

Technical Paper by K.R. Reddy and R.E. Saichek

PERFORMANCE OF PROTECTIVE COVER SYSTEMS FOR LANDFILL GEOMEMBRANE LINERS UNDER LONG-TERM MSW LOADING

ABSTRACT: This paper presents the results of large-scale laboratory simulation tests conducted to evaluate the relative performance of different cover systems, consisting of a granular soil layer (i.e. a drainage layer) both with and without the presence of a needle-punched nonwoven geotextile, to protect a 1.5 mm thick smooth HDPE geomembrane liner under long-term municipal solid waste (MSW) loading conditions. Five different granular soils that range from a coarse gravel to a medium sand were used in the testing program. The protective cover system and the geomembrane liner were subjected to incremental loading to a maximum pressure of 1.4 MPa. The effect of long-term loading on the characteristics of the cover soils was assessed by performing particle size analyses, and the physical damage that occurred to the geomembrane liner was visually assessed in addition to performing multi-axial tension, wide strip tension, and water vapor transmission tests. The test results revealed that the degree of geomembrane liner protection decreases as the soil mean particle size increases and as the soil particle sphericity decreases. This study demonstrates that a 300 mm thick granular soil layer consisting of particles with a mean size less than 30 mm and a sphericity greater than 0.8, combined with a 270 g/m² nonwoven geotextile provides adequate protection for a 1.5 mm thick HDPE geomembrane liner from MSW loading.

KEYWORDS: Protective cover, Drainage layer, Liner systems, Geomembrane, Laboratory simulation, Long-term loading, Landfill.

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1 INTRODUCTION

Composite landfill liner systems are constructed in order to protect public health and the environment by preventing the hazardous constituents of leachate from infiltrating into the subsurface. Single composite landfill liner systems that consist of a thick layer of compacted clay overlain by a geomembrane liner are commonly used for municipal solid waste (MSW) landfills in the United States. A leachate collection system that typically consists of a granular soil layer and a network of perforated pipes, i.e. a drainage layer, is constructed over the geomembrane liner. The geomembrane liner acts as the primary leachate barrier; however, the liner is susceptible to mechanical damage during construction and after subsequent waste placement and must be protected. In order to protect the geomembrane liner, the granular soil layer should also function as a protective cover system. Frequently, a geotextile is inserted between the granular soil (also called a cover soil) and the geomembrane liner for added extra geomembrane liner protection against mechanical damage.

Presently, the regulations for the drainage layer only stipulate that the material must possess a hydraulic conductivity of at least 1×10^{-3} cm/s and should not allow the accumulation of a leachate head over 300 mm. These criteria ensure proper leachate drainage and can be met with a number of different soils, but, in order to ensure proper geomembrane liner protection, additional criteria are warranted. For instance, the physical soil characteristics, such as the particle size and shape may affect the ability of the soil to protect the geomembrane liner. In addition, if a geotextile is incorporated in the protective cover system, the degree of geomembrane liner protection also depends on the type and mass per unit area of the geotextile used. The protection of the geomembrane liner from damage must be ensured with regard to both stresses produced during construction and under long-term waste loading.

Since 1993, research has been in progress at the University of Illinois at Chicago (UIC), Chicago, Illinois, USA, to develop a design and construction procedure that will ensure that a selected protective cover system will adequately protect the geomembrane liner. An evaluation of protective cover systems under construction loading conditions was completed in 1996 as part of the research program (Reddy et al. 1996). The current paper presents the results of a complementary study that investigated the performance of protective cover systems under long-term waste loading. First, an overview of previous protective cover system studies is presented. Then, the experimental investigation performed at UIC to evaluate different protective cover systems under long-term waste loading conditions is described. Finally, the results are utilized to assess the relative performance of the protective cover systems.

2 BACKGROUND

An investigation of the degree of geomembrane liner protection provided by a variety of geosynthetic cushions under construction loading was reported by Richardson (1996). In this evaluation, a lightweight bulldozer and a fully loaded dump truck were used to simulate the loading conditions. One specific type of protective cover soil that consisted of the American Association of State Highway and Transportation Officials (AASHTO) #57 stone was placed in 300 and 600 mm thick layers. After the field testing

was completed, the exhumed geomembrane specimens were visually inspected and tested in the laboratory. Visual inspection revealed that even the lightest geosynthetic cushions offered some protection and reduced surficial geomembrane specimen scratches and dents. Laboratory wide strip tensile testing showed that a reduction in both the strain and load at yield correlated well with the measured field observations of damage, but the ultimate load and strains were less impacted by stone-induced scratches. Richardson (1996) recommended using a 407 g/m^2 nonwoven geotextile for a normal pressure of 345 kPa and that the mass per unit area of the nonwoven geotextile be increased linearly to approximately $1,526 \text{ g/m}^2$ for a pressure of 2,070 kPa.

An evaluation of protective cover systems for landfill geomembrane liners under construction loading was also performed by Reddy et al. (1996). A 300 mm layer of medium gravel or fine gravel was used as the protective cover soil, and field tests were performed with and without the presence of a 270 g/m^2 nonwoven geotextile over the geomembrane liner. The field tests employed light and heavy bulldozers that subjected the liner systems to simulated construction loading conditions. Upon completion of the field testing, the geomembranes were exhumed, visually inspected, and tested in the laboratory. The visual inspection revealed that none of the geomembrane specimens had apparent damage in the form of tears or holes; however, the specimens without a geotextile had surficial scratches and dents. Laboratory testing of the exhumed geomembrane specimens to measure the elongation at burst value, determined from multi-axial tension tests, and the ultimate or break stress and strain values, determined from wide strip tensile tests, indicated that the geomembrane specimens underwent physical changes due to the construction loading. Contrary to the findings of Richardson (1996), the yield stress values for the tested geomembrane specimens were approximately equal to those for the virgin geomembrane specimens. Overall, Reddy et al. (1996) showed that even though physical changes in the geomembrane specimens had taken place, these changes did not adversely affect geomembrane performance, and a low mass per unit area geotextile, 270 g/m^2 , adequately protected the geomembrane.

A comprehensive study of the puncture protection of geomembranes under static loading was performed by Koerner and co-investigators (Wilson-Fahmy et al. 1996; Narejo et al. 1996; Koerner et al. 1996). A design methodology was developed based on a theoretical analysis and an experimental program. The theoretical analysis was based on a single protruding object rising from the subgrade, and computational methods were used to determine the relationship between the pressure and the tensile force in the geomembrane liner. The use of a geotextile was also included in the theoretical analysis. The experimental program included a group of puncture tests with and without the use of a variety of geotextile specimens to determine the pressures necessary to cause geomembrane specimen puncture. Most of the experiments employed truncated cones beneath the geomembrane specimen, but packed and isolated stones were also used. Visual examination of the geomembrane specimen was performed to determine the pressure that caused the specimen to yield because failure could not be achieved in the packed stone test. Lastly, trends were examined and a design methodology was developed based on the equations and design tables that were produced.

