is identified on the state highway system as State Route (SR) 11, Segment 650-661 (Traffic Route U.S. 11) in the Borough of Wyoming, Luzerne County. As a principal arterial highway, it is designated as Primary on the Federal-Aid System. Current average daily traffic (ADT) is about 14,000 vehicles.

The pavement section is a tangent 4,350 ft long, 55 ft wide, and curbed; there are four travel lanes with parking in both directions. Originally constructed and maintained by the county, the road was turned over to state jurisdiction in 1934. Today the pavement consists of both a rigid and a flexible base, because the original portland cement concrete was separated by a trolley-car area constructed on native stone (in the center of the highway). When the trolley service was abandoned before 1934, the track area was paved with bituminous concrete. A schematic of the pavement's cross section (Figure 1) summarizes the construction and maintenance history.

Preconstruction Roadway Condition and Analysis

Two types of survey were utilized to describe the roadway condition before overlay construction. A pavement-condition survey was performed using the Systematic Technique to Analyze and Manage Pennsylvania Pavements (STAMPP) format to analyze the observed surface conditions (*6*). A structural survey based on deflection measurements with a road rater was also obtained to determine relative movement of the underlying base when under load. Although the condition survey, which is based on visual observation, readily identified surface distress, such as cracking, it was essential to determine whether any distress was related to structural weakness. According to the Road Rater data, areas or pockets of base failure had occurred. Identification of these areas was particularly important to prevent biased evaluation.

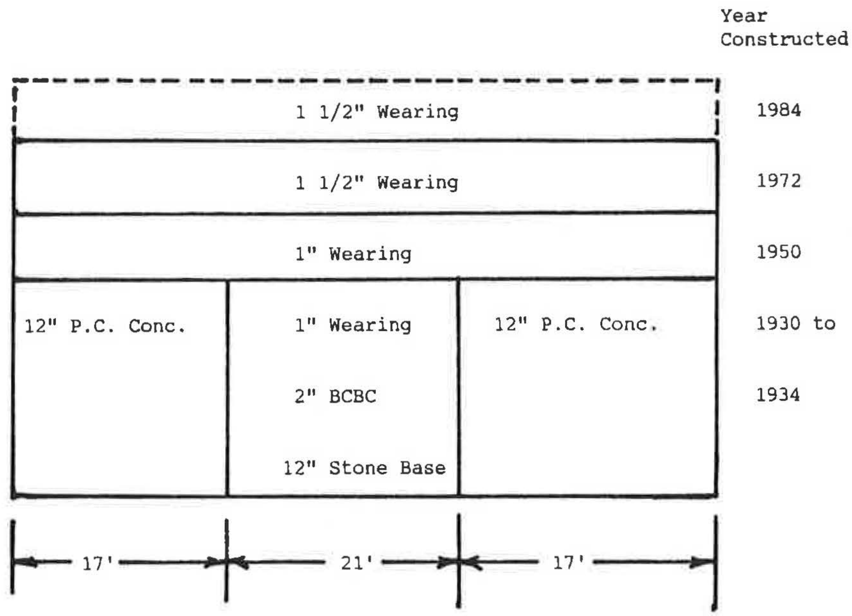

FIGURE 1 Pavement cross section.

TABLE 2 PRECONSTRUCTION PAVEMENT DISTRESS RATING

Location: Sec. No.	Location: Begin Sta.	STAMPP Condition Survey: Block Cracking	Joint Cracking	Alligator Cracking	Patching	Potholes	Widening Drop-off	Road Rater: Average Deflection (Mils)	Total Rating Cumulative	Subjective Rating
		1 2 LOW	3 4	5 6 MEDIUM	7 8 HIGH	9				
NB 1	145+50	2,4	3	0	4	0	0	*	13***	L
2	150+00	2,5	2	0	1,4	1,4	0	1.01	20.01	M
3	156+00	2,5	2	0	0	0	0	1.04**	10.04	L
4	162+00	3,6	2	1,4	4,7	2	0	1.11	30.11	MH
5	168+00	3,6	2	1	1	0	0	1.06**	14.06	L
6	174+00	3,5	2	0	1,4	1,4	0	1.03	21.03	M
1	180+00	3,5	2	1	4,7	3	1	1.49	27.49	MH
7	184+40	3,5	2	1	4,7	3	1	1.49	27.49	MH
SB 7	145+50	3,5	2	1	4,7	1	0	*	23***	M
1	152+00	3,5	2	1	4,7	1	0	1.29	24.29	M
6	156+00	6,7	2	1	4,7	5,7	0	1.20**	40.20	H
5	162+00	6,7	2	1	1	1	0	1.01	19.01	ML
4	168+00	6,7	2	0	1	1	0	0.94**	17.94	ML
3	174+00	5,7	2	4	4	1	1	0.90	24.90	M
2	180+00	3,5	2	4	1	2,4	1	1.16	23.16	M
1	186+00	6,8	3,7	0	1,4	0	3	1.16	33.16	H

Total Rating Key

15.35 - Low (L) 15.35 - 19.20 - Medium Low (ML) 91.20 - 26.90 Med. (M)
26.90 - 30.75 Med. High (MH) 30.75 High (H)

*No reading taken **Interpolated from readings ***Missing Data

By combining the results of both surveys, a numerical rating was developed for each pavement section. Statistical analyses of the sections' total ratings revealed that the data closely approximated a normal distribution or bell-shaped curve. Five subjective categories of distress were determined on the assumption that the calculated mean represents average or medium distress. The five distress levels were classified as low, medium-low, medium, medium-high, and high. A summary of distress rating based on the preconstruction surveys is presented in Table 2.

Despite the range of initial pavement distress, one type of cracking—block cracking—appeared to be dominant and more or less uniformly distributed throughout the project. This distress, as the primary object of treatment in this study, was considered an important indicator of relative performance between treatments. Other types of distress, as identified in Table 2, were also considered significant in the performance analysis, because of the application of selective preliminary repair work, which included base patching and placement of a scratch course for sealing and leveling.

CONSTRUCTION

Preliminary Work

Areas exhibiting the highest level of distress received base repair in combination with a variable-width scratch course for leveling and sealing of open cracks. Areas indicating the least distress received nothing or only minimal scratch course placement, primarily for the purpose of leveling.

Although crack sealing was not made part of this contract, many of the numerous cracks had been previously sealed by maintenance forces during the fall of 1983 or were covered by the scratch course. It should be noted that not all cracks had been sealed or covered before interlayer placement. Generally, it is recommended by the paving fabric manufacturers that cracks averaging ¼ in. or wider be treated in this manner.

General Description of Interlayer and Overlay Construction

Interlayer and overlay placement was accomplished as a consecutive and continuous two-step process. When control and fiber-reinforced ID-2 hot mix were specified, the interlayer step was eliminated and no changes in conventional paving operations were required. Paving of approximately 27,000 yd^2 was completed in 3 days (June 26–28, 1984). A fourth day was spent sealing joints with asphalt cement (construction joints, curbs, manholes, etc.). Weather conditions during this period were good for paving construction. Daily temperatures averaged between approximately 56° to 80°F during working hours.

The additional procedures required in conjunction with each treatment were variable and thus the effect on paving efficiency varied. In general, delays due to such procedures were infrequent; however, on occasion significant problems were encountered, causing delays and less satisfactory treatment. Early occurrence and greater frequency of these more significant problems tend to indicate that inexperience with the applications was a major factor.

Although the contractor indicated some experience in installing paving fabric, this experience was quite limited. This was most evident during the first fabric placement which resulted in the poorest application of all treated pavement sections. However, there were other factors that were less dependent on experience and more relevant to a treatment's application requirements or material properties. In yet other instances, problems occurred because the equipment for a particular operation was improper, not correctly adjusted, or just difficult to use.

The bituminous paving on this project was governed and accepted in accordance with PennDOT's Restricted Performance Specifications (RPS) (7).

A summary of loose and compacted field samples of hot mix tested for acceptance is presented in Table 3. Although spot deviations in the mix composition, particularly low asphalt content, are noted, the overall quality of the mix and its placement is acceptable on the basis of the bonus-penalty point system, which is a standard part of the specification.

Although not required by contract, field samples of all treatment products were obtained and tested in the laboratory. A summary of the test results is presented in Table 4. Primarily, testing was to verify certain physical properties and composition relative to those specified or published by the manufacturers.

TREATMENT PLACEMENTS

Paving Fabric Interlayer

Fabrics supplied by four manufacturers were installed in test sections 2, 3, 4, and 5, generally conforming with the prescribed procedures and methods provided by those technical representatives in attendance. The recommended procedures and requirements for placement are essentially the same for each fabric.

Based on the observations from this project's construction and the recommendations by technical representatives, five critical considerations affect satisfactory placement of a paving fabric.

1. The tack coat should be applied at the proper rate and uniformly spread for complete coverage.
2. Fabric laydown should be smooth, with minimal wrinkling.
3. The tack coat application and fabric laydown should be coordinated for effective tacking.
4. Overlapped joint construction should be used to achieve complete coverage.
5. The pavement overlay should closely follow fabric placement to avoid potential damage by traffic.

Extremely poor placement was observed during the first day's fabric laydown. The laydown crew had difficulty in maintaining a straight and wrinkle-free roll despite guidance by the fabric technical representative. The first day's placement, attempted by using the tractor-mounted rig and then manual rolling, was unsuccessful. Perhaps the most significant causes of trouble for this placement were the crew's inexperience and a poorly applied tack coat preceding the laydown.

Inadequate heating of the AC-20 resulted in clogging of the distributor nozzles in the middle of the spray pattern, causing nonuniform and inadequate coverage. To correct the skips, hot AC-20 was applied with a hand-held pot. This method did not provide a uniform and satisfactory correction. The initial heating of AC-20 to approximately 300°F was apparently insufficient to prevent the distributor nozzles from clogging. Not until the next application, when a heating range between 350° and 375°F was maintained in the kettle, did the distributor produced a continuously uniform spray pattern.

Poor bonding between the hot-mix overlay and the underlying pavement was also documented to have occurred, but only during the first day's placement. Two of the five core samples taken for density acceptance indicated either total or partial bond failure. It was easily understood that poor bonding occurred with one of the samples, because the location had been insufficiently tacked. For the second sample the fabric had bonded to the underlying pavement but the overlay achieved only partial bonding to the top of the fabric. Apparently, the tack was not drawn up through the fabric sufficiently. Normally, complete absorption occurs because of the heat of the hot mix and the pressure of the rollers. Insufficient pressure was most likely the problem here, because the den-

TABLE 3 SUMMARY OF LABORATORY TESTS OF FIELD SAMPLES FOR OVERLAY ACCEPTANCE: STANDARD HOT MIX (ID-2 WEARING) EXTRACTION SUMMARY

No. Samples		U.S. Sieve Size (Opening) - Percent Passing									Asphalt Content (%)
		1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200	A.C.
	Upper Limit	100	100	72	51	40	32	23	14	6.3	6.8
	Design	100	96	64	45	34	26	17	8	4.3	6.4
	Lower Limit	92	88	56	39	28	20	11	2	2.3	6.0
(5)	Ave. 1st Day	100	96	61	45	34	25	15	8	3.9	6.0*
(5)	Ave. 2nd Day	100	94	60	44	34	26	16	9	4.6	6.0*
(7)	Ave. 3rd Day	100	95	64	46	35	26	16	8	5.0**	6.2

* 1 sample each day below lower limit (5.9)
**1 sample above upper limit, calculated to be an outlier (8.6) statistically

ID-2 Wearing Density Summary

Design Density (Theoretical, voidless mix) - 150.4 lbs/cu. ft.

No. Samples		Density (lb/cu. ft.)	Compaction (%)
(5)	Ave. 1st day	140.6	94
(5)	Ave. 2nd day	141.4	94
(7)	Ave. 3rd Day	142.0	94

sity core measured a marginal compaction of 90 percent; this was the lowest compaction recorded for the project.

The two most common problems observed initially—poor tack coat application and badly wrinkled fabric laydown—were largely influenced by the contractor's inexperience. However, as early as the second day of placement, the efficiency and quality of laydown efforts improved considerably. Poor laydown observed after this could be attributed to other factors, mostly related to individual fabric properties.

Difference in fabric manufacture is identified as the primary factor contributing to the ease or difficulty of laydown. Because all the fabrics considered are nonwoven, their structure is formed by locking or bonding the fibers together by methods other than weaving. The bonding methods considered here consisted of varying combinations of spun bonding, needle-punching, and heat bonding.

Fabric 2 is formed by a combination of spun bonding and heat bonding. Heat bonding for this fabric is the primary method of locking the fibers together into a mat. The fibers are brought to a semiliquid state and pressed together. This process results in a fabric with significantly different physical properties than one formed by needle-punching, a mechanical bonding method. This fabric is thinner, lighter, and more rigid than the other fabrics. Table 4 indicates that lower grab-strength values were obtained with Fabric 2 than with the other fabrics. Apparently because of this rigid nature, Fabric 2 was considerably more difficult to place wrinkle-free, even after almost 3 days' experience with fabric laydown.

Fabric 5 presented similar, but less severe, wrinkling during placement. Although needle-punched, it is also partially heat bonded, which results in a smooth glossy surface on one side.

Heat bonding may also have been partially responsible for another minor problem experienced during paving, which was only observed during placement of Fabrics 2 and 5. Occasionally, the paving foreman noted that the paver was slipping and the underlying fabric was moving. This was minimized by shoveling hot mix in front of and underneath the paver tires, as recommended by fabric technical representatives.

Fiber-Reinforced Asphalt Membrane Interlayer

This treatment (No. 6) was considered an alternative method to placing paving fabrics. It consists of placing an asphalt cement membrane formed from AC-20 and polypropylene fibers. The fiber-reinforced membrane was selected for comparison with paving fabrics because of prior evaluation. As part of another research project (*8*), it was indicated that when applied in a narrow band over joints and cracks, the asphalt membrane performed well as a sealant. When this treatment is applied full width across the pavement, as in this project, it results in a fiberized SAMI.

TABLE 4 SUMMARY OF LABORATORY TESTS FOR FIELD SAMPLES OF TREATMENT MATERIALS: FABRIC PHYSICAL PROPERTIES

Fabric Treatment Designation Number	Weight	Thickness	Grab Tensile Strength[a] (lb)	Elongation[a] (%)	Calculated Tack Coat Requirement[b]
	oz./yd^2	mils	*MD/CD	*MD/CD	gal./yd^2
2	2.86 (3.0-4.0)	14.2 (-)	96/73 (-)	27/32 (-)	0.17 (0.20-0.30)
3	4.80 (4.0)	55.9 (-)	132/127 (90)	42/36 (55)	0.29 (0.20-0.25)
4	4.58 (4.5)	55.8 (85)	155/114 (130/110)	45/51 (85/95)	0.29 (0.25-0.30)
5	5.91 (4.0)	73.2 (-)	169/134 (115)	35/37 (60)	0.34 (0.20-0.25)

a - Test method ASTM-D-1682
b - Based on formula developed by Caltrans laboratory research using measured weight and thickness properties of fabric
( ) - Available manufacturer data or recommendations
* - Machine Direction/Cross Direction

Extraction Results of Fiber-Reinforced ID-2

	U.S. Sieve Size (Opening) - Percent Passing									Fiber Content	Asphalt Content (%)
	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200	(%)	
Upper Limit	100	100	72	51	40	32	23	14	7.3	---	7.3
Design	100	96	64	45	34	26	17	8	4.3	0.38	6.6
Lower Limit	100	88	58	39	28	20	11	2	3.0	---	5.9
Sample (6-28-84)	100	96	64	47	38	29	18	8	3.6	0.3	6.9

Sample represents 2nd section of fiber-reinforced mix (3rd day paving, southbound lanes). Sample contained 0.3% fibers by weight, which is equivalent to 6.0 lb/ton of hot mix. The fiber manufacturer recommends 7-1/2 lbs/ton when traffic density is greater than 10,000 ADT.

Fiber Content of Fiber Reinforced Asphaltic Membrane

Sample (6-28-84) 8.9% fibers (weight basis; average of 2 increments).
Sample represents 2nd section of fiber-reinforced membrane (3rd day paving, southbound lane
The manufacturer recommends a minimum of 6.0% fibers.

The mix formulation for this project specified proprietary fibers at a rate of 6.0 percent by weight of the asphalt. An additive, which is an adhesion promoter, was also blended in the mix at a rate of 2.0 percent by weight of the asphalt. The mixture was first heated and blended in a special trailer-mounted, kettle applicator provided by the manufacturer. After the proper heating and blending were achieved, the mixture was applied directly on the old pavement surface (no tacking was required).

Because the treatment requires the operation of specialized equipment, the mixture was prepared and applied by the manufacturer's technical representatives. The only work performed by the contractor was the application of the stone cover following the membrane laydown. The two sections of this treatment were placed on separate days. The northbound section's placement was the first feature observed on the project, and similar to the first fabric placement, the startup was plagued with problems, which resulted in significant delay of the overlay paving. The overall control and efficiency of the second placement was better, apparently because of the experience gained during the first day's work.

The aggregate cover to protect the membrane before and during paving was considered to be poorly applied for both section placements. This was the result of using inappropriate equipment for the material applied. The use of a dump truck with a hand-held tailgate lever resulted in coverage that varied from excessive in many areas to inadequate in others. Also, the aggregate, which is a Pennsylvania 1-B (equivalent to an AASHTO No. 8), was noted to contain high-moisture pockets. To complicate the situation further, the aggregate was rolled into the membrane using a steel-wheeled rather than a pneumatic roller, which resulted in considerable crushing and pulverizing of the aggregate.

Much of the responsibility for the improper application lies with the fiber manufacturer. The original membrane design had specified a sand cover, which required a steel-wheeled roller. Within only several days of the scheduled work, the manufacturer recommended changing the cover to stone because recent experience had shown that a more stable mat resulted, with less tendency for the asphalt to bleed. However, the contractor was not prepared to provide the proper roller for stone or a more sophisticated aggregate spreader.

Fiber-Reinforced Asphalt Concrete (No Interlayer)

A single proprietary polyester fiber was selected at the request of the District, even though other fibers, such as polypropylene, are also marketed for hot-mix reinforcement. The District's selection was primarily based on the paving contractor's recommendation and his prior experience with this fiber. Fibers of polypropylene and polyester differ in a number of ways, including physical and dimensional characteristics. Perhaps the most significant difference between them is that polypropylene melts and the fibers are destroyed when exposed to temperatures between 320° and 350°F, whereas polyester does the same but at temperatures between 480° and 490°F. Thus, if polypropylene fibers are used to reinforce a hot mix, it is essential that mix temperatures be tightly and properly controlled.

The mix formulation for this project was 0.3 percent fiber content or 6 lb of fiber per ton of hot mix. The fibers were added to the mix in premeasured and packaged bags at the beginning of the dry mixing cycle along with the dried aggregate.

This treatment, without question, was the easiest application observed on the project to adapt to normal paving operations. No additional manpower was required and the modified hot mix was applied with conventional equipment without any noticeable difficulty or delay.

RATING OF TREATMENTS BASED ON APPLICATION/COST

To summarize and provide a means of comparing the relative constructibility of the treatments observed, a rating system was developed. The rating summary of treatments is presented in Table 5. The criteria for comparison are essentially the three general factors: cost, potential for causing delay in construction, and potential for causing related paving or post-application problems.

