
FIELD EVALUATION OF PROTECTIVE COVERS FOR LANDFILL GEOMEMBRANE LINERS UNDER CONSTRUCTION LOADING

ABSTRACT: The performance of landfill geomembrane liner protective cover systems with and without a geotextile is evaluated using field tests. The physical properties of the protective cover soils and the geomembrane liner before and after field testing were determined using laboratory tests. The hydraulic properties of the geomembrane field samples were measured using water vapor transmission (WVT) tests, and the mechanical properties were measured using multi-axial tension tests and wide strip tensile tests. A low mass per unit area geotextile was demonstrated to completely protect the geomembrane in this study.

KEYWORDS: Protective cover, Drainage layer, Liner systems, Geomembrane, Field testing, Laboratory testing, Landfill.


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1 INTRODUCTION

Liner systems for waste containment facilities serve as barriers that prevent subsurface contamination by minimizing the migration of waste constituents into the subsurface environment. In the case of landfills, the liner systems can vary from a single composite system consisting of a compacted clay layer overlain by a geomembrane to a composite system consisting of multiple layers of compacted clay, geomembranes, geotextiles, geonets, and geocomposites as depicted in Figure 1. The integrity of the liner system during its installation, as well as throughout its entire lifetime, is of paramount importance. The most damage prone components of liner systems are the geosynthetic layers. In the case of composite liner systems, protecting the geomembrane from tearing or puncturing during construction and after waste placement is critical for the entire liner system to function properly. The geomembranes are subjected to heavy

Figure 1. Protective cover systems for landfill liners used in the United States: (a) single composite liner; (b) double composite liner.
loadings from construction equipment particularly during installation. As a result, a protective cover is required for placement of materials over the geomembrane liner to prevent damage from construction loading, and to prevent overstressing of the geomembrane liner due to subsequent waste placement.

Various types of protective covers are currently being used for landfill liners. In the United States, the general practice is to use either a geotextile or a protective cover soil or both over the geomembrane liner. The use of a geotextile over a geomembrane liner increases the puncture resistance of the geomembrane liner and cushions loads caused by initial waste lift placement. The protective cover soil prevents direct contact of the construction equipment with the geomembrane liner, and distributes the vehicular loading to a larger area, thus, reducing the stresses on the geomembrane liner. The protective cover soil generally consists of a free-draining granular soil that also serves as a drainage layer for the leachate collection and removal system (Figure 1). The degree of geomembrane liner protection that the protective cover offers depends on the type and properties of the geotextile, and the composition and thickness of the soil layer used.

An ideal protective cover system for landfill geomembrane liners should fulfill the following requirements both during construction and after subsequent waste placement:

- Prevent damage to the geomembrane liner from stresses induced by drainage layer construction and waste placement.
- Prevent damage to the geomembrane liner such as tearing, bursting, puncturing or impact.
- Possess properties that allow placement with minimum rutting and formation of irregularities, since easy access across large areas during construction is critical to achieve cost effective, timely construction.
- Consist of a free draining material that can also serve as an effective drainage medium for the landfill leachate.
- Be capable of withstanding landfill construction, operation and closure conditions without undergoing major changes in physical properties.

The current practice in the United States for design and construction of protective cover systems for landfill geomembrane liners has several deficiencies as outlined below:

- The specific type of soils that can be used as protective covers has not been well documented. As a result, the suitability of locally available soils for use as protective covers cannot be rationally evaluated. The protective cover soil must also serve as a drainage layer: from a regulatory perspective, it should have a hydraulic conductivity greater than $1 \times 10^{-4}$ m/s. Several soil types meet this criterion, however, an additional criterion, in terms of physical or strength characteristics, is needed for the evaluation of a soil as an effective geomembrane liner protective material.
- A specific rationale for the selection of the thickness of the protective cover soil has not been formulated. From a regulatory perspective, the minimum thickness of the drainage layer must be 0.3 m. Currently, the thickness of protective cover soils range from 0.3 m to 0.9 m. The use of smaller thicknesses may create the potential for geo-
membrane liner damage, while the use of larger cover soil thicknesses may prove to be uneconomical.