In Germany, a mechanical performance test has been used to select a protective cover system (Seeger and Muller 1996). In this test, a 0.5 to 1.0 mm thick soft plate is laid on an approximately 20 mm thick elastomer inside a 300 to 500 mm diameter cylindrical container and is covered with a geomembrane specimen. The protective layer is then

placed and covered with a 200 mm thick layer of 16 to 32 mm rounded drainage gravel. A nonwoven geotextile separation layer is laid on the gravel and, lastly, a load-distributing 50 mm thick sand layer is placed on top. The specified load is exerted by means of a load plate for 1,000 hours and deformations of the geomembrane specimen are recorded as the plastic deformation of the soft plate. Quantitative measurements of the worst indentations are determined and, if a strain magnitude of 0.25% is exceeded, the protective layer is deemed to be inadequate. Soil layers, nonwoven geotextiles, combinations of nonwoven geotextiles, or combinations of geotextiles and soils are all used as protective layers.

3 EXPERIMENTAL METHODOLOGY

3.1 Objective and Scope

The objective of the current study is to evaluate the relative performance of different protective covers/drainage soils to protect the geomembrane liner under long-term waste loading conditions. In addition, the study was also focused on determining the beneficial effects of using a geotextile in the protective cover system to protect the geomembrane liner. Although beyond the scope of this paper, the results of the current study, in combination with the previous study that dealt with construction loading (Reddy et al. 1996), will facilitate the development of a rational design approach for the protective cover system.

The scope of the current study included the completion of the following tasks:

- design and construction of a test setup for simulating typical long-term waste loading conditions;
- identification and characterization of five different granular soils currently used as leachate drainage material;
- testing of various protective cover systems consisting of five different soils both with and without a geotextile; and
- visual assessment of the geomembrane liner damage and the completion of several laboratory tests performed to quantify the changes in the physical and hydraulic properties of the geomembrane liner.

The experimental materials and test procedures are described in Sections 3.2 to 3.6.

3.2 Test Setup

A test setup was designed and constructed to simulate the protective cover system and to subject it to high stresses that are equivalent to long-term MSW loading. Figure 1 is a schematic of the test setup. The test box was bolted and welded together using 6.35 mm thick steel plates, 0.35 mm × 51 mm × 51 mm steel angles, and 19.1 mm (diameter) × 51.0 mm long bolts. The interior dimensions of the constructed test box were 508 mm (width) × 457 mm (height) × 914 mm (length). A steel plate was placed on top of the protective cover system inside the test box for a uniform load application. The dimensions of the loading plate were 6.35 mm × 495 mm × 902 mm, covering an area of

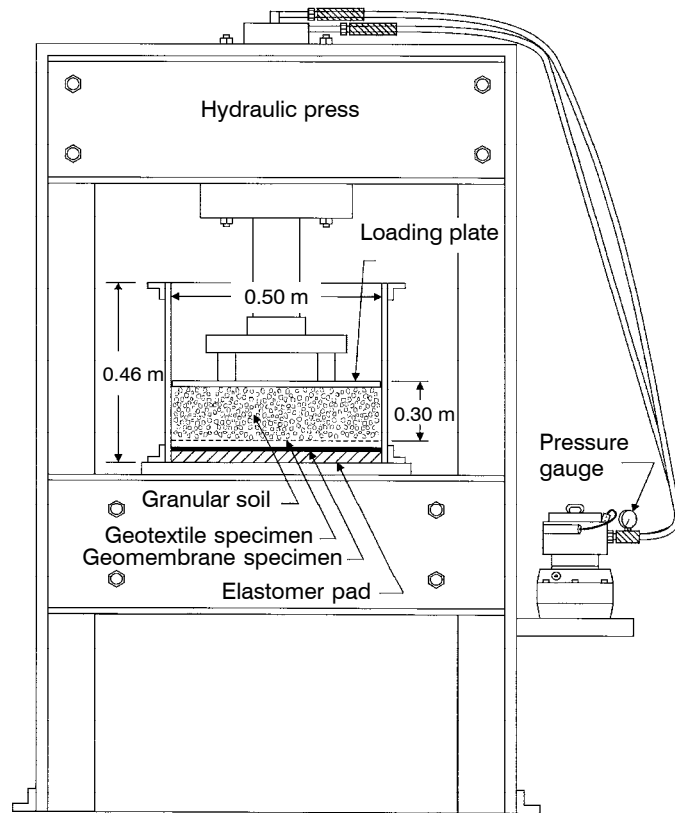


Figure 1. Schematic of the geomembrane liner protective cover simulation test setup.

approximately 0.45 m^2 . The loading plate was reinforced with two $38 \text{ mm} \times 76 \text{ mm} \times 749 \text{ mm}$ steel bars and a $51 \text{ mm} \times 305 \text{ mm} \times 457 \text{ mm}$ steel plate that was attached to the bottom of the loading piston. The load was applied using a 890 kN Enerpac hydraulic press. The maximum pressure applied was approximately 1.4 MPa, which is equivalent to the pressure exerted by a height of MSW greater than 100 m with a unit weight of 14 kN/m^3 .

3.3 Simulation of the Clay Liner

An elastomer was selected to simulate a typical compacted clay liner. The physical properties of clay liners can change depending on mineral composition, water content, and degree of compaction. Therefore, the elastomer facilitated the evaluation of the relative performance of each different protective cover system under identical simulated clay liner conditions. One-dimensional compression tests were conducted on several elastomer materials of varying thickness and hardness, and the stress versus strain data were compared to the consolidation test results for a compacted clay. The standard test method ASTM D 2435 was used for consolidation testing of the compacted clay, and

the elastomer was tested in a 102 mm inside diameter steel ring under dry conditions. Figure 2 shows the one-dimensional compression data for the different elastomers and the compacted clay. Based on these test results, a 13 mm thick, 80 durometer hardness elastomer was selected for use in the current study to simulate a compacted clay liner.