PERFORMANCE

An initial crack survey was performed on February 26, 1985, 8 months after construction. Approximately 350 distinct cracks were identified, which totaled approximately 1,500 linear ft. The primary type of crack observed was a tight 2- to 4-ft transverse crack; however, the length of the cracks varied considerably, including a few that extended the full width of

TABLE 5 CONSTRUCTION APPLICATION RATING

Rank	Test Product	Cost	No. Steps	Ease of Application[a]	Potential for Related Paving Problems[b]	Total* Score
		($/yd^2)				
6	2	1.65	2	4	2	9.65
2	3	1.50	2	2	0	5.5
3	4	1.70	2	2	0	5.7
5	5	1.45	2	3	1	7.45
4	6	2.00	2	3	0	7.0
1	7	1.04	1	1	0	3.04

[a]Key
1 - Easy 2 - Moderately Easy 3 - Moderately Difficult
4 - Difficult

[b]Key

0 - None observed 1 - One problem observed
2 - Two or more problems observed

*Lowest score is equivalent to highest ranking

What is desired most is a treatment that is cost-effective as well as trouble free to apply. However, cost-effectiveness is dependent on performance data which indicates relative benefit versus distress treated at a reduced cost.

a treatment section or were severe in nature (¼ in. wide or more). Approximately 7 percent of the transverse cracks measured a full paving-lane width or more. Of all the cracks observed, 60 percent were located in the travel lane. Although the number of longitudinal cracks accounted for only 10 percent of the total number observed, this was equivalent in length to about 20 percent of all cracking. Many of the longitudinal cracks were located along the paving joints where interlayer treatments were not overlapped during construction.

Follow-up Crack Surveys

A follow-up crack survey was performed on August 13 and 14, 1985, during the first of three scheduled annual pavement condition surveys. No new distress conditions were apparent and there was no significant change in the relative number and location of cracks. Even though some of the tight hairline cracks noted in February were no longer easily seen, the relative condition between all pavement sections was unchanged since the earlier survey.

Two additional crack surveys were performed after the evaluation of construction and early performance data in September 1985, the first occurring at 26 months and the last at 44 months after construction. By identifying the location and length of each crack during each survey, the growth of initial cracks and development of new cracks has been documented with reasonable precision. Postconstruction deflection measurements should also have been gathered because of the varying base conditions resulting from construction; however, this aspect of the evaluation was overlooked.

Crack Development

Overall, cracking has been increasing at a significant rate. Cracking multiplied more than eight times between the 8- and 44-month surveys. The 26-month survey indicated that cracking had more than doubled relative to the first survey, whereas the 44-month survey determined that cracking had more than tripled since the previous survey. Examination of the 16 individual sections indicated that the rate, in feet per month, has fluctuated, with most sections actually measuring a decrease in rate between 8 and 26 months. This trend was even consistent in the control areas. However, all sections indicate a relatively sharp increase in cracking rate after 26 months (see Table 6).

Data summaries provided in Table 6 indicate some relative performance factors regarding crack development and growth. This may explain some of the differences observed. Deflection measurements (as indicated by the Road Rater) and adequate preliminary treatment (such as base patching and scratch-course placement, when required) may be the significant factors correlating relative performance. Separating the project into two components, northbound and southbound, appears to illustrate this best.

Table 7 summarizes crack development by type (transverse and longitudinal) for each project half (northbound and southbound). The southbound lanes received a significantly greater portion of preliminary treatment in the form of base patching and scratch-course placement relative to the northbound lanes. It is apparent that an initial benefit from this treatment of additional retarding of all types of cracking occurred for a period of approximately 1 to 2 years. However, after that period, the treatment's effectiveness diminished and both halves of the project cracked at very nearly equal rates. This trend is apparent for both transverse and longitudinal cracking. It is also apparent that even though primarily transverse cracks occurred initially, the longitudinal type had increased by the time of the 44-month evaluation, and both longitudinal and transverse cracks were occurring at a nearly uniform rate. The block-cracked, preconstruction condition had clearly reflected through the overlay at 44 months.

Table 7 also includes an additional summary of control

TABLE 6 RELATIVE CRACK OCCURRENCE BETWEEN TREATMENTS

Treatment Designation	Total Area (ft^2)	Total Cracking Identified by Survey (Time After Construction) 8 months (ft)	26 months (ft)	44 months (ft)	Crack Ratio Length Relative to Area 8 Months (ft/ft^2)	26 Months (ft/ft^2)	44 Months (ft/ft^2)	Crack Ratio Reduction Relative To Control 8 Months (%)	26 Months (%)	44 Months (%)
(1)	38,160	543	1,118	3,633	0.0142	0.0293	0.0952	---	---	---
(2)	28,800	225	565	2,134	0.0078	0.0196	0.0741	45.0	33.0	22.2
(3)	28,800	164	469	1,586	0.0057	0.0163	0.0551	59.9	44.4	42.2
(4)	28,800	32	308	1,298	0.0011	0.0107	0.0451	92.2	63.5	52.7
(5)	28,800	183	474	1,508	0.0064	0.0165	0.0524	55.2	43.8	45.0
(6)	28,800	103	260	1,471	0.0036	0.0090	0.0511	74.8	69.2	46.4
(7)	26,640	277	454	1,247	0.0104	0.0170	0.0468	26.8	41.8	50.8
Overall	208,800	1,527	3,648	12,877	0.0073	0.0175	0.0617	*59.4	*49.4	*43.1

*Based on Overall Excluding Control

TABLE 7 CRACK COMPARISON BY TYPE AND LANE DIRECTION

ALL TREATMENT SECTIONS*

	Transverse Cracks (FT)			Longitudinal Cracks (FT)		
Direction	8 Months	26 Months	44 Months	8 Months	26 Months	44 Months
Northbound Lanes	807	1,015	3,362	192	1,010	3,065
Southbound Lanes	450	884	3,441	78	739	3,009
Combined	1,257	1,899	6,803	270	1,749	6,074

CONTROL SECTIONS

	Transverse Cracks (FT)			Longitudinal Cracks (FT)		
Direction	8 Months	26 Months	44 Months	8 Months	26 Months	44 Months
Northbound Lanes	306	365	921	86	342	905
Southbound Lanes	106	194	816	45	217	991
Combined	412	559	1,737	131	559	1,896

*Including Control

sections only. This was done primarily to verify that the trends noted overall were also occurring in untreated pavement (as defined in Table 1).

Cost-Benefit Analysis

Given the apparent conclusion that all treatments have provided some benefit in performance by retarding crack development for a period of time, it is important to determine whether the benefit is of sufficient magnitude and long-term enough to provide a true life-cycle cost benefit. This is particularly important because for most of the treatments the benefits are currently diminishing.

Based on a life cycle of 10 years for the applied overlay and using current performance and costs, several estimates of future performance and the related costs are proposed and summarized in Table 8. An initial maintenance activity of crack sealing is proposed, followed by a second sealing activity during the life cycle. Several estimates of future total cracking are proposed, because this is an important unknown and will have a significant impact on life-cycle costs. The proposed rates are based on current weighted averages calculated using the three previous crack surveys as a basis. It is assumed that cracking will continue at an average rate not greater than the current weighted average and that proportional differences in performance between treatments will remain the same. This is obviously a hypothetical assumption and is subject to future verification.

However, it is the opinion of the authors of this paper that the estimates are conservative and that future increases may be actually much higher in the treated sections relative to the control because of diminishing benefits.

Despite probable inaccuracies in the assumptions presented, several conclusions appear to be significant. It is apparent that crack sealing as proposed is a relatively low-cost item in the life-cycle cost prediction relative to the initial construction costs of all of the treatments compared.

These relative cost factors indicate that currently observed crack reduction ratios are insufficient to offset the construction costs by the end of the proposed life-cycle. In fact, even if no further cracking occurs in any of the treated sections while it continues at the maximum proposed rate in control pavement, a cost benefit will still not be realized.

On the basis of this analysis, none of the fabric and fiber treatments evaluated in this study are considered cost-effective for crack control when applied to a pavement with similar conditions and distress levels as those identified in this project. However, it is recommended that additional future surveys of this test site be conducted and that additional field testing, including full-depth pavement core samples, be evaluated to further document long-term results and effects of such treatments.

SUMMARY OF OBSERVATIONS AND CONCLUSIONS

Construction

- Primarily due to contractor inexperience, the construction using paving fabrics with fiberized membrane interlayer

TABLE 8 ESTIMATE OF LIFE-CYCLE COSTS

Treatment Designation	Current Cracks (LF)	Prop. Seal Cost ($) ($.25/LF)	Const. Treatment Cost ($)	Prop. Total Cost ($) @ 44 Mo. After Const.	Estimated Cracks (Total) (LF) 80 Mo. After Const. 1 Method A	2 Method B	3 Method C	Estimated Costs ($) Seal & Reseal @ 80 Mo. (Assume Cost Escalates @ 5% Annually, ($0.29/LF) Method A	Method B	Method C	** Total Life Cycle Costs Based on Estimates ($) Method A	Method B	Method C
(1)	2,742*	686	---	686	4,987	4,248	3,866	1,466	1,232	1,121	2,132	1,918	1,807
(2)	2,134	534	5,280	5,814	3,880	3,304	3,007	1,125	958	872	6,939	6,772	6,686
(3)	1,586	396	4,800	5,196	2,882	2,454	2,234	836	712	648	6,032	5,908	5,844
(4)	1,298	324	5,440	5,764	2,360	2,010	1,829	684	583	530	6,449	6,347	6,295
(5)	1,508	377	4,640	5,017	2,739	2,323	2,124	794	674	616	5,811	5,691	5,633
(6)	1,471	368	6,400	6,768	2,677	2,279	2,074	776	661	601	7,544	7,429	7,369
(7)	1,348*	337	3,285	3,622	2,450	2,086	1,899	710	605	551	4,332	4,227	4,173

1 - Cracking will continue at 100% of the current 44 month weighted average rate LF/Mo.

2 - Cracking will continue at 67% of the current 44 month weighted average rate LF/Mo.

3 - Cracking will continue at 50% of the current 44 month weighted average rate LF/Mo.

* - Adjusted to equivalent area of other treatments (28,000 SF)

** - Assume 10 year life cycle and this is last maintenance to be performed initially had some problems, resulting in less than satisfactory placement. The two most common problems encountered with paving fabric placement were poor tack coat application and excessive wrinkling of the fabric during laydown. Problems occurring with the fiberized membrane were primarily related to the equipment used.

- The fabric manufacturing process contributed to the laydown ease and quality. There were more construction difficulties with fabrics that were heat bonded, even if only partially.
- The fiberized hot-mix asphalt overlay (Treatment No. 7) was placed using normal paving equipment and operations. No additional manpower was required, and placement was achieved without difficulty or delay.

Performance

- Based on the cracking evident after 44 months and considering crack-sealing and construction costs, none of the treatments tested is now considered cost-effective. However, this is dependent on the assumptions that projected future cracking rates, sealing costs, and a normal pavement overlay service life of 10 years are reasonably correct.
- The differential movement of pavement layers produced stresses of greater magnitude than those previously assumed to occur in block-cracked pavement. None of the treatments considered could provide sufficient tensile strength to effectively resist those stresses for longer than about 1 to 2 years.
- All treatments retarded cracks over the evaluation period, although the amount and rates of reduction were very different. Based on all evaluation factors—ease of construction, cost, and final performance relative to distress treated—Treatment 7 is given the best current rating among all the treatments compared.
- Cracking in the southbound lanes were less than that in the northbound lanes after the initial crack survey. It is presumed that this is the result of the greater amount of base repair, patching, and scratch-course placement in the southbound lanes. However, by the time of the 44-month survey, the cracking became essentially equal in both directions. It can be inferred that the additional preliminary work contributed substantially to early crack reduction, but did not appreciably reduce it in the long term.

RECOMMENDATIONS

The following recommendations are made on the basis of this study:

1. Use of paving fabrics and fibrous treatments to retard reflective cracking is not recommended on the basis of the current analysis of life-cycle costs.
2. Cores should be removed from all sections of the experimental pavement to verify whether any sealing qualities remain from use of the interlayer-type treatments.
3. A follow-up inspection and crack survey should be made within 3 years to verify crack estimates and cost-evaluation considering actual sealing costs.
4. If similar investigations are considered by others, detailed documentation of surface and base distress, both before and after construction, is strongly recommended to minimize bias due to variations in distress conditions.

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Overlay Construction and Performance Using Geotextiles

Joe W. Button

Geotextiles (engineering fabrics) were installed at four locations in Texas to evaluate their potential as cost-effective measures to reduce or delay reflection cracking in asphalt concrete overlays. Test pavements were 0.25 mi long with the fabric installed edge to edge. Nine different types of commercially available geotextiles made of nonwoven polypropylene or polyester were tested. One woven experimental product composed of polypropylene and polyester was also tested. Resistance to reflective cracking has been evaluated for up to 9 years. Results, based solely on these test pavements, indicate that geotextiles are not cost-effective methods in addressing reflective cracking. However, limited evidence indicates that geotextiles will reduce pumping after cracking occurs. Additional data are presented showing that a fabric can be effective in reducing reflective cracking. Recommendations are made to maximize the probability of success when geotextiles are installed to reduce or delay reflective cracking.

Fabrics or geotextiles have been placed in asphalt concrete overlay systems since the 1960s for the purpose of reducing or delaying the occurrence of reflection cracking, or for both purposes. Results of field trials around the nation are available but often inconclusive in many respects. A field and laboratory research program (*1*) was initiated by the Texas Transportation Institute under sponsorship of the Texas State Department of Highways and Public Transportation (SDHPT) and FHWA. The primary objectives of this study were to develop the information necessary to evaluate the performance of geotextiles in asphalt overlay applications in order to

1. Determine the types of distress, if any, that fabrics can economically be used to correct,
2. Ascertain fabric properties that will optimize field performance,
3. Define satisfactory field installation procedures for utilizing fabrics, and
4. Establish realistic specification limits.

Field installations were constructed consisting of eight to thirteen 0.25-mi test sections in four different areas of the state. Two projects were constructed in 1979, one in 1980, and one in 1981. The test sections involved placement of a fabric followed by a hot-mix asphalt concrete (HMAC) overlay. Ten different geotextiles were compared with control sections consisting of either a conventional HMAC overlay with no interlayer or one with a chip seal as an interlayer. All test pavements were installed over cracked asphalt concrete or portland cement concrete pavements to evaluate the relative ability of the interlayer to reduce reflection cracking. Field performance of these test pavements has been evaluated for periods up to 9 years. Although not reported in this paper, laboratory tests were also conducted on all paving materials.

The purpose of this paper is to describe the construction of the field installation, identify the properties of the construction materials, and evaluate performance to date of the test pavements.

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SUMMARY OF FIELD PROJECTS

Four projects were installed in different geographic and climatic regions of Texas (Figure 1). Within each geographical location, the only variable was the type of geotextile. Ten different fabrics, applied to cover the complete pavement width, were evaluated. Fabric weights ranged from 3 to 8 oz/yd^2. Typical tack coats to accommodate these fabric weights ranged from 20 to 40 gal/yd^2, respectively. Specific information about each project is furnished in Table 1. Engineering fabrics installed at each of the four research projects are listed in Table 1 and described in Tables 2 and 3.

FINDINGS

The four field trials are described in detail in the following paragraphs. They are presented in chronological order according to installation.

Ozona

An 8.75-mi section of Interstate Highway 10 east of Ozona, Texas, was overlaid with HMAC in the fall of 1979. Thirteen 0.25-mi (1,320-ft) test pavements were designed and installed to evaluate the comparative ability of fabric interlayers to reduce or delay reflection cracking in an overlay. Geotextiles evaluated included Bidim C-22, Bidim C-34, Old Petromat, New Petromat, and 8 oz Petromat. The control section contained a conventional seal coat interlayer made of AC-5 and precoated grade 3 crushed limestone.

Preconstruction

The existing asphalt concrete pavement structure before the overlay is described briefly in Table 1. Transverse, longitudinal, and alligator cracking were prevalent in the travel lane for the entire length of this project. The most severe cracking

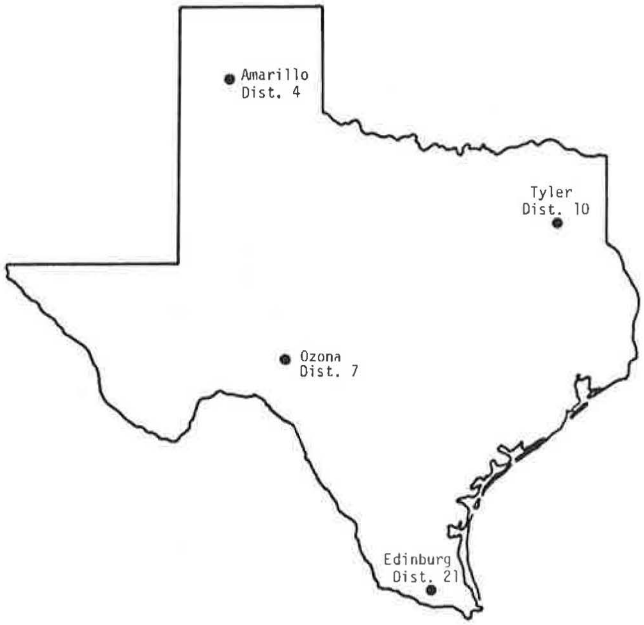

FIGURE 1 Location of trial field sections.

was in the right wheelpath of the westbound (WB) travel lane, which was also displaced downward in certain areas. This displacement was apparently due to severe pumping, which removed a significant volume of base material. Very little cracking was evident in the westbound passing lane. There was significantly less cracking in the eastbound (EB) lanes than in the westbound lanes. Although total traffic volume on this roadway is rather low, the percentage of trucks is quite high (Table 1).

Construction

After the existing pavement was patched to repair localized failures, a predetermined quantity of asphalt tack (AC-20) was applied to the pavement surface. A small tractor with special attachments was used to apply the fabric to the tacked pavement within 2 to 20 min after the asphalt tack was applied. A pneumatic roller was employed to strengthen the bond between the fabric and the old pavement surface. Transverse fabric joints were typically overlapped 6 in. and tacked with emulsified asphalt. Following a light application of sand, the test sections were opened to traffic for a period of 1 to 3 weeks. An HMAC overlay was placed on each test section

TABLE 1 SUMMARY FIELD PROJECTS INVOLVING GEOTEXTILES

Item	Location: West of Ozona	West of Amarillo	Edinburg		East of Tyler	
Highway Designation	IH-10	IH-40	US 281 and SH 107		IH 20	
No. of Lanes each Direction	2	2	2		2	
Existing Pavement						
Layer 1 (top)	3″ HMAC[1]	1″ HMAC (Type D)[2]	1″ HMAC[1]		8″ CRCP	
Layer 2	15″ Flex Base	3″ HMAC (Type A)	12″ Flex Base		RC-2 membrane	
Layer 3	Subbase	12″ Flex Base	Subgrade		6″ Soil Cement	
Layer 4	—	6″ lime Tr. Subgr.	—		Subgrade	
Date of Overlay Construction	Aug–Sept 1979	Sept 1979	Feb 1980		July 1981	
Materials Evaluated	Chipseal (Control) Bidim C-22 Bidim C-34 Old Petromat New Petromat Petromat 8 oz	Control Bidim C-22 Bidim C-34 Old Petromat New Petromat Petromat 8 oz	Control Bidim C-22 Bidim C-34 Old Petromat New Petromat Petromat 8 oz Bidim C-28		Control Old Petromat New Petromat Reepav—3 oz Reepav—4 oz Crown-Zellerbach Mirafi 900×	
HMAC Overlay	Type D	Type D	Type D		Type B[3]	Type D
Asphalt Type & Grade	AC-10	AC-10	AC-10		AC-20	AC-20
Asphalt Source	Refinery 4	Refinery 5	Refinery 15		Refinery 6	Refinery 24
Aggregate Type	Crsh Limestone + Field Sand	Crsh Limestone + Field Sand + Blow Sand	River Gravel + Sand		Crsh Limestone + Field Sand	Lt wt + conc. Sand + Fld Sand
Asphalt Additives	None	None	None		TexEmuls M-200	Pavebond AP
Thickness	1 ¾-inch	1 ¼-inch	1.6-inch		2-inch	1 ½-inch
Traffic Data (1980)			(US 281)	(SH 107)		
ADT	3,400	7,900	19,500	13,000	14,000	
Percent Trucks	24.1	23.8	3.4	18.2	22	
Equivalent 18K axle loads	5.983	15,468	19,043	1,476	—	
Percent Tandem Axles	90	20	90	40	40	

[1]HMAC—Hot-mix asphalt concrete.
[2]Type D—Dense-graded surface course HMAC containing a maximum aggregate size of ½ in.
[3]Type B—Dense-graded base or level-up course HMAC containing a maximum aggregate size of 1 in.