3.4 Drainage/Protective Soils

Five different granular soils were chosen for the current study. The properties of these soils are summarized in Table 1, and the particle size distributions prior to loading are shown in Figure 3. The particle size distributions were determined according to the standard test method ASTM D 422. The volumetric coefficient, VC , and sphericity, S_p , values, which represent the shape of the particles, were determined according to the procedures specified by Winterkorn and Fang (1975, pp. 93-96). The volumetric coefficient is defined as follows:

$$VC = \frac{6v}{\pi a^3} \tag{1}$$

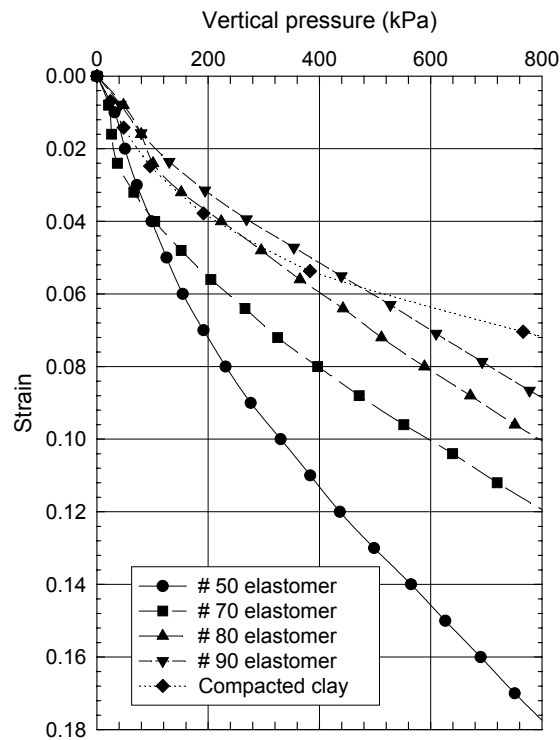


Figure 2. One-dimensional compression data for different elastomers and a compacted clay.

Table 1. Properties of the protective cover soils used in the current study.

Soil type	Particle size and shape characteristics									USCS symbol	k (cm/s)	Insoluble residue (%)
	% Gravel	% Sand	% Fines	D_{50} (mm)	C_u	C_c	Particle shape	VC	S_p			
Crushed gravel	99	1	0	17.0	1.42	0.83	Subangular	0.121	0.798	GP	0.975	39.5
Medium gravel	100	0	0	30.0	1.48	0.96	Subrounded	0.117	0.804	GP	> 1.0	42.2
Fine gravel	98	2	0	13.0	2.26	1.27	Subrounded	0.170	0.846	GP	> 1.0	36.7
Very fine gravel	63	37	0	5.8	2.25	1.00	Rounded	0.188	0.829	GP	> 1.0	48.0
Medium sand	0	99	1	0.65	4.30	0.80	Rounded	NA	NA	SP	0.025	70.1

Notes: D_{50} = mean particle size; C_u = coefficient of uniformity; C_c = coefficient of curvature; VC = volumetric coefficient; S_p = sphericity; USCS = Unified Soil Classification System; k = hydraulic conductivity; GP = poorly graded gravel; and SP = poorly graded sand. D_{50} , C_u , and C_c are calculated in accordance with ASTM D 422; NA = not analyzed. VC and S_p are calculated using Equations 1 and 2, respectively.

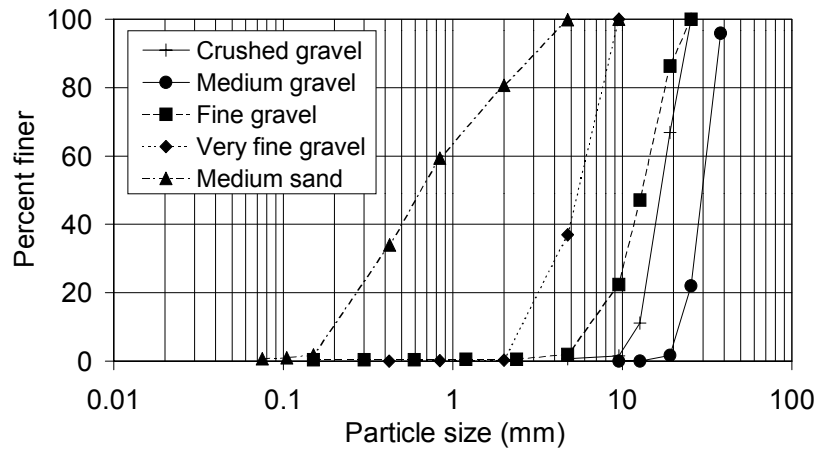


Figure 3. Particle size distribution of the protective cover soils prior to loading.

where: v = particle volume (measured based on the volume of water displaced); and a = largest particle dimension. If b is the intermediate and c is the smallest dimension of a particle, then the flatness ratio, p , is defined as the ratio, c/b , and the elongation ratio, q , is defined as the ratio, b/a . The sphericity, S_p , is defined in terms of p and q as follows:

$$S_p = \frac{12.8 (p^2 q)^{\frac{1}{3}}}{1 + p(1 + q) + 6[1 + p^2(1 + q^2)]^{\frac{1}{2}}} \quad (2)$$

The hydraulic conductivity of the soils was determined using a large-scale constant head permeameter (Saichek 1997). To assess the chemical resistance of each soil, the insoluble residue was determined in accordance with the standard test method ASTM D 3042.

The particle size distributions (Figure 3) indicate that all of the soils were poorly graded and that the ranges of particle sizes are between coarse gravel and medium sand with very little or no silt or clay particles. All of the five different soils have been used at landfills as the drainage layer based solely on the criterion that they meet the hydraulic conductivity requirement of 1×10^{-3} cm/s. However, it can be seen that these soils possess different physical characteristics that may have a significant influence on their protective cover performance. The gravels differed mainly in particle size, and one gravel differed in particle shape. Three of the gravels were primarily comprised of rounded to subrounded particles, and the fourth gravel was a crushed stone gravel with subangular particles. The chemical resistance of the protective cover soils, as reflected by the amount of insoluble residue, depends on the mineral content of the soils.

3.5 Geotextile and Geomembrane

A 270 g/m² needle-punched, nonwoven polypropylene geotextile and a smooth, 1.5 mm thick high density polyethylene (HDPE) geomembrane were selected for testing. The dimensions of the geotextile and geomembrane specimens were 495 mm × 902 mm. Each geotextile and geomembrane specimen was carefully inspected for any signs of damage before testing.

3.6 Testing Procedure

The testing procedure involved placing the 495 mm × 902 mm elastomer pad on the bottom of the test box, laying the geomembrane specimen on top of the elastomer, installing the geotextile over the geomembrane, if needed, and then carefully placing the prescribed soil to the correct thickness. Thickness lines were drawn at the 300 mm level on the test box interior prior to the placement of the soil in order to ensure that the soil was level and filled to the correct depth. The top load plate was then placed on the soil and the first load increment was slowly applied. The loading for all of the tests was applied in increments of 205 kPa every 30 minutes until the maximum pressure of 1.4 MPa was attained in order to simulate long-term waste loading conditions. This maximum pressure was then maintained constant for 48 hours to allow for deformation and creep of the geomembrane specimen to take place. After 48 hours, the load was then incrementally decreased at the same rate as during application. When the load was fully released, the top load plate was removed, and a portion of the soil was carefully removed until an end of the test box could be safely unbolted. The end of the test box was detached in order to facilitate the careful removal of the remaining soil. The geotextile specimen, if used, was then removed, and the geomembrane was cleaned, visually inspected, and tested in the laboratory for damage assessment. A total of 10 tests was conducted using different variables as shown in Table 2.

Table 2. Laboratory simulation test parameters.

Test no.	Soil type	Thickness (m)	Geotextile used (mass per unit area)	Initial soil density (g/cm^3)	Maximum applied stress (kPa)	Duration under maximum load (hours)
1	Crushed gravel	0.30	None	1.79	1,436	48
2	Crushed gravel	0.30	270 g/m^2	1.79	1,436	48
3	Medium gravel	0.30	None	1.84	1,436	48
4	Medium gravel	0.30	270 g/m^2	1.84	1,436	48
5	Fine gravel	0.30	None	1.86	1,436	48
6	Fine gravel	0.30	270 g/m^2	1.86	1,436	48
7	Very fine gravel	0.30	None	1.92	1,436	48
8	Very fine gravel	0.30	270 g/m^2	1.92	1,436	48
9	Medium sand	0.30	None	1.97	1,436	48
10	Medium sand	0.30	270 g/m^2	1.97	1,436	48

3.7 Damage Assessment Procedure

The particle size distribution and hydraulic conductivity of each soil was measured to evaluate the physical and hydraulic changes due to long-term loading conditions. The geomembrane specimens exhumed after testing were carefully cleaned with a cloth, and each specimen was then inspected for punctures or tears. The condition of the geomembrane specimens was recorded to assess damage in the form of scratches, dents, or gouges. The following tests were then conducted to determine the physical and hydraulic properties of the geomembrane specimens: (i) multi-axial tension tests; (ii) wide strip tensile tests; and (iii) water vapor transmission (WVT) tests. These tests were also performed on virgin geomembrane specimens for comparison purposes and to quantify the mechanical and hydraulic property changes of the geomembrane specimens.

The multi-axial tension tests were performed in accordance with the standard test method ASTM D 5617. In this test, a geomembrane specimen was secured at the edges of a large 300 mm diameter pressure vessel. The pressure in the vessel was gradually increased and the specimen deformation was measured. The testing was continued until failure occurred which was indicated by the sudden loss of pressure in the vessel. The recorded pressure and deformation data were used to calculate the stress and strain at failure, i.e. break. Reddy et al. (1996) have shown that the results obtained using 300 and 600 mm diameter pressure vessels were in close agreement; therefore, the effect of geomembrane specimen size on the multi-axial test results is not significant.

The wide strip tensile tests were performed in accordance with the standard test method ASTM D 4885. In this test, a 200 mm wide by at least 200 mm long geomembrane specimen was clamped across its width in a tensile testing apparatus and stretched at a constant, specified rate of extension. The uniaxial load was applied until the specimen ruptured. The load and deformation data were used to calculate the geomembrane specimen yield stress, yield strain, ultimate stress, and ultimate strain.

The WVT tests were performed in accordance with the standard test method ASTM E 96. In this test, a geomembrane specimen was sealed over a noncorroding, impermeable test dish containing water. The assembled test dish was placed in a temperature and humidity controlled chamber, and the weight loss due to escaping water vapor was periodically recorded. The specimen weight was recorded until the rate of weight change reached a steady state. The data was then used to calculate the permeance of the geomembrane specimen.

4 RESULTS AND ANALYSIS

4.1 Effect of Loading on the Protective Cover Soils

The particle size distributions of the soils after the simulated testing are shown in Figure 4. The particle size distribution after long-term loading is approximately the same as before loading for the sand, fine gravel, and medium gravel; however, the particle size distribution slightly changes for the very fine gravel and the crushed gravel. In spite of the changes in the particle size distribution, the hydraulic conductivity of all of the soils was found to satisfy the regulatory limit of 1×10^{-3} cm/s.

4.2 Effect of Loading on the Geomembrane Liner

4.2.1 Observations

Observations of the geomembrane specimens, including the virgin specimen, were made to document any macroscopic damage that may have occurred before and during testing. The observations indicated that all of the tested geomembrane specimens, including the virgin geomembrane specimen, had some surface marks.

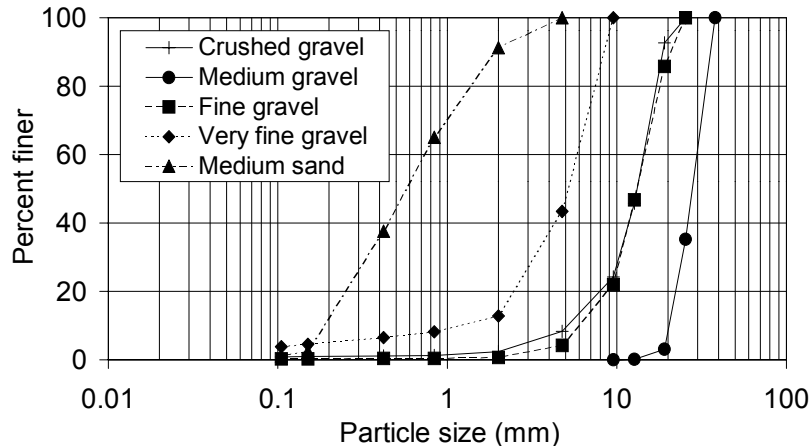


Figure 4. Particle size distribution of the protective cover soils after loading.

Generally, the geomembrane specimens tested with soils containing larger-sized particles, specifically, the crushed, medium, and fine gravels, incurred the most visual damage in the form of dents and creases. Geomembrane specimens tested with the crushed gravel appeared to sustain the most damage in the form of deep dents. The medium and fine gravels experienced less severe damage in the form of dents. The geomembrane specimens that were tested with the crushed, medium, and fine gravels combined with a geotextile also incurred damage in the form of dents, but scratches were practically eliminated and the denting appeared less severe. The geomembrane specimen tested with the very fine gravel without a geotextile produced some very small dents and, when the geotextile was employed, the number of dents was greatly reduced. Lastly, the geomembrane specimens exhumed from the medium sand tests, with or without the geotextile, appeared to be in good condition, the only visual damage being a few surface marks.