TABLE 2 PHYSICAL DESCRIPTION OF FABRICS INSTALLED IN TEST SECTIONS

Fabric I. D.	Nominal Weight, oz/yd^2	Nominal Thickness, mils	Material	Type Construction	Type Filament	Fiber Bonding
Bidim C-22	4	60	Polyester	Nonwoven	Continuous	Needle-punched
Bidim C-34	8	90	Polyester	Nonwoven	Continuous	Needle-punched
Old Petromat	4	--	Polypropylene	Nonwoven	Staple	Needle-punched and heat bonded on both sides
New Petromat	4	--	Polypropylene	Nonwoven	Staple	Needle-punched and heat bonded on one side
Petromat - 8 oz.	8	--	Polypropylene	Nonwoven	Staple	Needle-punched and heat bonded on one side
Bidim C-28	6	75	Polyester	Nonwoven	Continuous	Needle-punched
Reepav - 3 oz.	3	15	Polyester	Nonwoven	Continuous	Spunbonded and heat bonded
Reepav - 4 oz.	4	17	Polyester	Nonwoven	Continuous	Spunbounded and heat bonded
Crown-Zellerbach	5	60	Polypropylene	Nonwoven	Continuous	Spunbounded and needle-punched
Mirafi 900 X	5	---	Polyester and Polypropylene	Woven	Continuous	Woven

TABLE 3 PROPERTIES OF FABRICS

Test Pavement Location	Fabric I. D.	Average Fabric Weight oz/yd^2	Machine Direction [4] Elongation, percent	Machine Direction [4] Break, pounds	Cross Machine [4] Elongation, percent	Cross Machine [4] Break, pounds	Asphalt Rentention,[2] oz/ft^2	Change in Area,[3] Percent
Ozona	Bidim C-22[1]	4.4	85	148	84	128	4.2	0
	Bidim C-34[1]	7.1	91	215	108	211	5.2	0
	Old Petromat[1]	4.2	103	75	65	92	2.2	-2
	New Petromat[1]	4.2	76	121	67	154	3.6	-5
	Petromat - 8 oz.	8.6	78	300+	97	300+	4.9	0
Amarillo	Bidim C-22	---	---	---	---	---	---	---
	Bidim C-34	---	---	---	---	---	---	---
	Old Petromat	4.3	84	91	71	112	2.2	-2.0
	New Petromat	4.3	69	115	82.9	133	3.6	-4.8
	Petromat - 8 oz.[1]	8.4	71	300+	71	300+	4.2	0
Edinburg	Bidim C-22	4.9	95	113	99.8	116	3.6	-2.3
	Bidim C-34	---	---	---	---	---	---	---
	Old Petromat	---	---	---	---	---	---	---
	New Petromat	4.6	104	124	91	186	4.0	-9.0
	Petromat - 8 oz.	---	---	---	---	---	---	---
	Bidim C-28	6.5	83	162	91	113	3.8	0
Tyler	Old Petromat	4.6	90	154	79	110	3.4[1]	0[1]
	New Petromat	4.5	94	81	76	118	2.3[1]	0[1]
	Reepav - 3 oz.	3.0	50	89	59	73	---	---
	Reepave - 4 oz.	4.1	52	116	57	96	1.6	0
	Crown-Zellerbach	5.1	140	117	161	112	3.9[1]	0[1]
	Mirafi 900 X	4.9	58	102	47	76	---	---

NOTE: Properties were measured by SDHPT in accordance with specifications in Item 3099.
[1]Only one sample tested.
[2]Asphalt required to saturate fabric.
[3]Change in area (shrinkage upon exposure to asphalt at 275°F for 60 minutes).
[4]Grab tensile test, ASTM D1682.

at a rate of approximately 180 lb/yd² (about 1 ¾-in. compacted thickness).

Soon after Bidim C22 and C34 were applied, they were observed to "fluff up" due to the action of traffic. It appeared that the tires became sticky due to tracking in asphalt sprayed outside the edge of the fabric or asphalt that bled through the fabric. The sticky tires subsequently pulled up the fibers near the surface of the fabric, which gave the surface the fluffed appearance. The Bidim products were most susceptible to this phenomenon, but a notable quantity of fibers was completely removed from all the fabrics and deposited alongside the roadway. After a few hours and a light application of sand, the fabric was once again pressed flat onto the pavement by traffic.

Visual inspection during construction showed that New Petromat did not slip as much under the wheels of the pneumatic roller as did Old Petromat. This was particularly noticeable when the pneumatic roller was used on a grade. Old Petromat was manufactured with a thermally bonded "glaze" on both sides of the fabric, whereas New Petromat has the glaze on one side and is fuzzy on the other side. The fuzzy side, which provides a greater effective surface area for better adhesive and shear strength, is designated to be placed next to the asphalt tack on the old pavement surface to provide reinforcement at the interface. This is in agreement with results observed in the laboratory by Button et al. (*2*).

In one fabric, blisters up to approximately 6 in. in diameter were observed in one area (not in a test section). This segment of fabric was installed on a surface-dry pavement shortly after a shower. It is postulated that moisture in small crevices in the pavement was sealed in by the fabric-asphalt membrane; the trapped moisture was later vaporized by the sun's heat on the dark fabric surface, thus forming the blisters. The blisters were slit to allow the vapors to escape and pressed down before the overlay was placed.

Postconstruction

By February of 1980, after a severe winter, a few transverse cracks had appeared in the shoulder along certain sections of the EB travel lane, but they did not continue into the travel lane. No fabric was installed on the shoulders. It is therefore reasonable to assume that the fabrics delayed reflection cracking. Cracks began to appear in the travelway about 3.5 years after construction.

Figures 2 through 4 show transverse, longitudinal and total reflection cracking as a function of time in three representative 100-ft segments of pavement in the WB lanes. In the WB lanes the Petromat products most often exhibited the best resistance to reflective cracking; however, their performance is not a notable improvement over that of the seal-coat interlayer. Figure 5 shows total cracking in the EB test pavements. Although little cracking has occurred to date in the EB lanes, the seal coat is outperforming the fabrics. Observations after rainfall indicate that the fabrics may be reducing pumping well after cracks appear at the pavement surface.

Amarillo

A 13.2-mi section of Interstate Highway 40 near Vega, about 25 mi west of Amarillo, Texas, was overlaid with HMAC in

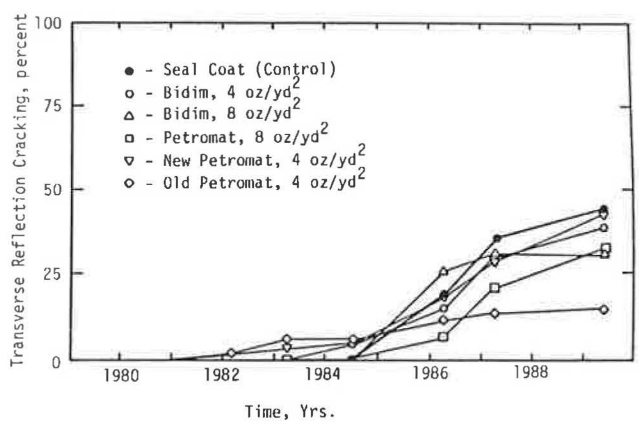

FIGURE 2 Percent transverse reflection cracking as a function of time for westbound test pavements on IH 10 near Ozona, Texas.

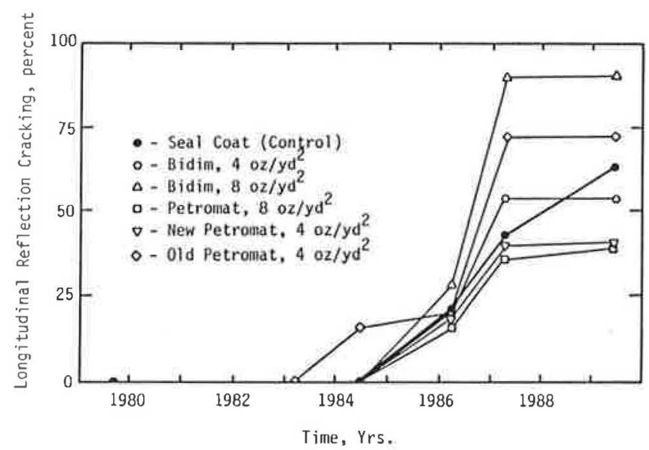

FIGURE 3 Percent longitudinal reflection cracking as a function of time for westbound test pavements on IH 10 near Ozona, Texas.

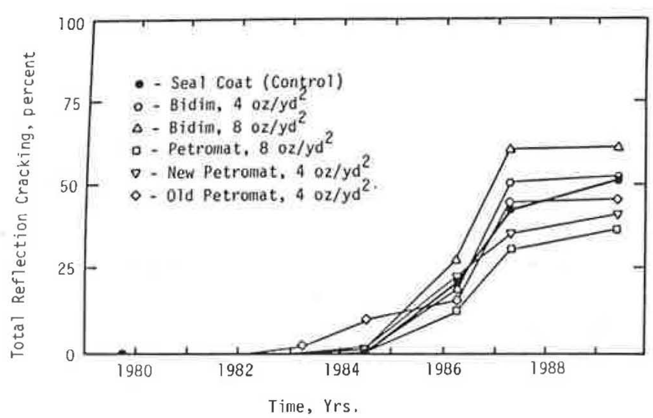

FIGURE 4 Percent total reflection cracking as a function of time for westbound test pavement on IH 10 near Ozona, Texas.

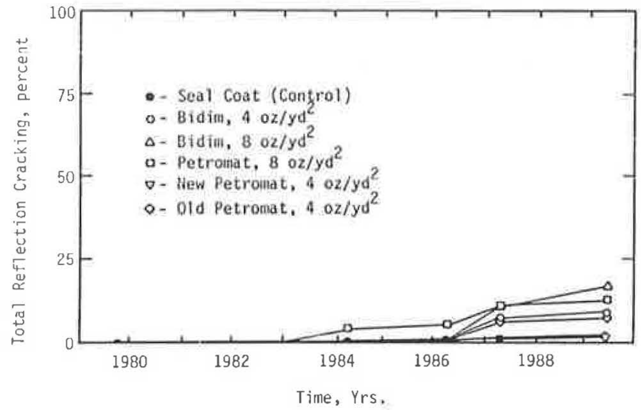

FIGURE 5 Percent total reflection cracking as a function of time for eastbound test pavements on IH 10 near Ozona, Texas.

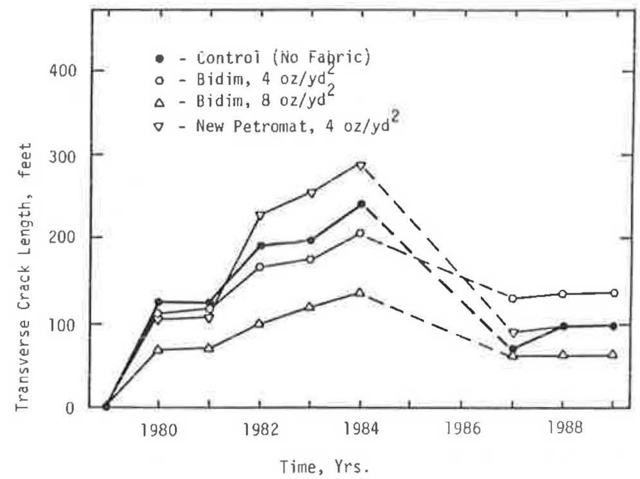

FIGURE 6 Length of transverse cracks in eastbound lanes as a function of time on IH 40 near Amarillo, Texas (600 lane ft).

the summer and fall of 1979. An area containing eight ¼-mi test sections was designated for a field trial to evaluate five different geotextiles (Table 1). The existing pavement was asphalt concrete. Different fabric combinations were used in the EB and WB lanes.

Preconstruction

In the summer of 1978, a seal coat was applied using Grade 3 precoated crushed stone. There was concern about placing the fabrics directly on this abrasive surface, because the action of traffic in conjunction with the highly textured surface might damage the fabric. Therefore, a level-up course of HMAC was placed in May 1979.

This construction project was not designated as a field trial for this study until after the seal coat was placed. Consequently, the researcher was unable to record the cracks in the existing pavement. However, verbal communication with the District Construction Engineer and an exhaustive series of photographs prepared by SDHPT personnel revealed that there was considerable fatigue cracking in the travel lane originally, with some thermal (transverse) cracking and moderate rutting throughout the project.

Construction

The fabric and HMAC overlay were placed in September 1979, about 4 months after the level-up course. Fabric was applied to both traveled lanes following application of an appropriate quantity of asphalt tack (AC-10). The fabric was rolled using a pneumatic roller. It was noted during construction that the thick fabrics (8 oz/yd^2) were installed with significantly fewer wrinkles than similar thinner fabrics (4 oz/yd^2). Fabric construction joints were tacked using a slow-setting anionic emulsion. After sand was applied to the fabric surface to aid in absorbing excess asphalt tack, the roadway was opened to traffic. Soon after the areas containing Bidim C22 and C34 were opened to traffic, the fabrics were observed to fluff up, as previously reported. The fabrics were exposed to traffic for 2 to 7 days before the overlay was placed. An

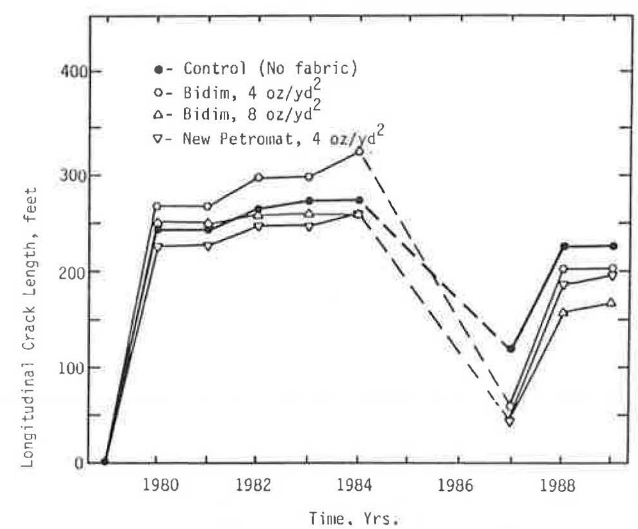

FIGURE 7 Length of longitudinal cracks in eastbound lanes as a function of time on IH 40 near Amarillo, Texas (600 lane ft).

HMAC overlay was placed on each section at 125 lb/yd^2 (about 1.25 in.). Control sections contained only a light tack between the level-up and the final overlay.

Post-Construction

Three 100-ft segments of pavement in each test section have been monitored periodically to evaluate the ability of the fabrics to reduce cracking. After 7 months in service, following the severe winter of 1979–1980, a visual evaluation revealed a considerable quantity of cracks. Figures 6 through 11 show that the cracks have continued to grow, but at a slower rate. Because the original crack patterns were not recorded, only crack length is shown in the figures and not the percentage of reflection cracking. In 1985 the pavements were heater-scarified to a depth of 0.75 in., an asphalt rubber seal con-

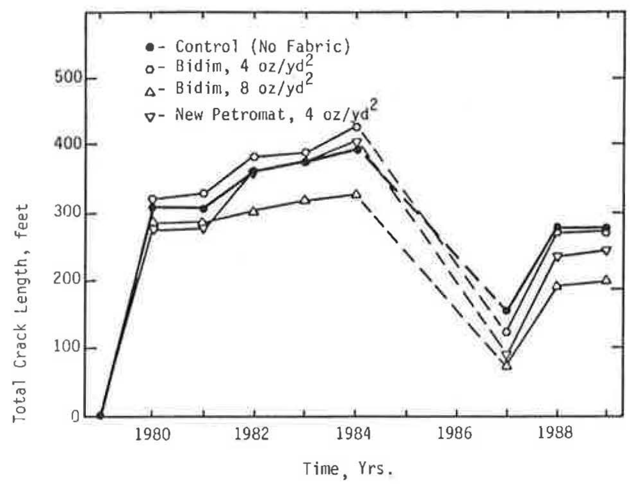

FIGURE 8 Total crack length in eastbound lanes as a function of time on IH 40 near Amarillo, Texas (600 lane ft).

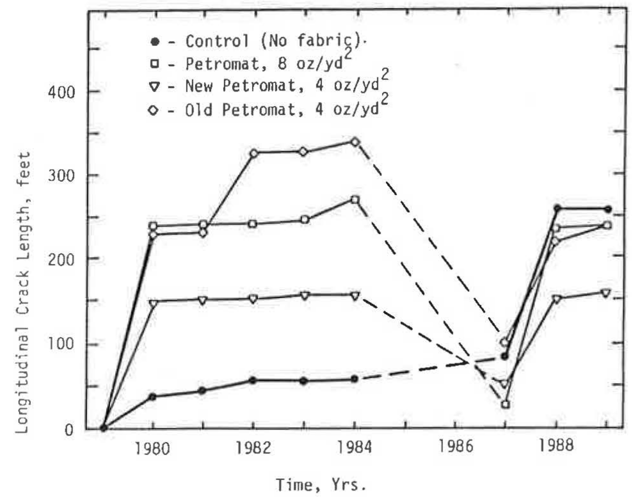

FIGURE 10 Length of longitudinal cracks in westbound lanes as a function of time on IH 40 near Amarillo, Texas (600 lane ft).

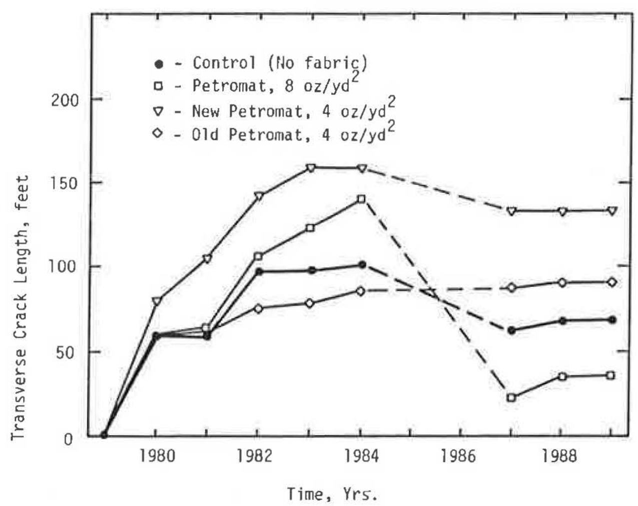

FIGURE 9 Length of transverse cracks in westbound lanes as a function of time on IH 40 near Amarillo, Texas (600 lane ft).