4.2.2 Multi-Axial Tension Test Results

Figures 5a and 5b show the results of the multi-axial tension tests that were conducted on the geomembrane specimens exhumed from beneath the protective cover soils after the simulated long-term load testing was completed. Figure 5a shows the tensile stress at burst, while Figure 5b shows the percent elongation at burst. Figure 5a shows that the exhumed geomembrane specimens have tensile stresses that are approximately equal to the virgin geomembrane specimen. This was true for the long-term tests performed with or without a geotextile. However, Figure 5b shows that the elongations at burst for the exhumed geomembrane specimens varied significantly from that of the virgin geomembrane, and these variations are indications of the physical changes that took place during long-term load testing.

The effect of the type of protective soil used without the presence of a geotextile can be inferred from the results shown in Figure 5b. When the protective cover soil consists of crushed gravel or medium gravel, the geomembrane specimen exhibits smaller elongations at burst. In particular, the geomembrane specimen elongations at burst for these soils were approximately 35% lower than the virgin geomembrane specimen. When the protective soil consists of a fine gravel, the geomembrane specimen elongation at burst decreases by approximately 25%. When the protective soil consists of a very fine gravel or medium sand, the geomembrane liner exhibits relatively higher elongations at burst (12 and 10% lower, respectively, than that of the virgin geomembrane specimen).

The beneficial effects of incorporating a geotextile between the protective cover soil and the geomembrane specimen are clearly evident from the results shown in Figure 5b. When a geotextile is used, the exhumed geomembrane specimens have elongation values at burst that are close to the virgin geomembrane specimen elongation values at burst. The geomembrane specimens tested with the crushed and fine gravels and the medium sand, all have elongations at burst that slightly surpass the elongation value of the virgin geomembrane. However, the geomembrane specimens tested with the remaining two soils, the medium and very fine gravels, have elongations at burst that are only marginally lower than that of the virgin geomembrane specimen, i.e. 11.7 and 4.2% lower, respectively. Therefore, comparing the elongation at burst values for tests performed with and without a geotextile, it can be con-

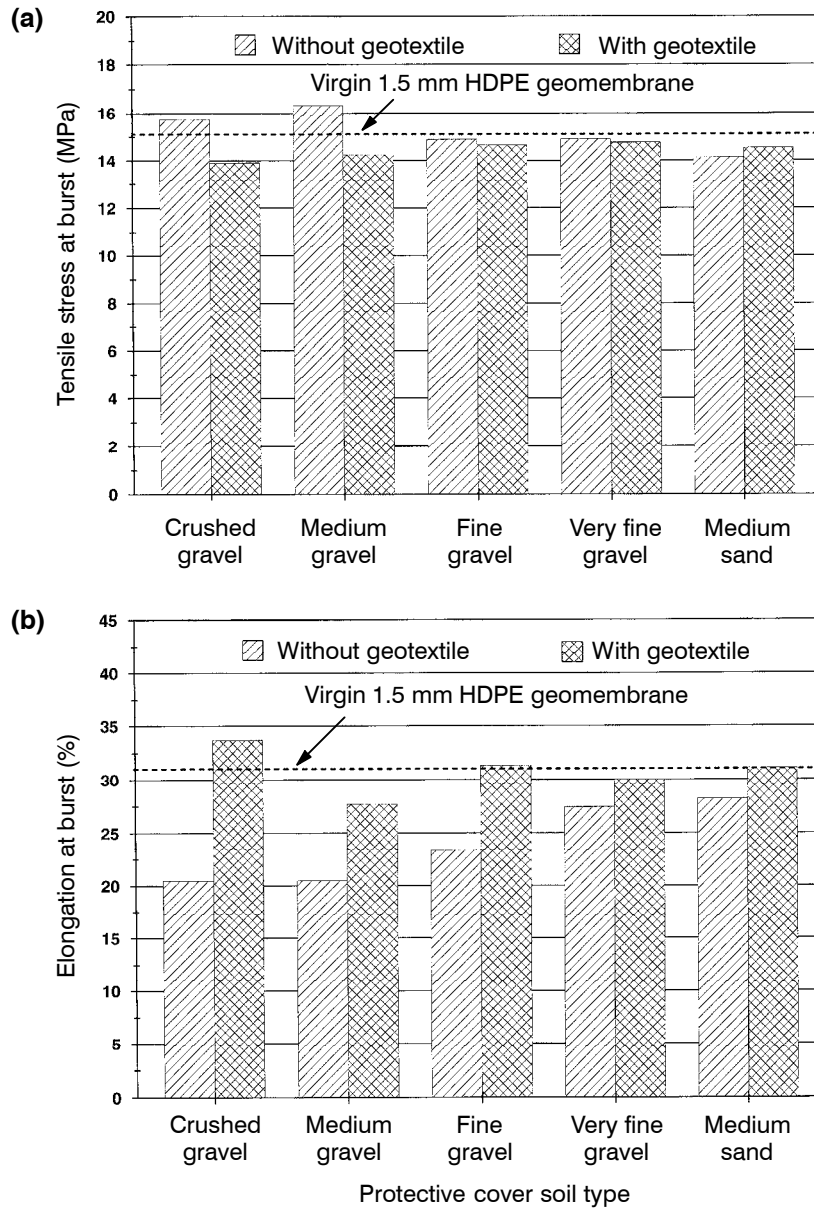


Figure 5. Multi-axial tension test results for the geomembrane specimens: (a) tensile stress at burst; (b) elongation at burst.

cluded that the presence of a geotextile in the geomembrane liner protective cover system provides significantly more protection.

4.2.3 Wide Strip Tensile Test Results

Figures 6a to 6d show the yield strain, yield stress, ultimate stress, and ultimate strain results, respectively, for the wide strip tensile tests that were performed on the geomem-

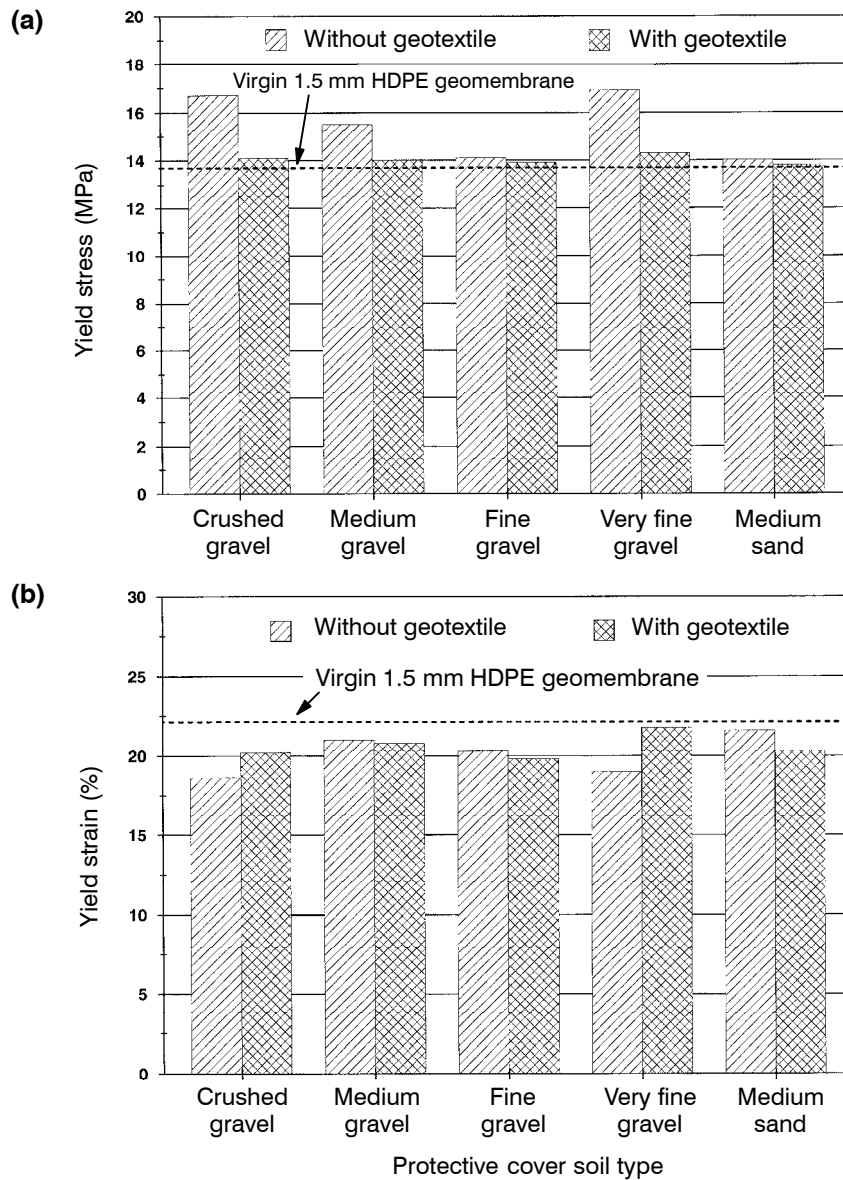


Figure 6. Wide strip tensile test results for the geomembrane specimens: (a) yield stress; (b) yield strain.

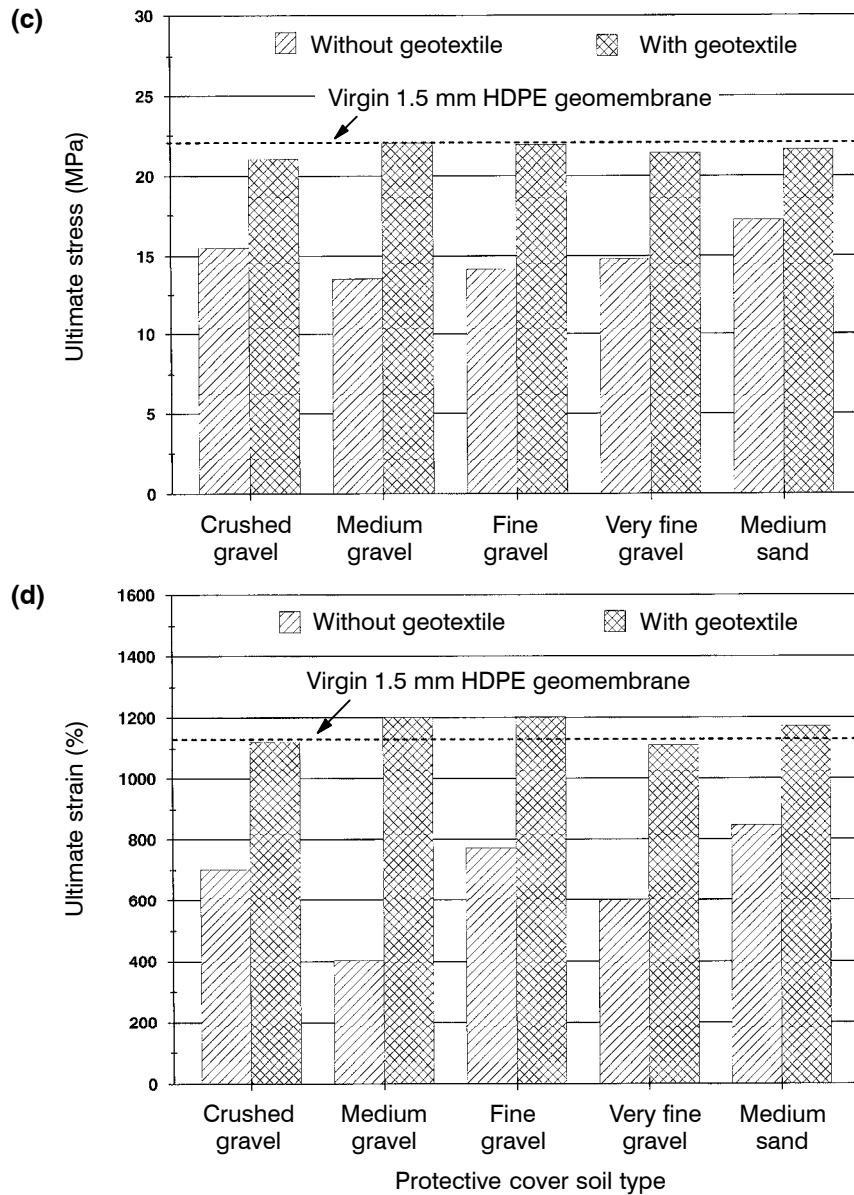


Figure 6 continued. (c) ultimate stress; (d) ultimate strain.

brane specimens exhumed after simulated long-term load testing. Figure 6a shows that the geomembrane specimen yield stress is equal to or slightly higher than that of the virgin geomembrane specimen, whereas Figure 6b shows that the geomembrane specimen yield strain is slightly lower than that of the virgin geomembrane specimen. Thus,

the yield characteristics of the tested geomembrane specimens are not significantly affected by the physical changes that occurred in the geomembrane specimens due to simulated long-term load application.

Figures 6c and 6d compare the ultimate stress and strain values for the exhumed geomembrane specimens with those of the virgin geomembrane specimen. These results clearly demonstrate that the ultimate stress and strain values of the exhumed geomembrane specimens decrease significantly when the protective cover system consists solely of a 0.3 m thick soil layer. In particular, geomembrane specimens tested with cover soils containing larger-sized soil particles generally have lower ultimate stress and strain values than geomembrane specimens tested with cover soils containing smaller-sized soil particles. Specifically, the geomembrane specimens tested with the medium gravel, containing the largest soil particles, result in the lowest ultimate stress and strain values, and, conversely, the geomembrane specimen tested with the medium sand, with the smallest-sized soil particles, result in the highest ultimate stress and strain values. These results show that if a geotextile is not used, the performance of the protective cover soil greatly depends on the size of the soil particles.