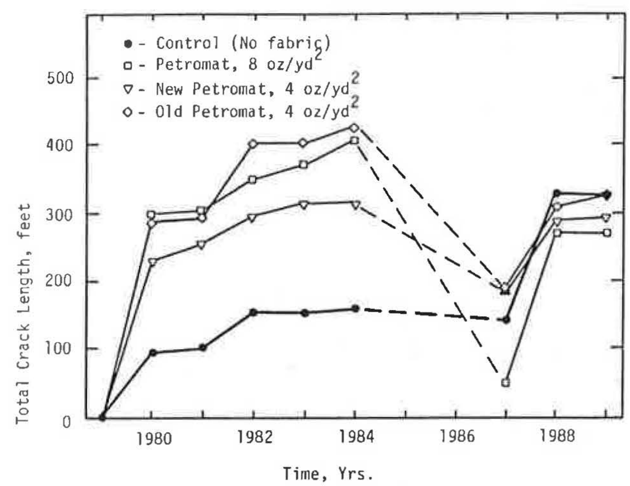

FIGURE 11 Total crack length in westbound lanes as a function of time on IH 40 near Amarillo, Texas (600 lane ft).

sisting of 0.65 gal/yd^2 of binder and 1 yd^3 of grade 3 precoated aggregate per 75 yd^2 of surface was applied, and the pavements were then overlaid with 2 in. of Type D HMAC.

Prior to the maintenance activity in 1985, the control pavements exhibited about the same or less cracking than the sections containing a fabric. After the maintenance activity in 1985, the control pavements, on average, exhibited more cracks in the new surface than the pavement sections containing a fabric. However, in most cases, the differences in crack lengths between the different sections are not considered to be significant. (These data, by their nature, did not lend themselves to a formal statistical analysis.) In these tests, the 8-oz/yd^2 products exhibited the best resistance to cracking in the overlay applied in 1985 but not in the original overlay. No single type of fabric consistently improved resistance to cracking throughout the 10-year evaluation period.

Observations shortly after rainfall indicate that the fabrics reduce pumping, which implies that even after cracks appear, the asphalt-impregnated fabric is acting as a moisture barrier. Admittedly, these observations of pumping have been sporadic and are probably biased.

Edinburg

In February, 1980, seven geotextile test pavements and a control section were installed on US 281 and SH 107 in Edinburg, Texas.

Preconstruction

Before construction, 1¾ to 3 in. of the existing asphalt concrete was removed by cold milling to preserve the curb line. The resulting surface texture was quite rough. Cracking patterns visible at the pavement surface before milling were mostly of the fatigue variety, with some transverse cracks in isolated areas. Cracking patterns were quite variable from one location to another and ranged in intensity from almost none in a 100-ft length to continuous, severe alligator cracking in one or both wheelpaths. There was evidence of rutting and pumping in isolated areas. Cracking patterns were no longer visible after the milling operation.

Construction

Because the test sections are located in an urban area, they are exposed to a considerable quantity of shear forces produced by acceleration, deceleration, and turning movements of traffic. The fabrics were applied curb to curb directly onto the highly textured milled surface after application of predetermined quantities of an asphalt tack coat (AC-10). The fabrics were exposed to traffic for periods ranging from 1 day to 2 weeks. Fluffing of the fabrics due to traffic was again observed.

An HMAC overlay was placed on each test section at a rate of 160 lb/yd^2 (about 1 ⅝ in. thick after compaction). Seven 1,500-ft test sections containing a fabric and one 385-ft control section containing no fabric were built.

Because of heavy, prolonged rainfall immediately after application of certain fabrics, it became necessary to replace the fabric in a few areas.

Post-Construction

Minor cracking began within 3 months after construction. Initially, pavement distress appeared as longitudinal cracks and block or alligator cracking in or near the wheelpaths, thus indicating their association with traffic loadings and insufficient base stiffness. The nature of the cracking patterns caused difficulty in quantifying and plotting the data. On the basis of a subjective evaluation of patterns, quantities, and severity of cracking, there were no noteworthy differences in reflective cracking between pavements with and without fabrics.

Low stability of the river gravel overlay mixture led to plastic deformation such that the overlay was milled off and replaced in 1985, terminating the experiment.

Tyler

Continuously reinforced portland cement concrete (CRCP) was repaired and a geotextile interlayer and two lifts of HMAC (2-inch Type D over 1½-in Type B) were placed in a project on IH 20 near Tyler, Texas. Seven 0.25-mi geotextile test pavements were installed on a portion of this project in July 1981.

Preconstruction

The original CRCP was constructed in 1965. Transverse cracks spaced about 3.3 ft apart, on the average, were prevalent throughout this project. In the most severely cracked areas, particularly those exhibiting substantial vertical movement upon loading, the concrete was completely removed and replaced with new reinforced concrete.

Construction

A specified quantity of asphalt tack (AC-20) was applied to the pavement surface. Fabrics were installed in the usual manner using a small tractor with special attachments. Both the traveled roadway and the shoulders were covered. Fabric construction joints were tacked at the overlap using hot AC-20. The fabrics were typically overlapped about 6 to 8 in. Two passes of a pneumatic roller ensured good adhesion of the fabric to the pavement surface. The fabrics were not exposed to traffic.

Postconstruction

Annual observations for 6 years revealed only a few isolated transverse reflection cracks (about one per 500 ft) dispersed uniformly throughout the test pavements without regard to type or presence of fabric. The overlay system performed to reasonable satisfaction in arresting reflection cracking, but apparently the fabrics were unnecessary in this instance. In the summer of 1987, major maintenance activities were needed to address rutting, including milling 0 to 1 in. from the pavement surface in the travel (outside) lane and overlaying with about 1 in. of HMAC.

PROJECT COST DATA

Cost information supplied by district personnel and based on 1980 contractor bid prices is presented in Table 4. From these data (*1*), an overall average cost for furnishing and placing a 4-oz/yd^2 fabric interlayer is about \$1.10/yd^2, including asphalt tack. At this writing the costs of fabric and asphalt cement were down from the 1980 values, but the cost of labor was somewhat greater.

Solely on the basis of the data obtained from the aforementioned test pavements, it appears that fabrics are not a cost-effective measure for reducing or delaying reflection cracking in asphalt concrete overlays. Fabrics may, however, have other advantages that were not evaluated in this study, such as service as a moisture barrier even after pavement cracking occurs.

OTHER EXPERIENCE IN TEXAS

Numerous pavement rehabilitation projects in Texas have involved the use of fabric interlayers or underseals. Most of these have been successful; a few have been disastrous. Two common elements appear in many of the "disasters"—thin overlays and high traffic volume.

Overlays less than 1 ½ in. thick placed over a fabric interlayer on high-volume facilities have exhibited premature distress in several locations (Table 5). Similar problems have been reported in other states (*3*; H. Tyner and W. Gulden, Georgia Department of Transportation, unpublished data). Distress typically occurs during the first year after construction and appears as alligator cracking or slippage at the fabric interface. Alligator cracking is most likely to appear in the wheelpaths on straight sections, whereas slippage is more probable in urban areas at intersections or in curves where

TABLE 4 APPROXIMATE COSTS ASSOCIATED WITH FABRIC INTERLAYS AND COMPARATIVE COSTS OF ADDITIONAL 1-IN. OVERLAY AND CONVENTIONAL SEAL COAT

Item	Ozona	Amarillo	Edinburg	Tyler
Fabric & Placement	0.84	1.10	1.09	0.50
Tack Coat @ \$0.25 gal/yd^2	0.19	0.24	0.19	0.25
Fabric Placement Only (Labor)	--	--	0.39	--
Total Fabric Installation	1.03	1.34	1.28	0.75
Additional 1" of Overlay	1.69	2.00	1.20	1.73
Conventional Seal Coat	0.77	0.65	0.39	0.85

NOTE: Based on 1980 contractor bid prices and a hypothetical average tack coat of 0.25 gal/yd^2.

TABLE 5 SUMMARY OF SELECTED FIELD PROJECTS CONTAINING GEOTEXTILES: PROBLEMS EXPERIENCED

Location in Texas	Thickness of Overlay, in.	Date of Installation	Date of Distress	Type(s) of Distress	Comments
Parmer Co. US 60	1 1/4	July-Sept 80	Spring 81	Extensive slippage and shoving with cracking.	Similar mix performing well on adjacent sections with no fabric.
Lubbock Loop 289N	1 1/4	May 80	Winter 80/81	Extensive cracking	Drum mix plant, low quality HMAC.
Smith Co. IH-20	1 1/2	July 81	Jan 82	Alligator cracking wheelpath.	First occurred after snow, ice and severe cold weather.
McAllen 10th St.	1	Aug 79	Sept 79	Rutting and shoving.	Most likely due to low stability of overlay mixture.
Donna Silver St.	1	Spring 79	Summer 79	Slippage near intersections.	Slippage at fabric-pavement interface.
El Paso Alameda Ave.	1 1/2	Sept 78	Aug 80	Slippage at curves and intersections.	Occurred during period of abnormally high temperatures.
City of Wichita Falls Hempstead and 9th Streets	1 1/2	May 81	July 81	Slippage at intersections and curves with cracking	No problems with similar construction and no fabric. Low tack likely contributed to problem.

shear forces (from braking or turning movements) are maximal.

Thin overlays are difficult to compact adequately, which of course results in comparatively high air voids. Water can penetrate this permeable layer until it reaches the asphalt-impregnated fabric interlayer. The water may remain near the bottom of the new overlay for extended periods depending on the weather. This moisture in combination with traffic can weaken the overlay by freeze-thaw cycling or possibly by stripping near the bottom of the layer. Distress develops first in the wheelpaths from repetitive loading of traffic on the weakened pavement layer.

Shear forces of considerable magnitude develop at the base of thin pavement sections simply by the passage of heavy wheel loads. According to laboratory tests (*2*), under normal conditions, the shear strength at a fabric interface is more than adequate to sustain these stresses. However, if the overlay has been weakened, particularly in the vicinity of the fabric interface (say, by moisture), excessive lateral movement at, or just above, the fabric interface is likely to occur with the passage of each heavy wheel load. This, of course, will result in premature fatigue failure of the new overlay.

In areas where high shear forces are developed, the distress may appear as slippage. Slippage cracks are typically crescent-shaped, with the arched side of the crack pattern pointing in the direction opposite that of vehicle travel. Shear strength at the fabric interface as well as compressive and tensile strength of the asphalt concrete (all of which must be exceeded for localized slippage to occur) are lowest at high ambient temperatures. Therefore, slippage problems are most likely to occur in urban areas during hot weather.

Slippage should not be confused with problems resulting from unstable overlay pavement mixtures. Distress due to low stability will appear as plastic deformation within the mixture such as rutting, shoving, corrugations, and so on. Fabrics should not be blamed for these types of distress.

Moisture, which can migrate upward through cracks and pores in the old pavement, can be trapped below an undersealed and overlaid pavement. Evidence indicates that moisture can accumulate at the underside of the fabric interlayer and, after a period of time, seriously reduce the bond strength between the fabric and the old pavement. Horizontal components of stresses imparted by repetitive vertical wheel loads and other shear forces can eventually result in fatigue-related overlay distress or slippage.

Test sections containing various combinations of fabric, seal coat, and HMAC overlays were installed on IH 20 near Midland, Texas, in 1973 and 1974 (R. S. Neal, unpublished data). Chronological progression of reflection cracking for selected test sections is shown in Figure 12. This plot illustrates the rapid progression of reflection cracks during the first 2 years for the seal coat plus fabric and the conventional thin (1 ¼-in.) overlay. In contrast, the thicker (2 ½-in.) overlay and those overlays with a fabric or a seal coat, or both, exhibited a delay of 2 to 3 years before significant reflection cracking was visible.

CONCLUSIONS

On the basis of the four field trials studied, the following conclusions may be drawn:

1. After up to 10 years in service, no fabric type consistently showed significant improvements in resistance to reflective cracking over another fabric, a seal coat, or no fabric at all. However, other data show that fabrics delay reflective cracking for 2 to 3 years.
2. Thin overlays (less than 1 ½ in.) placed over fabric on high-volume roadways can, under certain conditions, result in premature failure of the overlay.
3. Traffic allowed on fabrics before placement of HMAC can delaminate or remove fibers from fabrics, or both. The needle-punched continuous-filament, non-heat bonded fabrics are more susceptible to this phenomenon than others.
4. Fabrics can be successfully employed on very highly textured surfaces such as freshly milled pavement; in fact, a highly textured surface at the fabric interface may decrease the probability of overlay slippage.
5. Pneumatic rolling of the fabric immediately after application maximizes adhesive strength and shear resistance and minimizes its disruption by traffic, construction equipment, or wind.
6. Pneumatic rolling of fabric on a slope sometimes results in slippage (downhill) of the fabric at the hot asphalt tack interface. Fabrics with a somewhat fuzzy surface next to the asphalt tack offer more resistance to slippage (and thus to wrinkling) under tires of construction equipment than the smoother-surfaced fabrics.
7. Additional tack (emulsified asphalt or hot asphalt cement) applied between overlapped layers of fabric at construction joints minimizes disruption of fabric by wind or construction equipment.
8. Some wrinkling of fabrics during installation is unavoidable. Heavier or thicker fabrics (8 oz/yd²) resist wrinkling during installation better than thinner fabrics (4 oz/yd²). Certain fabrics are noticeably stiffer than others of equal weight; they also seem to offer resistance to wrinkling.
9. Bulges or blisters 2 to 6 in. in diameter may appear in

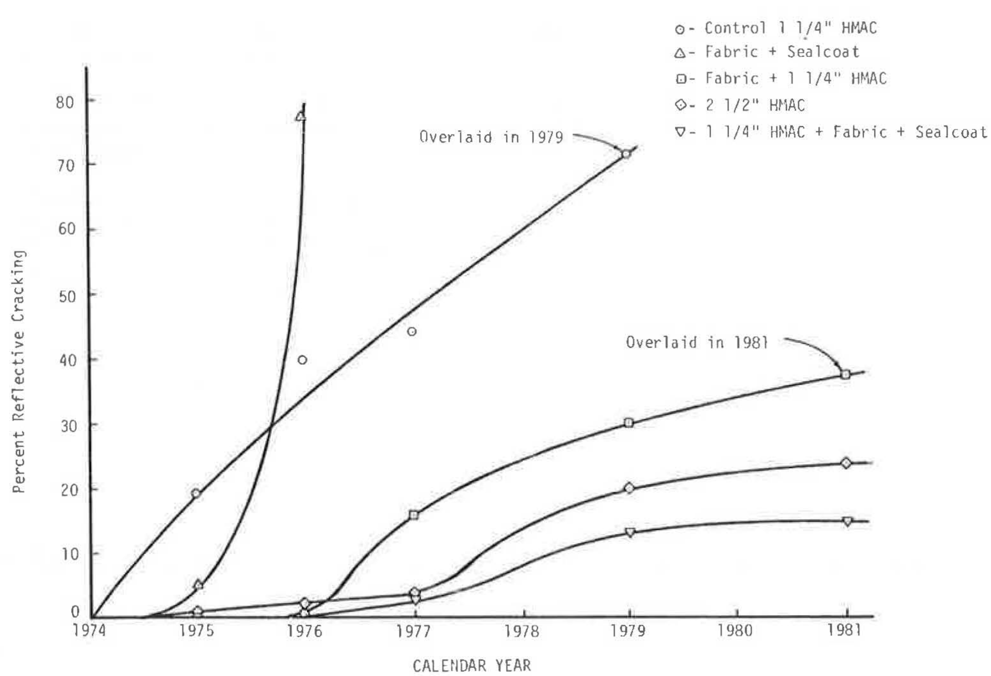

FIGURE 12 Reflection cracking progression for selected rehabilitative treatments (R. S. Neal, unpublished data).

a fabric that is placed shortly after a summer shower and left exposed for several days. Even though the pavement surface appears dry, small voids in the pavement contain water for fairly long periods. Moisture in the small openings is effectively sealed in by the fabric-asphalt membrane and later vaporized by solar heating, thus causing blisters to form. This situation should be avoided whenever possible, but, if blisters do form, they should be eliminated by being slit and rolled with a pneumatic roller before overlaying.

10. Exposure of fabric to prolonged rainfall and traffic action immediately after installation can adversely affect the fabric-to-pavement bond. In severe cases, isolated areas of fabric may become completely separated from the pavement. A highly textured pavement surface, in which there are significant voids between the fabric and the pavement surface, would most likely be detrimental in this situation.

11. Insufficient asphalt tack applied for fabric adhesion can result in failures due to slippage at the fabric interface, especially in areas of high shear forces during periods of hot weather. Excessive tack can migrate to the pavement surface and appear as flushing in the wheelpaths.

RECOMMENDATIONS

From the results of the study at this stage, the following recommendations are given as guides to minimize problems during construction and early service life and to maximize performance of geotextiles installed to reduce reflection cracking.

1. Potholes should be patched, cracks larger than ⅛ in. should be filled, and faulting should be eliminated prior to application of fabric or overlay, or both.

2. "Cure time" for the asphalt cement tack coat before placement of the overlay is not necessary. Only an insignificant quantity of volatiles will evaporate from asphalt cement at normal pavement service temperatures even after several months. Exposure to traffic and the elements of fabrics installed to reduce reflection cracking should be minimized. Exposure can only serve to damage the fabric and thus reduce its effectiveness, even though the fabric may not appear to be damaged. Traffic will abrade fibrous materials to varying degrees, depending upon the type of fabric. Tires will pinch or wear holes in the fabric at the peaks of the larger aggregate in the old surface. Fabric will be damaged predominantly where it is needed most—in the wheelpaths. Furthermore, from a skid-resistance standpoint, a dangerous situation could develop on exposed fabric, particularly during periods of wet weather.

3. Large wrinkles should be cut and overlapped to reduce the localized bulkiness of the fabric. Wrinkles can be a source of premature cracking in the overlay from compaction without firm support or possibly from fabric shrinkage (*4,5*).

4. The use of thin, high-void overlays with fabric should be avoided, particularly on high-traffic-volume facilities. An overlay thickness of 1 ½ in. should be considered a minimum for use over fabrics. Only dense-graded mixtures with low permeability should be installed over a fabric.

5. Asphalt saturation content of a fabric is dependent upon thickness and absorbency of the fabric and should be quantified before a pavement containing fabric is designed. Two methods of estimating asphalt retention of a fabric are reported in the literature (*6,7*). The proper quantity of asphalt tack is dependent not only on fabric properties but also on the condition of the old pavement surface.

6. Asphalt-impregnated fabrics usually remain intact even after moderate cracking and may therefore aid in reducing the flow of surface water into the base and thereby reduce pumping. Further investigation is needed.

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Geomembrane Use in Transportation Systems

ROBERT M. KOERNER AND BAO-LIN HWU

Included in this review paper is a brief introduction to geomembranes, their production, the resulting properties, and the current market demand. This introductory information is followed by a discussion on proper design philosophy, including a set of minimum recommended values based on installation survivability. The heart of the paper involves the review of the current areas of geomembrane use in transportation systems. As with all geomembrane applications, the primary function is as a barrier. In the applications cited, the barrier is intended to contain surface water, groundwater, or liquid pollutants. A wide range of applications is emerging whereby the different geomembranes can be used to excellent advantage and in a cost-effective manner. A summary table for each use area is also included. The conclusion gives an idea as to possible future trends.

According to ASTM, a geomembrane is defined as an essentially impermeable membrane used with foundation, soil, rock, earth or any other geotechnical engineering-related material as an integral part of a human-made project, structure, or system. The majority of geomembranes are thin sheets of flexible polymeric materials manufactured by one of the following three methods:

- Extrusion (nonreinforced),
- Calendaring (nonreinforced or reinforced), and
- Spread coating (reinforced).