Figures 6c and 6d show that all of the geomembrane specimens tested with different cover soils in combination with a geotextile have ultimate stress and strain values that are close to the virgin geomembrane specimen values. Therefore, the presence of a geotextile greatly improves the performance of the protective cover soils, which is in agreement with the elongation at burst test results determined from the multi-axial tension testing.

4.2.4 Water Vapor Transmission (WVT) Test Results

Figure 7 shows the permeance values for the exhumed geomembrane specimens based on WVT tests. The permeance of the virgin geomembrane specimen is also shown in Figure 7 for comparison purposes. The permeance values, for the geomembrane specimens tested with a cover soil and no geotextile, range from 1.2×10^{-14} to 2.6×10^{-14} cm/s-Pa, and, for geomembrane specimens tested with a cover soil and a geotextile, the values range from 1.3×10^{-14} to 2.1×10^{-14} cm/s-Pa. All of these permeance values are close to the virgin geomembrane specimen permeance value of 1.8×10^{-14} cm/s-Pa. These results indicate that the physical changes of a geomembrane liner caused by various protective cover conditions are not significant enough to change the hydraulic properties of the geomembrane liner.

4.3 Optimal Protective Cover System

The results of the simulation tests show that the protective performance of cover soils depends on the type of soil and, also, on the presence of a geotextile. The degree of geomembrane liner protection under each simulated cover condition can be inferred from the changes in the elongation at burst values (i.e. the multi-axial tension test results) and the ultimate stress and strain values (i.e. the wide strip tensile test results) as compared to those values for the virgin geomembrane specimens. Figure 8 shows the changes in the elongation at burst values and Figure 9 shows the changes in the ultimate stress and strain values as a function of the cover soil mean particle size, D_{50} , for geomembrane specimens with and without a protective geotextile. These results serve as a guide to

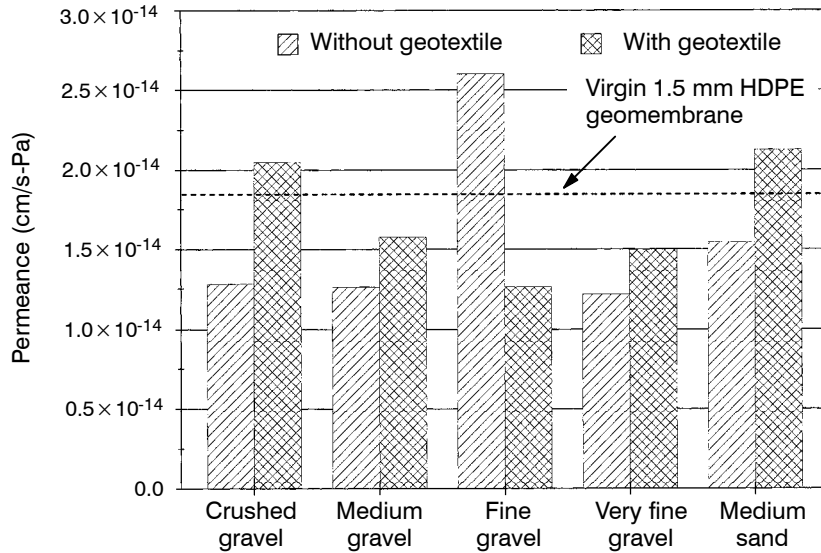


Figure 7. Water vapor transmission (WVT) test results for geomembrane specimens.

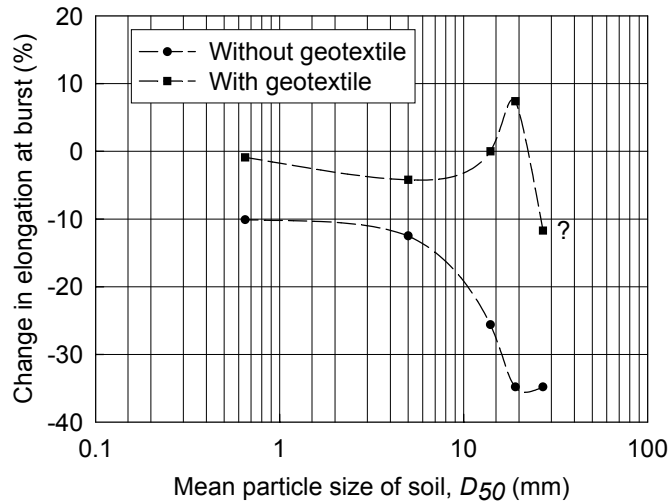


Figure 8. Relationship between the protective cover soil mean particle size versus the change in the geomembrane specimen elongation at burst measured using the multi-axial tension tests.

the selection of a protective cover system that will provide the maximum geomembrane liner protection.