The reinforced geomembranes have a fabric scrim or fabric substrate integrated within the separate piles or beneath the surface coating. Subsequent factory fabrication of geomembrane sheets leads to panels that are made as large as possible so as to expedite field placement and minimize field seaming.

Concerning the type of polymer, it should be recognized that all geomembranes are made from compounds that are blends of a primary resin (or resins) and other ingredients. For example, Haxo (*1*) gives the proper composition, as is shown in Table 1. With this table in mind, Table 2 is presented indicating the major generic types of geomembranes currently in use in North America.

The use of geomembranes in subsurface construction work has grown rapidly (*2*) to the point where current annual sales in North America are about 33 million yd^2, as shown in Table 3. Table 3 is arbitrarily divided into transportation, environmental, and geotechnical uses. Easily seen is that the environmental-related uses of liquid, solid, and vapor containment are the largest by far (80 percent), followed by transportation and geotechnical uses (about 10 percent each). It may also be noted that the types of geomembranes do not include thermoset materials (which today are seldom used) and are essentially nonreinforced PVC, reinforced CPE or CSPE, and semicrystalline PE. Most of the last group is HDPE.

The focus of this paper is completely on transportation-related uses. From Table 3 it may be seen that PVC is the material most used for transportation-related applications, followed closely by CPE/CSPE, and finally HPDE. The reason for the comparatively low use of HDPE with respect to environmental applications is that chemical resistance is not usually a compelling criterion (water versus leachate) and ease of constructability takes precedence. The specific uses of geomembranes in transportation applications will be described after a discussion of properties and design methods.

GEOMEMBRANE PROPERTIES AND DESIGN METHODS

As with any engineering material, a geomembrane's properties must be measured in an organized and quantifiable manner. Fortunately, ASTM has taken a leadership role in this regard with the formation of Committee D-35 on Geosynthetics. Carroll (*3*) gives a historical perspective of ASTM's involvement, as well as descriptions of other important Standards groups (e.g., AASHTO Task Force 25). It should be noted, however, that the individual states' involvement in geomembranes is very limited. Few make any mention of geomembranes in their regularly published specifications.

The major properties of geomembranes can be broken down by category (e.g., physical, mechanical) in such a way that a total perspective of a specific geomembrane can be obtained. Broad generalities as to what is typical, however, are difficult to make. Table 4 gives a recent compilation (*2*) in which the ranges are seen to be very broad. The importance of a particular value within this range comes into view when design is considered.

Design with geomembranes should be focused on its primary function and the related mechanism. As such, a traditional factor-of-safety equation can be formulated:

$$FS = \frac{\text{Allowable (test) property}}{\text{Required (design) property}} \qquad (1)$$

A test method, if it adequately models the reality of the situation, gives the allowable property in Equation 1 directly (e.g., thickness, tensile strength, puncture resistance). If the test method is not accurate, a reduced value becomes necessary. This can sometimes be obtained by a semiempirical technique (*4*).

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TABLE 1 MAJOR COMPONENTS IN POLYMERIC LINERS

Component	Composition in Parts by Weight		
	Thermoset	Thermoplastic	Semicrystalline
Polymer or Alloy	100	100	100
Oil or Plasticizer	5 - 40	5 - 55	0 - 10
Fillers			
carbon black	5 - 40	5 - 40	2 - 5
inorganics	5 - 40	5 - 40	-
Antidegradants	1 - 2	1 - 2	1
Crosslinking Agents			
inorganic	5 - 9	0 - 5	-
sulfur	5 - 9	-	-

TABLE 2 CATEGORIES AND TYPES OF GEOMEMBRANES CURRENTLY USED

Category	Acronym	Name
Thermoset	IIR	butyl rubber
	EPDM	ethylene propylene diene monomer
Thermoplastic	CPE	chlorinated polyethylene
	CPE-A	chlorinated polyethylene alloy
	CSPE	chlorosulfonated polyethylene
	EIA	ethylene interpolymer alloy (XR-5)
	PVC	polyvinyl chloride
	PVC-OR	oil resistant polyvinyl chloride
Semi-Crystalline	HDPE	high density polyethylene
	HDPE-A	high density polyethylene alloy
	MDPE	medium density polyethylene
	VLDPE	very low density polyethylene
	LLDPE	linear low density polyethylene

TABLE 3 GEOMEMBRANE USE IN NORTH AMERICA IN 1987

Application Area		PVC	CPE/CSPE	HDPE	Others
Transportation Related -					
all uses combined	10%	1.5 (1.3)	1.2 (1.0)	0.4 (0.3)	0.2 (0.2)
Environmental Related					
liquid containment	22%	1.9 (1.6)	3.6 (3.0)	0.5 (0.4)	1.3 (1.1)
solid containment	53%	1.4 (1.2)	2.5 (2.1)	12.0 (10.0)	1.3 (1.1)
vapor containment	5%	0.6 (0.5)	0.5 (0.4)	0.4 (0.3)	0.4 (0.3)
Geotechnical Related					
all uses combined	10%	2.5 (2.1)	0.5 (0.4)	0.1 (0.1)	0.2 (0.2)
Subtotal	100%	7.9 (6.7) or 24%	8.3 (6.9) or 25%	13.4 (11.1) or 41%	3.4 (2.9) or 10%

NOTE: Values are given in millions of square yards; square meters are given in parentheses.
Total Use = 33,000,000 yd² 100%
= 27,600,000 m² 100%
= 297,000,000 ft² 100%

The required property in Equation 1 is generally obtained by a design model, most of which have been adapted from geotechnical engineering analysis. For geomembranes in environmental liners and covers, a design guide by Richardson and Koerner (*5*) is available. Unfortunately, there is no such design guide for transportation applications per se, but this paper should help in this regard. A lower limit for the required properties in Equation 1 should focus on the installation survivability demands placed upon the candidate geomembrane. Table 5 provides insight as to the various required properties as a function of the anticipated demands placed on the geomembrane. It should be emphasized, however, that these are minimum values and cannot be used in place of rational design-generated values. If such design values come out

TABLE 4 MAJOR PROPERTIES OF GEOMEMBRANES AND TYPICAL VALUES (2)

Category and property	Approximate range of values Standard Units	International Units
Physical		
Thickness	10–100 mils	0.25–2.5 mm
Specific gravity	0.9–1.5	0.9–1.5
Weight (mass per unit area)	20–100 oz/yd^2	600–3000 g/m^2
Water vapor transmission	2–20 x 10^{-4} lb/ft^2-24 hr	1–10 g/m^2–24 hr
Mechanical		
Tensile strength at yield		
Unreinforced	5–25 lb/in.	1–5 kg/cm
Reinforced	25–100 lb/in.	5-20 kg/cm
Tensile strength at break		
Unreinforced	5–25 lb/in.	1–5 kg/cm
Reinforced	10–30lb/in.	2–6 kg/cm
Elongation at yield		
Unreinforced	20–100%	20–100%
Reinforced	10–30%	10–30%
Elongation at break		
Unreinforced	100–500%	100–500%
Reinforced	70–250%	70–250%
Modulus of elasticity		
Unreinforced	500–3,000 $lb/in.^2$	3.5–20 MPa
Reinforced	5,000–20,000 $lb/in.^2$	35–140 MPa
Tear Resistance		
Unreinforced	4–30 lb	2–15 kg
Reinforced	20–100 lb	10–50 kg
Impact Resistance		
Unreinforced	0.5–15 ft-lb	.05–2 kg-m
Reinforced	17–50 ft-lb	2–7 kg-m
Puncture Resistance		
Unreinforced	10–100 lb	5–50 kg
Reinforced	50–500 lb	25–250 kg
Soil to liner friction- (% of soil friction)	50–100%	50–100%
Seam strength (% of liner strength)	50–100%	50–100%
Chemical		
Ozone resistance	Varies with liner and location	
Ultraviolet light resistance	Varies with liner and location	
Chemical resistance	Must be specifically evaluated	
Thermal		
Hot climates or conditions	Usually no problem regarding material	
Cold climates or conditions	Decreases ductility, difficult to seam	
Biological		
Stability to microbe attack	Usually no problem	
Durability		
Water absorption	0–30%	0–30%
Aging	No standard procedure to evaluate over long time periods	

higher than those listed in Table 5, the design values must take precedence.

SPECIFIC TRANSPORTATION APPLICATIONS

Geomembranes have been used in numerous transportation-related applications. Although specific uses often do not cover extremely large areas, they can solve meaningful and often difficult problems. In the following paragraphs, each specific use will be described. A sketch accompanies each description as well as appropriate literature.

Prevention of Upward Groundwater Movement in Railroad Cut

As seen in Figure 1 this project, described by Lacey (*6*), used a scrim-reinforced CSPE geomembrane on the soil subgrade and beneath the railroad ballast to prevent upward flow of groundwater into a railroad cut. A needle-punched nonwoven geotextile was used above the geomembrane to provide puncture resistance from the ballast above. Waterproof seals were required at each of the concrete cantilever retaining walls paralleling the cut. These particular details were critical in the total performance of the system. It should be cautioned, however, that high porewater pressures often occur in railroad applications and the need for pressure-relief wells may be required.

Waterproofing of Transportation Tunnels

Water seeping into all types of transportation tunnels is a constant problem. When tunneling in rock by blasting, a shotcrete layer is often placed as soon as possible. This has been called the New Austrian Tunneling Method (NATM). By

TABLE 5 RECOMMENDED MINIMUM PROPERTIES FOR GENERAL GEOMEMBRANE INSTALLATION SURVIVABILITY (*2*)

Property and Test Method	Required Degree of Survivability			
	Low	Medium	High	Very High
Thickness (D-1593) mils (mm)	20 (0.50)	25 (0.63)	30 (0.75)	40 (1.00)
Tensile D-882 (1.0" (25 mm) strip) lb/in (kN/m)	30 (5.2)	40 (7.0)	50 (8.7)	60 (10.5)
Tear (D-1004 Die C) lb (N)	5 (22)	7.5 (33)	10 (45)	15 (67)
Puncture (D-3787 mod.) lb (N)	20 (90)	25 (110)	30 (130)	35 (160)
Impact (D-3998 mod.) ft-lb (J)	10 (7)	12 (9)	15 (11)	20 (15)

Notes:

"Low" - refers to careful hand placement on very uniform well graded subgrade with light loads of a static nature - typical of vapor barriers beneath building floor slabs.

"Medium" - refers to hand or machine placement on machine graded subgrade with medium loads - typical of canal liners.

"High" - refers to hand or machine placement on machind graded subgrade of poor texture with high loads - typical of landfill liners and covers.

"Very High" - refers to hand or machine placement on machine graded subgrade of very poor texture with high loads - typical of reservoir covers and liners for heap leach pads.

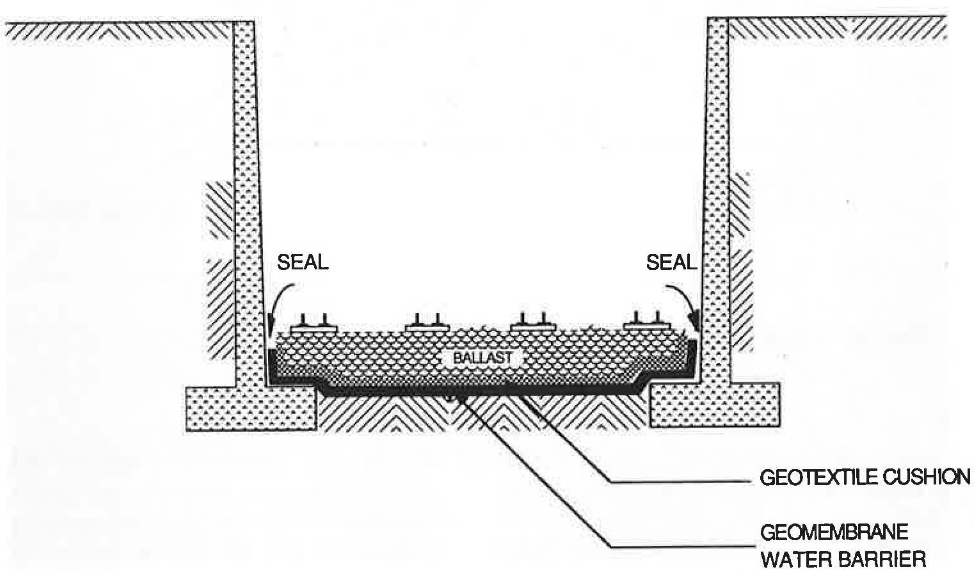

FIGURE 1 Upward movement of groundwater in railroad cut (relief of porewater may be necessary).

attaching a thick needle-punched nonwoven geotextile to the shotcrete, followed by a geomembrane, and then the final concrete liner, an excellent waterproofing system is achieved. As seen in Figure 2, the geotextile intercepts the seeping water and then drains into appropriate underdrains. Frobel (*7*) has used PVC geomembranes for this type of application.

Prevention of Contamination in Railroad Refueling Areas

A spread-coated butyl geomembrane has been used on a needle-punched nonwoven geotextile as a barrier against entrance of diesel fuel into the subsurface. The concept was first presented

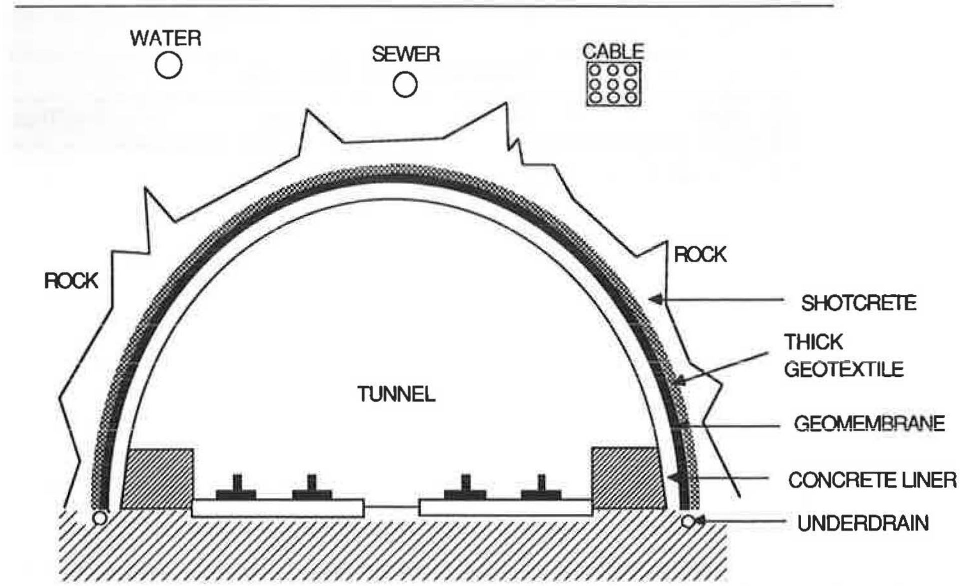

FIGURE 2 Tunnel waterproofing after NATM construction.

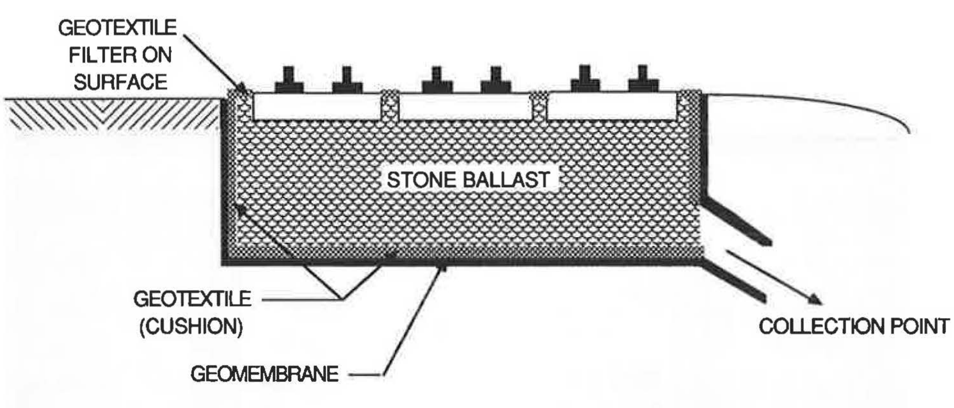

FIGURE 3 Railroad refueling areas.

by True Temper, Inc. As shown in Figure 3, the sides and bottom of the cross section were covered in this manner, and the surface had only a geotextile covering. The enclosure requires periodically spaced outlet drains for removal of the collected diesel fuel. The geotextile on the geomembrane faces inward against the ballast, thereby providing the necessary puncture protection.

Moistureproofing of Railroad Subgrades

Pumping of soil subgrades due to heavy, cyclic loads is a common railroad problem that rapidly contaminates ballast. Ayres (*8*) has given a good description of geomembrane use to prevent this occurrence. A geotextile cushion above the geomembrane for puncture resistance is again seen in Figure 4, which describes this application. As noted before, however, the high porewater pressures created in many railroad environments may require pressure-relief wells beneath the geomembrane.

Control of Expansive Soils (Vertical Infiltration)

Many parts of the world contain expansive, fine-grained soils that swell to alarming proportions when water is absorbed. To eliminate moisture from moving downward in the roadway cross section, a geomembrane has been used as shown in Figure 5. A geotextile is necessary (as a cushion) above and, depending on the quality of the subgrade, perhaps below the geomembrane. Sheffield and Steinberg (*9*) have reported on such applications in Mississippi and Texas.

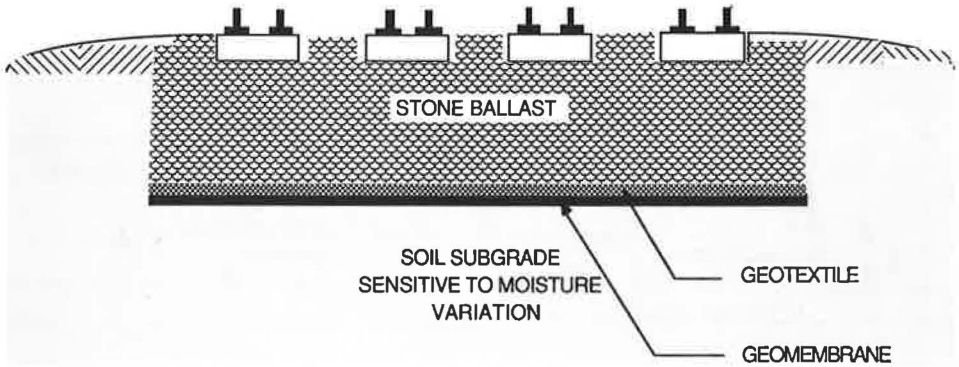

FIGURE 4 Soil subgrade moistureproofing (relief of porewater may be necessary).

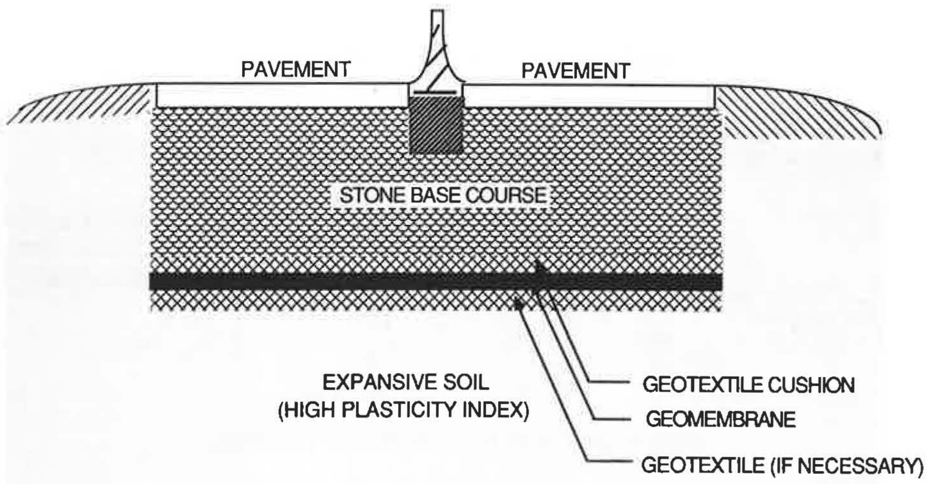

FIGURE 5 Control of expansive soils.

Prevention of Frost Heave

Upward migration of groundwater within a capillary zone will meet an elevation in the soil profile at which freezing conditions can exist. When this occurs, ice lenses will grow continuously, lifting everything located above them. Seen in Figure 6 is a possible remedial scheme using a geomembrane barrier with a geotextile or geonet drain beneath it. If a geonet is used, its underside must have a lightweight geotextile filter for protection (*2*). The geotextile or geonet drain must be connected to an underdrain beyond the limits of the area concerned. The underdrain could well be a synthetic edge drain composite.

Prevention of Enlargement of Karst Sinkholes

Many limestone formations are reactive when water comes in contact with them. This well-known solution phenomenon is called karst topography or sinkhole formation. As seen in Figure 7, the key to prevention of enlargement of an existing sinkhole is to prevent rainwater and snowmelt from entering the soil subgrade. This can be accomplished using a geomembrane with proper protection from the stone base above and, depending on the quality of the subgrade, from below.

Protection of Frost-Sensitive Soils

The concept of a membrane-encapsulated soil layer (MESL) has been pioneered by the Cold Regions Research Laboratory of the Corps of Engineers (*10, 11*) for the protection of frost-sensitive soils. Placed and maintained at their optimum water content, the encapsulated soils are suitable for light roadway use as shown in Figure 8. Without encapsulation, however, they would become saturated and lose their strength. The moisture barrier needed to prevent this can be one of those listed in Table 2, but is usually a nonwoven geotextile impregnated by an asphalt emulsion or elastomer spray. Various techniques have been described by Meader (*12*).

Protection of Friable Soils

The same MESL concept has been used to preserve the moisture content of friable soils in arid regions (*3*). Here the problem is the inverse of that in frost-sensitive soils in that drying

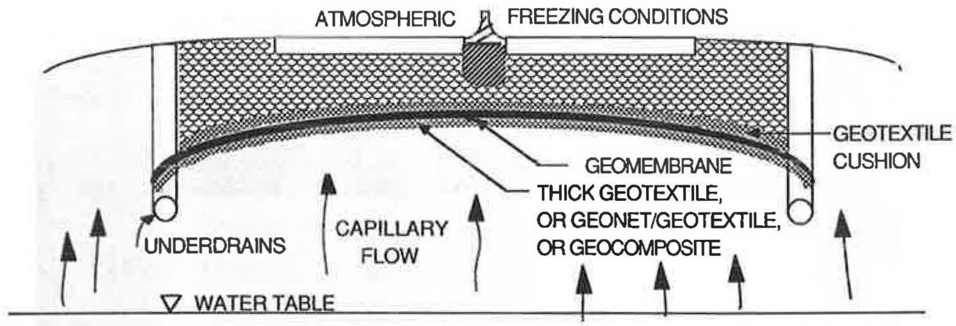

FIGURE 6 Prevention of frost heave.

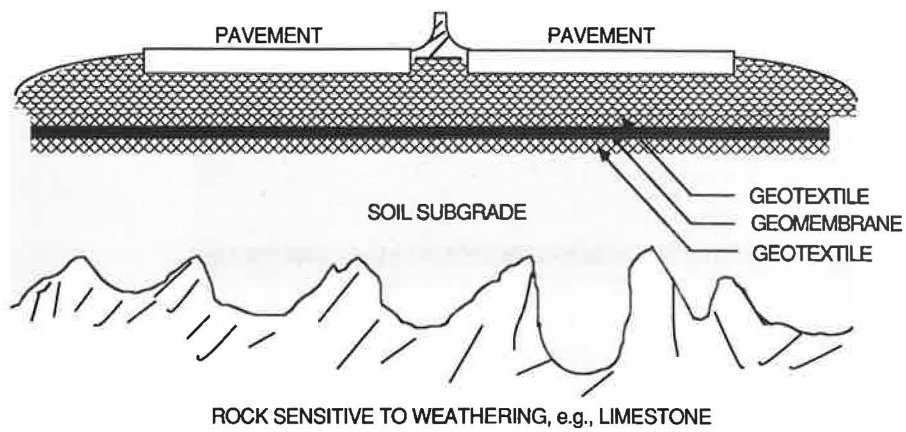

FIGURE 7 Prevention of karst-type sinkholes.

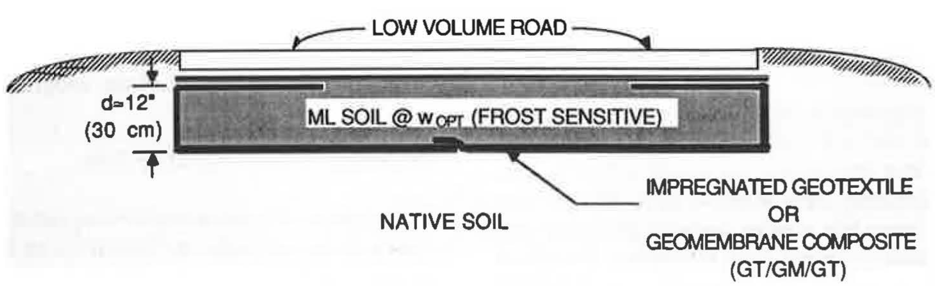

FIGURE 8 Maintenance of optimum water content.

causes the friable soils to simply fall apart. As shown in Figure 9, the concept is as previously described, but the encapsulated zone will probably be deeper than with frost-sensitive encapsulated soils.

Control of Expansive Soils (Horizontal Infiltration)

As was described earlier, moisture entering expansive soils beneath pavements can occur horizontally as well as vertically. To seal off the potentially affected zone, vertical barriers can be deployed as shown in Figure 10. As described by Sheffield and Steinberg (*9*) and in Phillips Fibers Corporation literature, the geotextile-geomembrane curtains can be installed with new pavement or with pavement overlays.

Secondary Containment of Underground Storage Tanks

As shown in Figure 11, underground fuel storage tanks in many states are requiring secondary containment. Using a

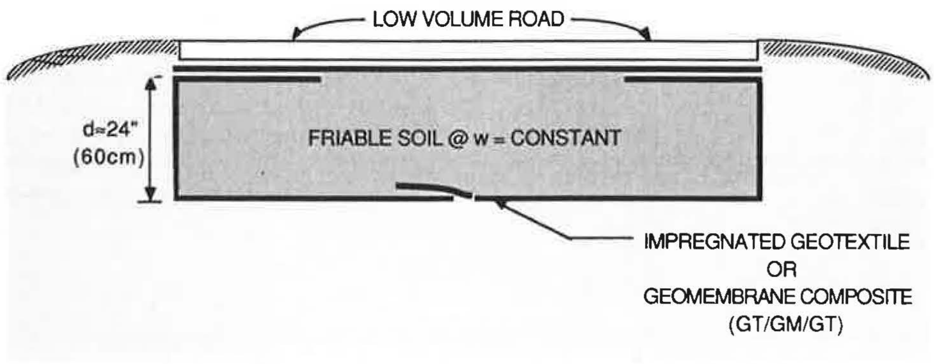

FIGURE 9 **Maintenance of constant water content.**

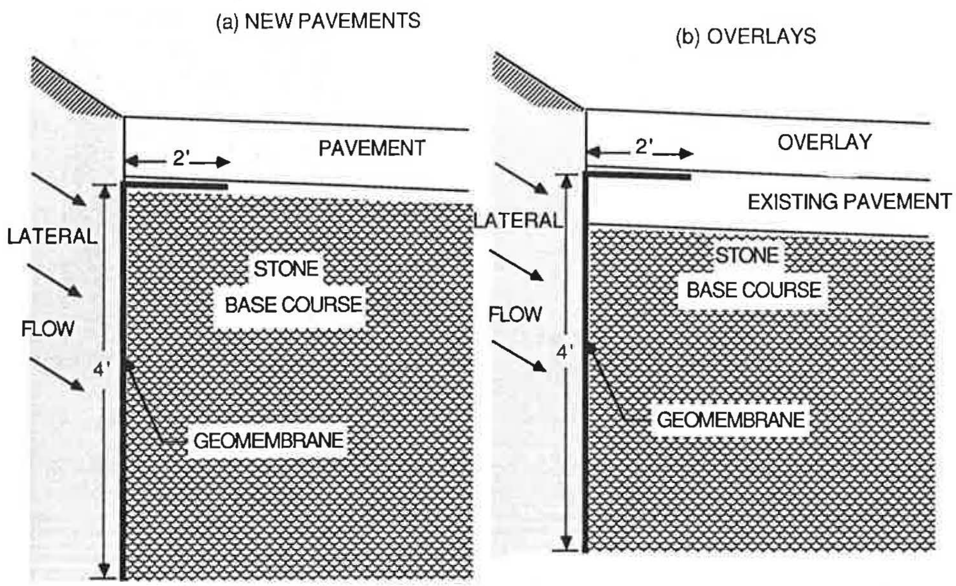

FIGURE 10 **Prevention of stone saturation from sides.**

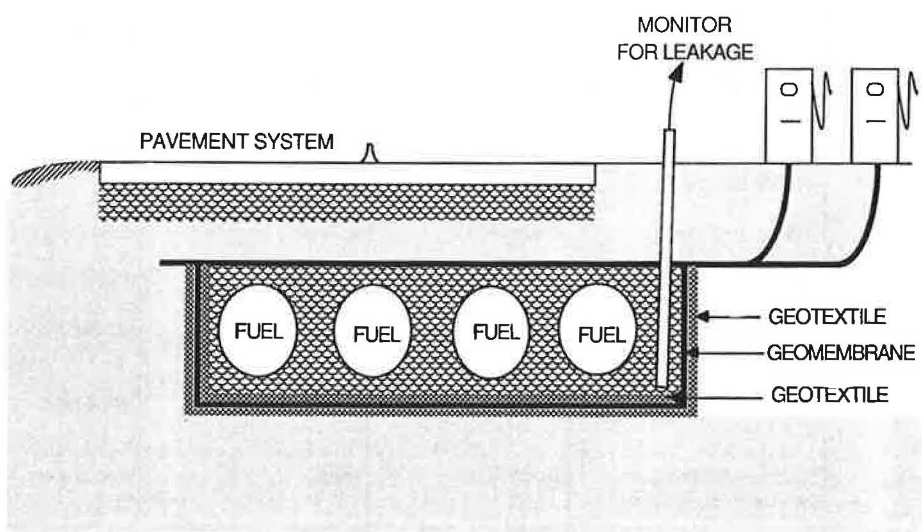

FIGURE 11 **Secondary containment of underground storage tanks.**

hydrocarbon-resistant geomembrane between two geotextiles, a secondary liner system with internal leak detection (the bedding stone) is formed. Such systems have been marketed by at least two organizations, Seamans, Inc. and MPC, Inc. A different scheme, by Total Containment, Inc., uses a geonet leak detector around the tank, with an encapsulating geomembrane on the outside.

Waterproofing of Walls

As shown in Figure 12, a number of schemes can be envisioned whereby surface water is kept from behind retaining walls. The reasons for this are numerous (e.g., to avoid corrosion of metal reinforcement strips or to provide relief of hydrostatic pressures). Many types of geomembranes are possible, but

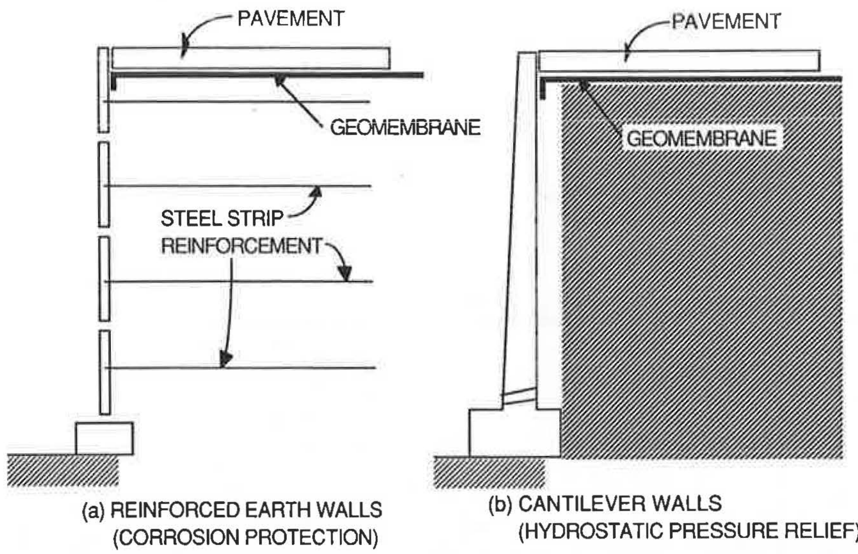

FIGURE 12 Waterproofing of walls.

TABLE 6 SUMMARY OF GEOMEMBRANE USE IN TRANSPORTATION SYSTEMS

Application No.	Description	Type of Liquid	Movement of Liquid	Implementation Status
1	flooding of railroad cut	groundwater	upward	limited use
2	waterproofing tunnels	groundwater	inward	regular use
3	railroad refueling areas	diesel fuel	downward	limited use
4	moisture proofing railroad subgrades	surface water	downward	unknown
5	control expansive soils (vertical infiltration)	surface water	downward	regular use
6	prevent frost heave	groundwater	upward	conceptual only
7	prevent karst sinkholes	surface water	downward	conceptual only
8	maintain water content - (frost sensitive soils)	surface and groundwater	inward	regular use
9	maintain water content - (friable soils)	moulding water	outward	limited use
10	control expansive soils - (horizontal infiltration)	groundwater	lateral	regular use
11	secondary containment	hydrocarbons	outward	regular use
12	wall waterproofing	surface water	downward	limited use

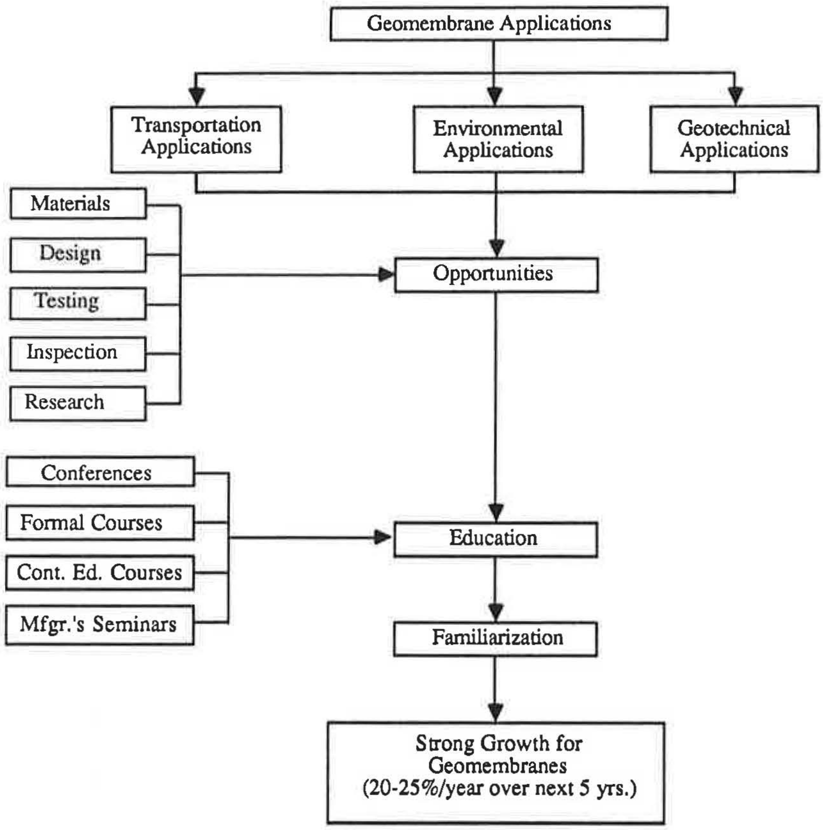

FIGURE 13 Conceptual implementation of geomembranes in subsurface applications.

all must be adequately protected if they are at or near the surface and if heavy loadings are anticipated.

SUMMARY AND CONCLUSIONS

Presented in this paper was a brief overview of geomembranes as they pertain to transportation applications and 12 specific application areas. These uses are summarized in Table 6 along with their approximate implementation status. With the exception of applications 3 and 11, all provide barriers to surface water or groundwater. As such, chemical resistance should not be a formidable concern and most of the polymer types listed in Table 2 should be adequate, taking into consideration mechanical properties, seamability, and cost. For applications 3 and 11, chemical resistance to hydrocarbons must be ensured.

A number of the applications presented require puncture protection of the geomembranes. This can be provided by placing a geotextile against the geomembrane, or by forming a geotextile-geomembrane composite by spread coating or postfabrication bonding. A number of these composites are commercially available. In some cases a geotextile is required on both sides of the geomembrane.

The type of geotextile generally preferred in these applications is a relatively thick needle-punched, nonwoven type. Thus a cushioning action is visualized in providing puncture resistance. Although such a mechanism is certainly obvious, other geotextiles might also be acceptable. For example, a woven or heat-set, nonwoven geotextile might also be feasible by virtue of its load-spreading capability. Investigations in this regard seem warranted.

Geomembrane seams are always of concern from the point of view of both strength and moisturetightness. These concerns are obviously site-specific situations and, in many cases, "absolute" tightness is not a necessity. In this regard, having to seam bonded geomembrane-geotextile composites is often not a detriment, and they can be mechanically seamed (e.g., by sewing) or sometimes merely overlapped.

In conclusion, the use of geomembranes for all types of subgrade applications is an exciting and growing field. As shown in Figure 13, many opportunities exist for all segments of the profession and related industries. It is felt that with a broad-based educational effort, there will come widespread familiarization and continued strong growth for geomembranes in the future.

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Transportation Tunnel Waterproofing Using Geosynthetics

RONALD K. FROBEL

This paper describes the New Austrian Tunneling Method (NATM) tunnel waterproofing system using geosynthetics. The advantages of using a nonwoven geotextile and a plastic geomembrane sheet material for the primary drainage and waterproofing are summarized. The method of installing and inspecting the geosynthetics is described and illustrated with photographs. Example material specifications for both polyvinyl chloride and high-density polyethylene are presented based on Washington Metropolitan Area Transit Authority (WMATA) tunnel specifications.

Water infiltration can lead to deterioration and substantial damage of structural and functional components, especially in transportation tunnels. Consideration must be given to intercepting and collecting leakage before damage occurs. There are five general methods of controlling water infiltration into tunnels (*1*):

1. Drainage,
2. Grouting,
3. Water stops and gaskets,
4. Sealants, and
5. Impervious membranes.

Frequently, in conventional tunnel linings, two or more of these methods are used in the construction of the same lining. Even after construction, remedial measures, such as injection grouting, may have to be undertaken to control excessive seepage. Impervious membranes used in conjunction with conventional tunnel linings are generally very labor-intensive and require careful workmanship (*1*).