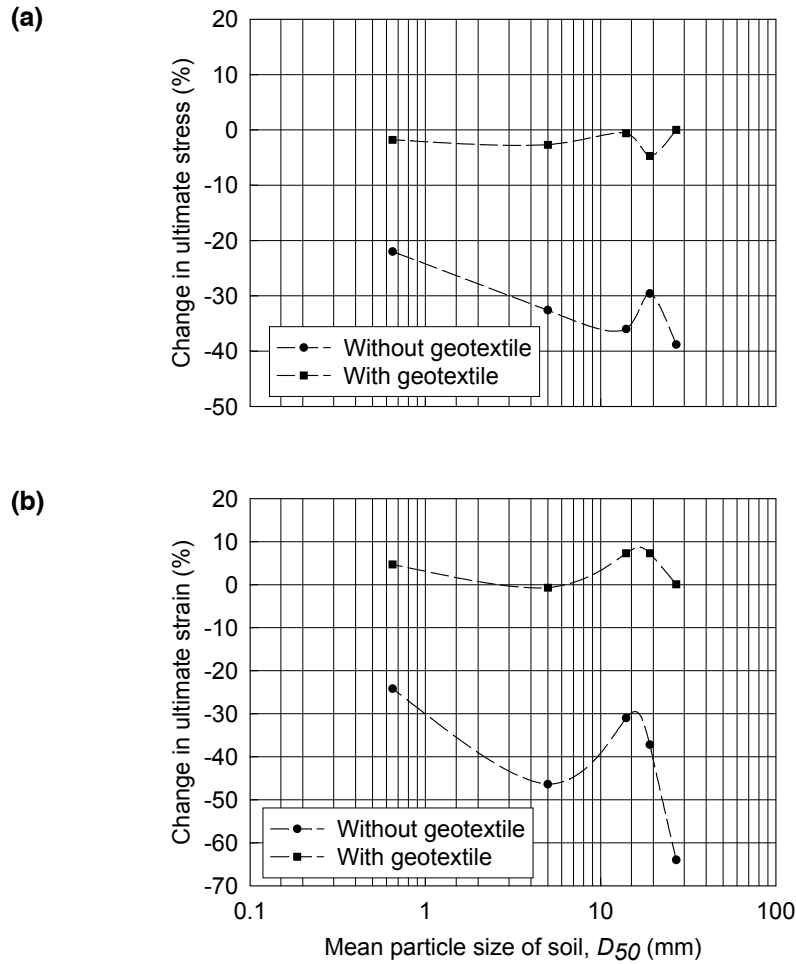


Figure 9. Wide strip tension test results for geomembrane specimens with and without a protective geotextile: (a) relationship between the cover soil mean particle size versus the change in the ultimate stress; (b) relationship between the cover soil mean particle size versus the change in the ultimate strain.

The results shown in Figures 8 and 9 indicate that the size of the soil particles significantly influences the protective performance of the cover system. When a geotextile is not employed, the elongation at burst and the ultimate stress and strain values of the geomembrane specimen generally decrease as the size of the soil particles increases. The variation in the pressure distribution on the geomembrane specimen may be responsible for this difference. The gravels consisting of larger-sized particles have larger void spaces at the geomembrane specimen-soil interface because the soils that were

tested were all poorly graded. Consequently, for the same amount of total normal pressure, an increased amount of pressure is applied at particle contact locations. The greater void space may also allow greater geomembrane specimen deformation. Soils containing smaller-sized particles distribute the pressure more evenly because there are more particle contact locations, which results in an increased area over which the load can be distributed.

In the authors' opinion, the elongation at burst values determined from multi-axial tension tests are generally more indicative of the physical changes that occurred in the geomembrane specimens as compared to the ultimate stress and strain values determined from wide strip tension tests. The reason for this is that a larger specimen size is used in multi-axial tension testing and the tensile forces are subjected to the specimen in all directions. Thus, multi-axial tension tests can reveal the physical changes that occur to a geomembrane specimen more accurately. Figure 8 shows that the cover soils with a mean particle size less than 5 mm exhibit less than a 10% change in the elongation at burst values as compared to the elongation at burst value for the virgin geomembrane specimen.

In addition to particle size, the degree of geomembrane liner protection also depends on particle shape. The five different soils used in this study consisted of particles with shapes ranging from rounded to subangular; however, the sphericity values, which are indicators of particle shape, were in the range of 0.8 to 0.85 for all of the cover soils. This shows that the particle shapes were not drastically different from each other. Therefore, additional testing with different cover soils containing distinctly different particle shapes is needed in order to systematically study the effect of particle shape on geomembrane liner protective performance.

When a relatively light, 270 g/m², nonwoven geotextile was used, it was observed that significant protection was offered to the geomembrane liner. Figures 8 and 9 show that combining the geotextile with any of the five selected cover soils results in less than a 10% change in the geomembrane specimen properties. Therefore, the use of a geotextile is highly recommended for any geomembrane liner protective cover system.

Overall, based on the test results presented in the current study, a protective cover system consisting of a 300 mm thick layer of soil containing particles with mean size less than 30 mm and a sphericity value greater than 0.8, combined with a nonwoven geotextile with a mass per unit area of 270 g/m² or greater, should provide adequate protection for a 1.5 mm thick HDPE geomembrane liner under a vertical stress of up to 1.4 MPa. The final selection of a geomembrane liner protective cover system, however, must also consider the effects of construction loading (Reddy et al. 1996) as well as drainage requirements to ensure that the system functions efficiently as leachate drainage media.

The authors emphasize that the simulated long-term load test results reported in the current study were accomplished by compressing each of the protective cover systems with an extremely high pressure of 1.4 MPa. Additionally, the long-term load tests were performed using only five different types of soil and one type of geotextile. Therefore, further testing to explore the effects of normal stress on a wider variety of soil types and geotextiles is highly desirable in order to establish a broad database for the selection of an optimal geomembrane liner protective cover system.

5 CONCLUSIONS

In the current study, long-term load simulation tests were performed to determine the relative protective performance of different cover systems for a 1.5 mm thick smooth HDPE geomembrane liner. The cover systems consisted of five different, 300 mm thick, granular soil layers both with and without the presence of a 270 g/m² nonwoven geotextile. All of the protective cover systems were subjected to the same maximum pressure of 1.4 MPa. The damage that the geomembrane liner incurred under different protective cover conditions was assessed visually as well as by performing multi-axial tension tests, wide strip tensile tests, and water vapor transmission (WVT) tests on the exhumed geomembrane specimens.

Overall, the current study showed that the size of the particles contained in the cover soil will significantly affect the degree of geomembrane liner protection. The degree of geomembrane liner protection will decrease as the protective cover soil particle size increases. When a geotextile was combined with the protective cover soil layer, a significant increase in geomembrane liner protection was observed for all of the soils tested. It is even more important to use a geotextile when the cover soil particle sizes are relatively large or angular. A relatively light, needle-punched nonwoven geotextile with a mass per unit area of 270 g/m² was used for the long-term simulation tests and, yet, the improvement in geomembrane liner protection compared to the simulation tests conducted without the geotextile was remarkable.

A protective cover system consisting of a 300 mm thick soil layer comprised of particles with a mean size less than 30 mm and a sphericity value greater than 0.8, underlain by a 270 g/m² needle-punched nonwoven geotextile provided adequate protection for a 1.5 mm smooth HDPE geomembrane liner. Additional research is warranted in order to determine the effects of the soil particle shape, type of geotextile, and normal stress, and to establish a broad database for the design of optimal protective cover systems. The final selection of the protective cover system, however, must be made based on both construction and long-term waste loading conditions as well as efficient leachate drainage.

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NOTATIONS

Basic SI units are given in parentheses.

- a = largest soil particle dimension (m)
 b = intermediate soil particle dimension (m)

c	=	smallest soil particle dimension (m)
C_c	=	coefficient of curvature (dimensionless)
C_u	=	coefficient of uniformity (dimensionless)
D_{50}	=	mean soil particle size (m)
k	=	hydraulic conductivity (m/s)
p	=	soil particle flatness ratio (dimensionless)
q	=	soil particle elongation ratio (dimensionless)
S_p	=	sphericity of soil particle (dimensionless)
VC	=	volumetric coefficient (dimensionless)
v	=	soil particle volume (m^3)