The New Austrian Tunneling Method (NATM) has been successfully applied worldwide in the construction of transportation tunnels. NATM is a method whereby the rock or soil formations surrounding the tunnel are integrated into an overall ringlike support structure, thus making the formations a part of the support system (*2*). An integral part of the NATM design is the incorporation of a highly technical sealing and drainage system composed of state-of-the-art geosynthetics. The geosynthetic system must provide watertight integrity for the life of the tunnel and must thereby withstand different kinds of stress and strain, both during installation and after construction, as well as variable and aggressive chemical environments. Plastic geomembrane sheet sealing with a protective nonwoven geotextile drainage layer has been the predominant system over conventional sealing methods such as asphalt membranes or spray-applied glass-fiber-reinforced plastic or bitumen-latex based products worldwide (*3*). The geosynthetic system developed for NATM meets the demands not only of rapid tunneling rates, but also of rough construction treatment. The requirement for absolute watertightness puts high technical demands on the system, in which the protection of the loosely laid geomembrane is of paramount importance. This paper describes the NATM waterproofing method using geosynthetics.

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NATM SYSTEM COMPONENTS

The essential components of the NATM system are the rock or shotcrete surface, the nonwoven geotextile, the fastening system, the geomembrane, and the final cast-in-place concrete lining. Detail A of Figure 1 illustrates all of these individual components in section. The minimum criteria that must be met by each of the components (*4*) are discussed in the following sections.

Rock and Shotcrete Surface

The loose laying of a geomembrane presupposes a backing of sufficient nondeformability and natural strength. A shotcrete layer with a minimum thickness of 40 mm is essential for the backing to serve as attachment for the nails of the fastening plates. The maximum size of the aggregate should not exceed 16 mm, and crushed rock generally must not be used. The surface condition of the backing is of special importance at the time of concreting. Consideration must be given to this from the time of installation of the geomembrane sheets. The sheets should lie against the shotcrete as solidly and as flush as possible without excessive stressing and damage. To achieve this, the shotcrete must be used to smooth the excavated surface and cover any metal protuberances. In addition to a smooth surface over the excavation, recent investigations show that the rock surface must be supported by shotcrete immediately after excavation so that radially acting forces can be accepted adhesively (*5*). This support is increased by the placement of rock bolts, steel arches, or reinforcing wire mats.

Nonwoven Geotextile

The nonwoven geotextile performs not only a protective function but also a drainage function, and therefore it is of decisive importance for the effectiveness of the total sealing system. The existing technical demands on the nonwovens in tunneling are a result of the various kinds of stress and strain during the construction stage as well as in service conditions. The

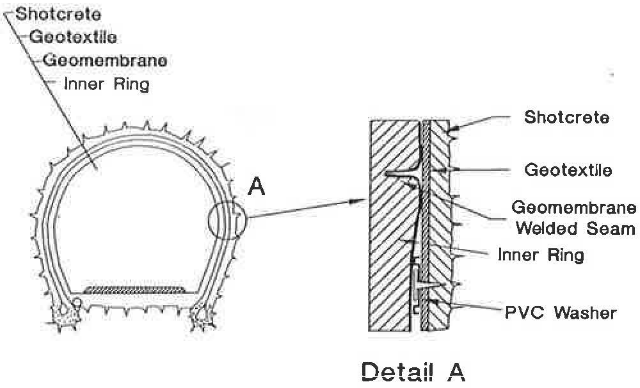

FIGURE 1 Section through a typical NATM design showing the various components of the structural and waterproofing system.

types of stress include those caused mechanically, chemically, and hydraulically; functional correlations can occur between them. It is therefore only possible to claim a permanent mechanical protection function of the nonwoven when it is permanently inert to acid and alkali attack. The following technical requirements for nonwoven fabrics used in underground construction in rock and soil correspond to state-of-the-art geotextile research (*4*):

- Chemical resistance—pH range of 2 to 13,
- Mechanical resistance,
- Hydraulic transmissivity, and
- Decay resistance.

Chemical Resistance

So that the nonwoven fabric can perform a lasting protective function, it is of paramount importance that it have a chemical resistance to all types of groundwater, especially to calcium hydroxide, $Ca(OH)_2$ (hydrated lime), and other aggressive compounds found in hydraulic binders (e.g., concrete and grout). Importantly, the requirement on a nonwoven can only be met (assuming that there is no doubt about the chemical compound of the base polymer material) by the inert nature of the final product. Polypropylene and polyethylene are resistant to the required pH range of 2 to 13, whereas polyester has only a limited resistance. Geotextiles made from more than one type of polymeric filament and nonwovens made from unknown regenerated materials should be avoided in tunnel construction. The importance of chemical stability cannot be overstated. Long after construction, stress redistribution within the surrounding rock or soil mass may lead to convergent movements of the tunnel. It is essential, therefore, that the nonwoven be still intact to protect the waterproof membrane and provide the necessary planar drainage.

Mechanical Resistance

Protective nonwoven geotextiles must have certain minimum values for mechanical strength and elasticity to absorb stresses resulting from mounting and concreting pressures and deformation of the tunnel lining due to load redistribution and temperature variation. It is also important that the nonwoven fabric structure resist the potentially damaging effects of high hydrostatic pressure, which can occur on a localized basis at fissures during final concreting of the inner ring. The fabric must absorb high-tensile elongation and tearing stress when being placed and when in contact with the partially sharp-edged shotcrete.

Hydraulic Transmissivity

Local entry of water is collected in the course of shotcrete lining by means of polyvinyl chloride (PVC) drain pipes or central, slotted pipes and conducted to the drain at the bottom. The residual water, which includes seepage water and other smaller types of water entry, can dissipate in the plane of the nonwoven geotextile. It is then conducted in longitudinal collection drains to the tunnel exit. The three-dimensional spatial structure and the void reduction of the nonwoven under pressure are important when designing for planar (transmissivity) permeability. Minimum values for the permeability in the geotextile plane under normal compressive loading are as follows (*4*): k-value under 2 kPa, 8×10^{-1} cm/sec; k-value under 200 kPa, 8×10^{-2} cm/sec.

These coefficients of permeability are based on the assumption that the nonwoven is pressed solidly against the shotcrete surface and that the dewatering takes place exclusively in its plane. However, this assumption does not very often occur in practice, because additional voids exist between the nonwoven fabric and the shotcrete lining into which seepage water can also drain. The values stated above are to be regarded as absolute minimum values; the real permeability in the plane generally will be about 10 times higher.

Decay Resistance

The geotextile could be in contact with soil or certainly with water, which may contain aggressive microorganisms. All nonwovens produced from 100 percent synthetic fibers are resistant to decay. The requirements for decay resistance are the same as those set out in the section Chemical Resistance and relate to all nonwovens including those made from regenerated material, those not produced from 100 percent synthetic fibers, and those that are produced from viscose (regenerated cellulose) fibers.

Fastening System

The nonwoven geotextile and the geomembrane sheets are installed with the help of a special scaffold. As a first step, the nonwoven fabric layer is fastened to the shotcrete (gunite) by means of plastic disks (plates) and fasteners (nails). As a second step the actual sheeting that will seal the tunnel is then secured to these disks by means of high-frequency ring welding or hot-air welding. On average, three fastening points per square meter are required to attach the protective geotextile layer to the tunnel wall (*6*). The fastening disk is designed in such a way that if the geomembrane sheet is overstressed and deformed at a weld, the failure will always occur in a certain plane of weakness inside the fastening disk, never in the geo-

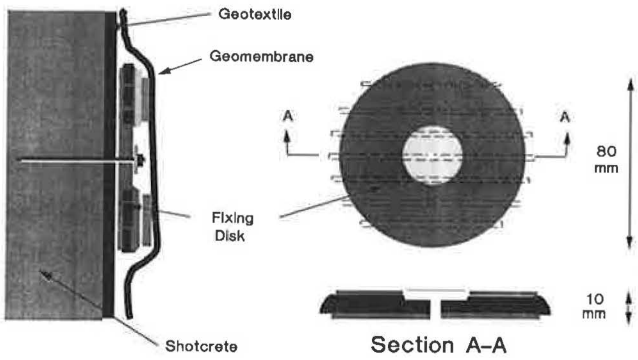

FIGURE 2 Support disk fastening system. (*6*)

membrane sheet itself (*3*). Thus it is possible to avoid excessive stress and distress of the geomembrane sheet during installation or when excessive deformation occurs when the internal tunnel ring is concreted. Figure 2 shows a support disk and fixing nail in detail both in isolation and in place on the tunnel wall.

Geomembrane Waterproofing System

The geomembrane is the integral part of the waterproofing function for the geosynthetic system. As such, the membrane must meet certain minimum criteria, as follows:

- Provide continuous enclosure, especially in critical areas of the construction;
- Provide permanent or tunnel design life imperviousness;
- Be adaptable to surface discontinuities;
- Not lose its waterproofing effect in spite of structural movements caused by shrinking, creep, temperature variation, settlements, or vibration;
- Be able to absorb stress over long discontinuities without being damaged (in this respect, the biaxial elongation of the geomembrane should be known and specified, because the material is actually subjected to two-dimensional strain);
- Be able to absorb tensile stress both during placement and during service;
- Be able to bridge cracks and discontinuities in the construction surface;
- Be chemically resistant to all types of aggressive water, whether from natural origin or leached from concrete, grouts, or other materials (pH range should be 2 to 13);
- Be resistant to biological attack;
- Be suitable for installation in wet areas also;
- Be easy to handle and install in large quantities;
- Be quickly and easily thermally welded with a reliable, mechanized welding method;
- Have welded seams constructed so that they are easily checked for watertightness;
- Be produced of material that is easily repaired when damaged;
- Be produced of a material compatible with the plastic fastening disks so that the geomembrane can be fused to the disks;
- Be fire resistant or at least self-extinguishing; and
- Have a low coefficient of friction to allow for gliding of the final concrete lining, thus reducing shrinkage and cracking and permitting larger lining segments to be cast monolithically.

Tunnel specifications for geomembrane material often call for a "high polymer," referring to a pure polymer as opposed to polymer-blended materials. Generally, three geomembrane materials have proven themselves as base materials for tunnel lining. These are plasticized PVC (PVC-soft), high-density polyethylene (HDPE), and ethylene copolymer bitumen (ECB). The most commonly specified material in the past, primarily from the experience of installing contractors and the know-how of the manufacturers producing PVC for tunnel lining, has been PVC-soft (*7*). PVC is also very flexible, workable, and easily welded even in the commonly specified thickness of 1.5 mm. PVC geomembrane sheets are generally from 1.6 to 1.8 m wide. Table 1 gives some recommended minimum properties for the PVC geomembrane. HDPE has also been specified in numerous tunnels worldwide and is also easily welded, generally by extrusion welding. HDPE sheets are usually 7 to 10 m wide and 2.0 to 2.5 mm thick.

INSTALLATION OF TUNNEL GEOSYNTHETICS

Once it has been decided to use a complete waterproofing system in the NATM design, a highly specialized, experienced subcontractor in such installations will work very closely with the prime contractor so as to effect a continuous rapid, sequential installation with minimal disruptions for the overall tunneling operation. The following methodology will include PVC and HDPE geomembranes as typical examples.

Pneumatically applied concrete (shotcrete)

The initial shotcreted outer lining is placed over all excavated rock or soil surfaces so as to form a relatively smooth surface with minimum depressions. Generally, the depth of depressions are not allowed to exceed 30 percent of the depression span. Any protruding steel wire or other construction/reinforcement related objects must be cut off flush with the surface of the shotcrete. All steel ribs, lattice or plates must be covered by additional shotcrete to provide a smooth surface of at least 40 mm using a grain size in the shotcrete not to exceed 16 mm (*4*). A minimum of 40 mm thickness is needed to facilitate nailing of the geotextile. Once the initial shotcrete has cured, the geotextile protective/drainage layer is applied to the shotcrete surface.

Geotextile and Fixing Disks

To facilitate rapid installation of both geotextile and geomembrane over the entire intrados of the tunnel, a special mobile rail-mounted scaffolding is used, as shown in Figure 3. The geotextile is unrolled in one continuous length radially and then fixed to the shotcrete of the tunnel sides and crown with a minimum of three fixing disks per square meter of surface (*6*). As shown in Figure 4, the plastic fixing disk is designed to be nailed against the geotextile and into the shotcrete with 40-mm-long nails and a pneumatic or explosive cartridge gun. The disk design is such that the yield point of the disk will cause it to fail under stress rather than the geomembrane that is eventually welded to it, thus preventing

TABLE 1 MINIMUM RECOMMENDED PROPERTIES FOR A PVC GEOMEMBRANE IN TUNNELING (*6*)

Property	Standard	Unit	Value
Ultimate Tensile Strength	DIN 53455 ASTM D638	kPa	17000
Ultimate Tensile Elongation	DIN 53455 ASTM D638	%	300
Tear Resistance	DIN 53363 ASTM D1004	N/mm	80

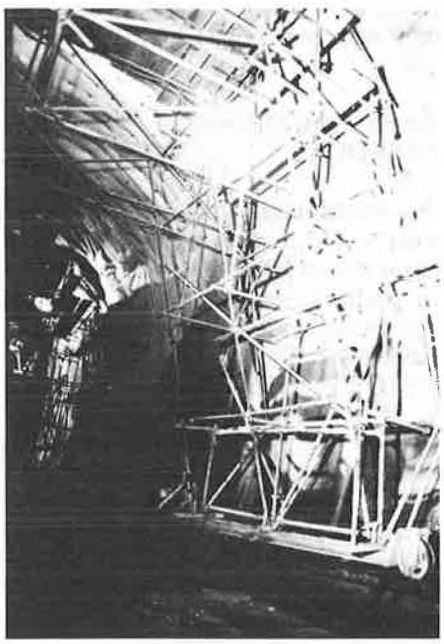

FIGURE 3 Mobile installation scaffolding.

damage to the geomembrane system. Once the geotextile strips have been nailed in place and overlapped a minimum of 100 mm, the geotextile is then heat-bonded at the seams as shown in Figure 5.

Geomembrane System

The geomembrane is unrolled and positioned from the mobile scaffold, also in a radial manner. As it is supported below the crown, it is manually hot-air-welded to the fixing disks, thus providing the required support for each strip, as shown in Figure 6. As the geomembrane strips are supported in place, they are positioned with a minimum 70-mm-wide overlap to facilitate thermal welding. Placement of the geomembrane strips is such that seam lengths are always radial within the tunnel.

At large crossovers or stations, there will also be a need for various other joints to effect a 100 percent waterproof coverage of the shotcrete surface. At these locations, HDPE sheeting may be more desirable due to its extrusion welding capability and its resistance to the mechanical damage that can occur in and around the reinforcing steel rebar. Figure 7 shows an installation of HDPE behind rebars in an underground station wall.

PVC seams are welded using an automatic, double-wedge, thermal self-tracking welder, as shown in Figure 8. The double-wedge weld produces a seam that contains a con-

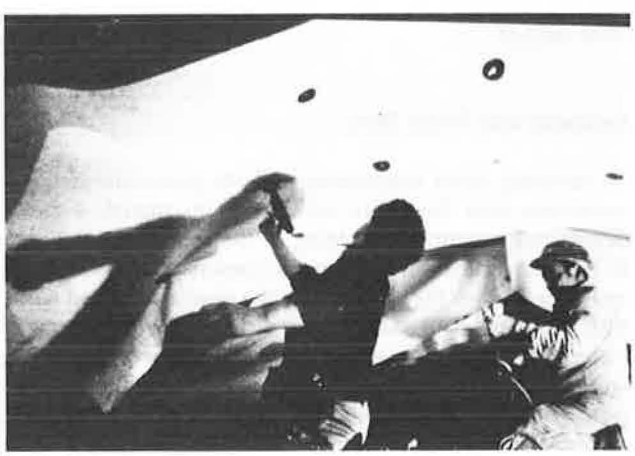

FIGURE 4 Nailing the geotextile with a fixing disk.

FIGURE 5 Heat seaming the geotextile.

FIGURE 6 Welding the PVC geomembrane to fixing disks.

FIGURE 8 Welding a PVC geomembrane panel.

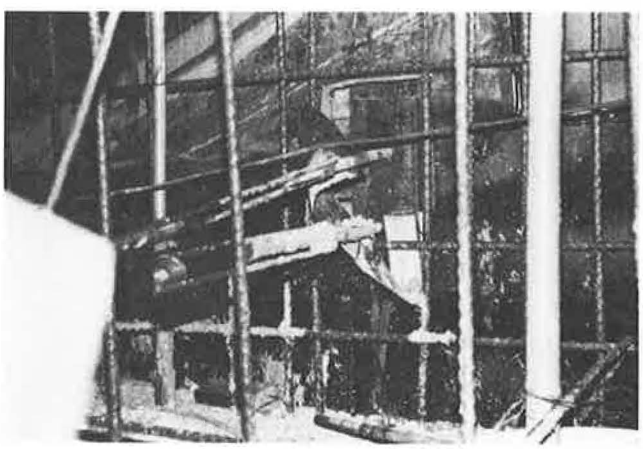

FIGURE 7 HDPE installation behind rebar.

tinuous channel between welded tracks. The channel is then used to test the continuity of the seam with air pressurization as a quality control procedure. The channel is generally subjected to a pressure of 2 Pa for approximately 10 min with a requirement for not more than 10 percent pressure loss (*6*). HDPE sheet material is generally welded by the extrusion welding process, as shown in Figure 9. This type of weld allows joining of the geomembrane panels in limited access areas. The seams can be inspected using the vacuum-box technique similar to steel weld testing.

The geotextile and geomembrane as a system are connected on each side of the tunnel to a drainage system that may be composed of a perforated drain line embedded in porous concrete. The lower ends of the geomembrane-geotextile cover the side drains. The geotextile directs all groundwater from the sides and crown down the geomembrane surface to the porous drainage system, and the drainage system directs the groundwater out of the tunnel. It is important to note that the drainage system should be designed so as to limit the exposure of groundwater to free air. This will help eliminate problems associated with calcification in the drainage system, as was found in the investigations for the Washington, D.C., Metro B-10a tunnels (*8*).

FIGURE 9 Extrusion welding of HDPE sheets.

U.S. NATM INSTALLATIONS AND TYPICAL MATERIAL SPECIFICATIONS

The first use of the NATM method in the United States was in a rail tunnel in Mt. Lebanon, Pennsylvania, built by ILBAU America under subcontract to an American firm. This project was largely paid for by a demonstration project grant from the Urban Mass Transportation Administration (UMTA) and did not receive great publicity (*9*).

The second and most notable use of NATM in the United States was on the Washington, D.C., Metro contract B-10a, which is an extension of the Washington Metropolitan Area Transit Authority (WMATA) Red Line in Wheaton, Maryland. The twin Wheaton tunnels and station were constructed using NATM and a geosynthetic waterproofing system as a result of a value engineering proposal submitted by the contractor, ILBAU America. The station was 183 m long and 36 m below the surface, and the two single-track tunnels were 4400 m long and as deep as 60 m below street level. Contract B-10c on the WMATA Project also calls for NATM for rock excavation and geosynthetics for waterproofing.

In addition to specified construction procedures, the minimum physical properties for the geosynthetic must be specified. An example of minimum values for a PVC geomembrane and polypropylene geotextile taken from the WMATA B-10a specifications is shown in Table 2. Table 3 gives minimum values for an HDPE geomembrane as extracted from the WMATA specifications for the Greenbelt route (Shaw Station) and tunnels.

SUMMARY

Although NATM has been in existence for almost two decades, the method obviously will be used to a greater extent with the completion and publicizing of projects such as the Washington, D.C., Metro. The use of geosynthetics in NATM is also not new but will certainly gain rapid acceptance in the United States, where the geosynthetics manufacturing industry and standardization are far ahead of the European community. The benefits of a geosynthetic waterproofing system in transportation tunnel construction include the following (*11*):

- Continuous waterproofing element,
- Continuous sidewall drainage,

TABLE 2 GEOSYNTHETIC PROPERTIES ACCORDING TO WMATA SPECIFICATIONS (*10*)

Property	Minimum Specifications	DIN	ASTM
A. GEOTEXTILE (non-woven polyproplyene)			
Thickness (mm)	4.0	53855/3	D1777
Unit Weight (g/m^2)	500	------	-----
Grab Strength (N)	1150	53858	D1682
Elongation (%)	80	53857	D1682
Trapezoid Tear Strength(N)	440	53363	D2263
Burst Strength (kPa)	2760	N/A[a]	D751
Chemical Resistance: (pH value)	2 to 13	E16726	N/A[a]
Flammability	Self Extinguishing	4102/1	D568
B. GEOMEMBRANE (PVC-soft)			
Thickness (mm)	1.5	53370	D374
Ultimate Tensile Strength (kPa)	7600	53455	D638
Ultimate Elongation (percent)	300	53455	D638
Brittleness Temperature	$\pm 7^{o}C$	53361 53372	D1790
Flammability	Self Extinguishing	4102/1	D568
Dimensional Stability 6 hr @ 80^{o}C (percent)	2	53377	D1204
Welded Lap Shear Strength	Pass	E16726 53455	D3163
Tear Resistance (N/mm)	40	53515	D1004
Chemical Resistance: (pH value)	2 to 13	E16726	N/A[a]

[a]N/A = not available

TABLE 3 HDPE MINIMUM PROPERTIES ACCORDING TO WMATA SPECIFICATIONS (*10*)

PHYSICAL PROPERTIES Property	Test Method	Value	Unit
Density, (minimum)	ASTM D1505	0.949±.003	g/cm^3
Melt flow rate	ASTM D1238, Condition E	0.20±.04	g/10minutes.
Average molecular weight	ASTM D2857	1.5 x 10^5	---
Coefficient of linear thermal expansion	ASTM D696	1.2 x 10^{-4}	Degree C^{-1}
Water absorption, (maximum)	ASTM D570	0.085	percent/ 4 days
Shore D hardness	ASTM D2240	65	Shore D
Impact resistance, (notched)	ASTM D256 Method B	No break	ft. lb/inch of notch
Elongation at yield	ASTM D638	15±3	percent
Elongation at break	Test Specimen	>800	percent
Tensile stress at yield	Type IV	2800±200	psi
Tensile stress at break		3800±300	psi
Stress cracking resistance	ASTM D1693, Condition C, w/notch depth for Condition A, Igapal Reagent	min. 500	hour
Thickness (nominal)	ASTM D374	0.100	inch

Waterproofing Sheet: High density polyethylene (HDPE) containing no additives, fillers, or extenders. Carbon black, 2 ± 0.5 percent, ASTM D1603, added to resin.

- Independence from concrete lining cracking,
- Rapid installation,
- Cost savings over conventional methods, and
- Cost savings in long-term maintenance.

With the technical advantages, reduced costs are also an added benefit—not only cost reduction during construction, which can be as much as 30 percent for NATM versus conventional tunnel construction, but also the long-term reduced maintenance costs provided by the geosynthetic waterproofing system.

Because of the highly technical requirements imposed on the geosynthetics used in tunnel construction, these materials must perform their function for the intended life of the tunnel. Once the final cast-in-place concrete lining is constructed, the geosynthetic system cannot be reached for repair. It is important to point out, however, that the individual geosynthetic components must be strictly specified as to material (polymer) type as well as minimum survivability properties. In addition, a sound quality control program must be established and adhered to, from initial manufacture of the geosynthetics through final installation.

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Prototype Turbidity Curtain for the Westway Highway

L. D. SUITS AND A. MINNITTI

In the late 1970s and early 1980s, the New York State Department of Transportation (NYSDOT) was involved in selecting geotextiles to be used in a turbidity curtain being designed by consulting engineers for the NYSDOT proposed replacement of the West Side Highway in New York City. The proposed designs involved dredging material from the Hudson River and constructing an embankment in the river over an approximate length of 4.5 km (2.8 mi), extending approximately 183 m (600 ft) into the river. The project's Water Quality Certificate required that turbidity curtains be placed along the U.S. Pierhead line, totally isolating the areas of dredging and filling operations. It was determined that a turbidity curtain of the depth required to comply with the Water Quality Certificate had never been constructed in a tidal estuary. It was therefore decided to develop a laboratory test program followed by the on-site installation of a 180-m (600-ft) long prototype turbidity curtain. Both programs were aimed at supplying data to be used in the design of the actual turbidity curtain. Details of the testing program, design considerations, and conclusions reached from the prototype installation are given. Because of environmental concerns, however, this project was not constructed.

In the 1970s the New York State Department of Transportation (NYSDOT) was involved in the design of a replacement for the deteriorating West Side Highway in New York City. The proposed design consisted of constructing a hydraulic embankment 4.5 km (2.8 mi) long extending 183 m (600 ft) into the Hudson River. Extensive dredging of organic material from the river bottom was going to be necessary to key the embankment into the foundation soils.

The Water Quality Certificate was granted in April 1979, with the following conditions on the permit:

(1) The Applicant shall provide the Department of Environmental Conservation (DEC) with the opportunity to participate, as necessary, in the on-going review of draft plans and specifications for dredging or filling in the project area in cooperation with the review team established by the New York State Department of Transportation. No portion of the project involving dredging or filling will be advertised for bidding purposes until final plans and specifications have been approved by the DEC insofar as they relate to maintenance of water quality in the project area. DEC review will be completed within 30 days.
(2) Dredging and placement inside the pierhead line of dredged soil shall be done by mechanical means. If methods become available in the future, which can be shown by the Applicant to result in reduced release of suspended and settleable solids, this condition may be modified by the DEC to accommodate such alternate methods.
(3) Silt screens (turbidity curtains) shall be placed along the U.S. Pierhead line (with returns to the shoreline where necessary) in order to totally isolate areas in which dredge and/or fill operations are conducted. The silt screens (turbidity curtains) shall be Carthage Mills woven plastic filter cloth (geotextile), or equivalent, with a 12-foot impermeable top curtain, and securely anchored to the river bottom.
(4) The Applicant shall, in cooperation with the DEC, develop a program for water quality testing and monitoring during the dredging or filling operation of project construction. The water quality testing and monitoring program shall be approved by the DEC prior to advertising for bids for dredging or filling.
(5) The Applicant shall be responsible for reimbursing the DEC for all costs incurred in reviewing of plans and specifications, assisting in development of a water quality testing and monitoring program, and for its continuing operation during all dredging and filling activity.
(6) If conditions are revealed during the dredging and filling operation which result in substantial water quality degradation, construction shall cease on that portion of the project causing the problem until corrective measures are determined and implemented.

The purpose of the turbidity curtain was to create a settling basin within the U.S. Pierhead line, isolating the area of dredging and filling operations from the main channel of the Hudson River. In the settling basin, sediment drops out of suspension with little influence from the outside environment. This was necessary to protect the channel from becoming overloaded with material from the dredge-and-fill operations, which would affect the aquatic life and result in river sedimentation.

The project was estimated to be constructed in five dredging contracts. The project had two objectives: to minimize the amount of material suspended because of the dredging and to minimize the amount of suspended material that could escape into the river channel. The reason for this concern was the toxic materials and heavy metals present in the bottom sediments of the river.

To meet certificate condition 3, "or equivalent," it was required that an extensive laboratory evaluation be performed of geotextiles on the market. Because little information existed on the performance of a turbidity curtain of this depth in a tidal estuary, the results of this evaluation were to be verified by constructing a prototype turbidity curtain.

The prototype curtain was built between Piers 59 and 60. The panels of the curtain consisted of two sections: a permeable geotextile and an impermeable barrier attached to the top of the geotextile. Installation of the prototype turbidity curtain was completed in October 1981, with testing and observations continuing through March 1982.

New York State Department of Transportation, Albany, N.Y. 12232.

TECHNICAL CONSIDERATIONS

Soil Profile

The soil profile for the site consisted of three strata. The upper stratum consisted of 11.3 m (37 ft) of very soft to soft black organic silty clay. The middle layer consisted of 11.9 m (39 ft) of stiff gray organic silty clay. Finally, the lower layer consisted of 36.6 m (120 ft) of medium to stiff clay with fine sand seams.

Turbidity Curtain Site Design

On the basis of site conditions, the following criteria were used in the design of the prototype turbidity curtain:

1. Approximate 1-m (3-ft) wave height,
2. Current of 0.5 knot perpendicular to the curtain,
3. Ice load of 2 kN/m,
4. Ballast weight sufficient to keep the curtain on the bottom during the dredging and filling operations,
5. Flotation a minimum of 4 times the submerged weight of the ballast,
6. Curtain height to be 1.5 times the mean high-water depth to allow vertical billow to reduce stress of the curtain geotextiles,
7. Horizontal billow 6.1 m (20 ft) from support center lines,
8. Differential head across the curtain of 63.5 mm (2.5 in.),
9. A 3.7-m (12-ft) high impermeable barrier at the top of the curtain to meet the Water Quality Certificate requirements,
10. Seams within the geotextile materials sewn with a minimum overlap of 75 mm (3 in.) and four lines of stitching. [The seams in the impermeable panels were thermally welded with a minimum overlap of 37.5 mm (1.5 in.).]

GEOTEXTILE SELECTION

Geotextile Properties

The properties selected for the geotextiles were to be a minimum wide width strength of 175 kN/m in the weakest principal direction and a minimum permittivity of 0.4 sec^{-1}, as determined by the NYSDOT Soil Mechanics Bureau (SMB). The strength criterion was based on the loadings described in the design criteria, applying a factor of safety of 2. The permittivity criterion of 0.4 sec^{-1} was selected on the basis of the anticipated volumetric flow rate anticipated from tidal action.

Early in the design, a soil retention criterion based on a NYSDOT–SMB Soil Retention Test was included. The criterion was 75 percent soil retention on a soil-and-water slurry with 7.6 g of soil per 1000 cc of Hudson River water (the anticipated field value).

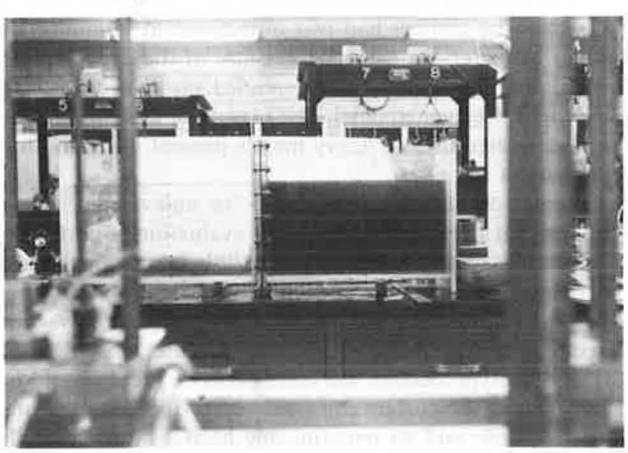

FIGURE 1 Soil retention test.

Laboratory Test Program

The laboratory test program in conjunction with the design of the prototype turbidity curtain consisted of performing the following tests on the various geotextiles available: (a) soil retention, (b) long-term water flow, (c) geotextile permittivity, (d) geotextile wide-width strength, and (e) geotextile seam strength.

Soil Retention Test

The soil retention test was performed using an acrylic tank as shown in Figure 1, the dimensions of which were approximately 1 m (37.5 in.) long, 152 mm (6 in.) wide, and 355 mm (14 in.) high. A slide panel held the test specimen in the middle of the tank, thus forming an upstream and a downstream chamber.

A slurry of water and soil was introduced on the upstream side and allowed to flow through the geotextile into the downstream chamber and out into a large circular tank. The percentage of soil retained by the test specimen was determined by taking a grab sample of the slurry after it had passed through the geotextile and performing a hydrometer analysis on it. The percentage retained was calculated on the basis of the initial slurry dilution of 7.6 g of soil/1000 cc of water. As previously indicated, the testing was performed using Hudson River water so as to duplicate actual conditions as closely as possible.

Rather than 7.6 g/1000 cc of water dilution, it was determined that only 2.3 g/1000 cc of Hudson River water would actually be in suspension at the turbidity curtain location. The sedimentation time for particle fall is highly dependent on the percentage of soil in suspension. The lower dilutions settle out faster, and therefore less soil is available to pass through the turbidity curtain. Initial laboratory testing of the 7.6-g/1000-cc dilution produced results well within the 75 percent retention criterion. Because the lower dilution would result in faster settlement, the retention percentage could only be better, so the test requirement was eliminated.

Long-Term Water Flow Test

Concern arose over what effect the existing conditions of the Hudson River water would have on the performance of the curtain. To answer this concern, long-term flow tests were performed using the tank from the soil retention test with the various geotextiles inserted.

Hudson River water was allowed to flow through the geotextile for 6 hr. For all the geotextiles tested, it was determined that by the end of the 6-hr period the river water had plugged the geotextiles to the point where little or no flow of water through the geotextile was taking place. This was another reason for eliminating the 75 percent retention criterion (i.e., because the geotextile clogged in a relatively short period of time, very little or no soil could pass through the geotextile regardless of the percent dilution).

Permittivity Test

The permittivity of a geotextile is defined as the volumetric flow rate of water in the normal direction through the geotextile per unit of head per unit of area. The testing was done using the constant head method (now ASTM Method D4491 for the water permeability of geotextiles). Figure 2 shows the device used. No testing was done on the impermeable barrier.

Wide-Width and Seam Strength Testing

The wide-width strength of the geotextiles being considered for use was determined using what is now ASTM Test Method D4595, Tensile Properties of Geotextile by the Wide Width Strip Method. The same technique was used in testing the seam strength.

Specimens 200 mm (8 in.) wide with 100 mm (4 in.) gage length were tested in both the geotextile and the seam test. The strain rate of the test was 10 percent/min.

No strength testing was done to investigate ultraviolet degradation of the impermeable barrier.

Materials Selected

On the basis of the criteria decribed above, the panels for the prototype turbidity curtain were fabricated from Amoco Propex 1325 and 4557, Bradely Materials Filterweave 70-C, and Hoechst Trevira 1160. The impermeable panels were made of Shelter-Rite 8028, a PVC-coated polyester material.

The prototype turbidity curtain consisted of four panels 34 m (110 ft) long by 11 m (35 ft) high, including the 3.7-m (12-ft) high impermeable barrier; one panel 34 m (111 ft) long by 5 m (16 ft) high; and two closure panels 5 m (15 ft) long by 11 m (35 ft) high. The closure panels provided a means of access in and out of the area within the curtain. Figure 3 shows the fabricated curtain, and Figure 4 shows the curtain in place.

PERFORMANCE AND RESULTS

The prototype turbidity curtain was evaluated for 5 months. The water quality was investigated by Lawler, Matusky & Shelly, and the entire system was evaluated by Mueser, Rutledge, Johnston and Desimone.

Monitoring the performance of the entire system resulted in the following findings:

1. Tension in the cables, monitored with load cells, showed a maximum load in the natural environment of approximately 45 kN. Ice conditions did not produce loads exceeding this.
2. Structural tests involved running a tugboat at various speeds and distances parallel to the curtain to generate wave action. The loading in the cables due to wave action and prop wash was measured. A maximum load of 42.4 kN was produced by the prop wash.

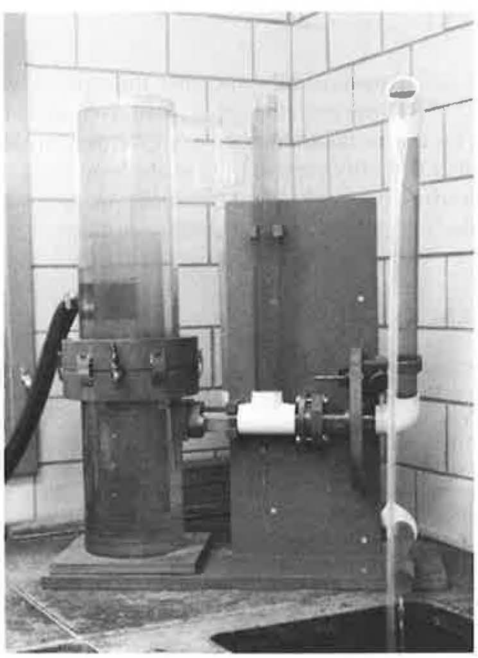

FIGURE 2 Permittivity test.

FIGURE 3 Fabricated curtain.

FIGURE 4 Curtain in place.

3. During stages of the structural testing, the curtain was visually inspected by a diver. Some of the grommets in the closure panels were seen to have pulled out.

4. After 4 weeks, two panels were removed for visual inspection, and laboratory permittivity testing was performed on one panel. Overall, the panels showed little or no damage from the structural tests. There was a brown, slimy coating over the curtain. Laboratory permittivity tests on one panel showed a reduction by a factor of 10 in this property.

5. One of the panels removed for inspection was reinstalled. This along with the others remained in place for 5 months through late fall and winter.

COST

NYSDOT had estimated the cost of the prototype turbidity curtain to be $454,380, including fabrication, structural support (three pile clusters driven in the river), installation, testing, and reports. The low bid received was $431,240.

CONCLUSIONS

Based on observations, the following conclusions were drawn concerning the prototype turbidity curtain system:

1. A curtain could be fabricated and installed to meet the Water Quality Certificate requirements.
2. Both the woven and nonwoven geotextiles performed satisfactorily.
3. Hudson River water in its natural environment quickly reduced the permittivity of the geotextile.
4. Because there was little accumulation of ice that year, it had relatively little effect on the curtain and its support system.
5. The criteria for selection of the geotextiles should be permittivity and wide-width strength properties.

RECOMMENDATIONS

Based on the results of this installation, several recommendations were made for the larger turbidity curtain proposed for use in the embankment construction on the project. Among these were the following:

1. Reduction in width of the thermally welded seams in the impermeable barrier,
2. Use of PVC-coated fabrics for the closure panels instead of urethane coating (urethane showed signs of deterioration and was significantly more expensive than PVC),
3. Reduction of the ballast weight in the closure panel,
4. Prohibition of the use of rolled microfilm for the flotation collar assemblies,
5. Reduction of the vertical billow in the curtain, and
6. Incorporation into the design of an opening in the curtain 150 m (500 ft) away from the turbidity source to compensate for clogging of the geotextile by Hudson River water. (This was to allow equalization of water elevation on both sides of the curtain from tidal activity. The distance was based on the relationship of the settlement velocity of suspended solids in the river environment and the water velocity due to the tidal fluctuations.)

COMMENT

Because of environmental concerns, the project was never constructed. However, the observations and conclusions reached for this installation were incorporated into the design of a smaller turbidity curtain in Upstate New York, and have also served as the basis for developing an approved list of geotextiles for general use in turbidity curtains.

REFERENCES

1. *West Side Highway Project Report on Prototype Turbidity Curtain*. Mueser, Rutledge, Johnstone & Desimone Consulting Engineers, New York City, May 1982.
2. *West Side Highway Project Evaluation of Test Results: Silt Curtain Fabrics*. Mueser, Rutledge, Johnstone & Desimone Consulting Engineers; Woodward-Clyde Consultants, Inc., New York City, Sept. 1983.
3. *Final Supplemental Environmental Impact Statement—Westside Highway Project*. U.S. Army Corps of Engineers; U.S. Department of Transportation, Nov. 1984.