- Few quantitative studies investigating the possibility of damage to geomembrane liners due to construction loading have been performed to date.
- A recommended construction procedure to avoid excessive construction-induced stresses in the geomembrane liner currently does not exist.

A comprehensive research program on protective cover systems for landfill liners was initiated in 1994 at the University of Illinois at Chicago (UIC). The purpose of this research is: (i) to assess the damage to landfill liners, in particular geomembrane liners, under different protective cover conditions both during construction and after subsequent waste placement; and (ii) to develop a rational design methodology for protective cover soils that involves the development of indicator parameters and/or design correlations that define the protective cover soil composition and thickness in order to provide adequate geomembrane liner protection.

The focus of this paper is the field tests that were performed as part of this research study. The purpose of the field tests was to evaluate the performance of different protective cover systems under construction loading. This paper first summarizes previous studies that were conducted on protective cover systems, and then provides details of the field testing procedures that were followed in this study to assess the performance of protective cover systems under construction loading. The laboratory tests that were performed to evaluate the construction damage incurred by the protective cover soils and geomembrane liners are then described. The results of the laboratory tests are then used to determine the effectiveness of each protective cover system.

2 BACKGROUND

In the United States, either a geotextile, a soil layer, or both are currently used as the protective cover system for a landfill geomembrane liner system. The thickness of the soil layer must be such that, in addition to preventing mechanical damage to the geomembrane liner, it also allows efficient drainage of leachate into the leachate collection pipes. In other countries, such as Germany, a protective cover is constructed as a separate layer directly above the geomembrane liner. The drainage layer is then constructed on top of the protective cover. According to German regulations, a protective cover is considered suitable if the local deformations produced by the drainage layer do not induce a strain greater than 0.25% in the underlying geomembrane liner both during construction and landfill operations. This regulatory requirement spurred the interest of several German investigators to develop and evaluate different types of protective covers, and thus, a wide variety of protective cover materials have been suggested. Figure 2 shows a few of the suggested protective cover materials: gravel, a concrete-filled geotextile, a sand-filled geotextile, a gravel-filled geotextile, or composite layers composed of different filaments and fabrics (Brummermann et al. 1994; Muller-Rochholz and Asser 1994; Kirschner and Krelt 1994; Saathoff and Sehrbrock 1994).

A typical sequence of landfill liner and protective cover construction followed in the United States is shown in Figure 3. The liner system which consists of a compacted clay layer and a geomembrane liner is first constructed. A geotextile is then installed over
Figure 2. Different protective covers for landfill liner systems used in Germany.

Figure 3. Cross section of a landfill liner and protective cover system at different stages of construction and use: (a) construction of the protective cover system; (b) placement of waste over the protective cover system.
the geomembrane liner. The protective cover soil is initially positioned by end dumping, and bulldozers (dozers) are used to spread the soil over the entire landfill liner surface to the desired thickness. During construction, extreme care must be taken to protect both the geomembrane liner and the geotextile from mechanical damage due to construction equipment loading and placement of the protective cover soil. The construction equipment should not be driven directly on the geotextile and the underlying geomembrane liner, and a minimum soil cover should be maintained at all times.

A few studies on the level of protection offered by the geotextile have been reported (Koerner et al. 1986; Motan et al. 1993). These studies have shown that the performance of geomembrane liners with regard to tear strength and puncture strength is increased when a geotextile is used; however, the study conducted by Motan et al. (1993) did not provide consistent results on this beneficial behavior. The effect of introducing different types of geosynthetics including geocomposites and geosynthetic clay liners in the protective cover system was evaluated by Richardson (1996) using field experiments. In general, improved performance of the landfill liner system was observed when these geosynthetics were included in the protective cover system.

In most cases, the level of protection offered by the different types of geosynthetics alone is considered inadequate for preventing mechanical damage to the geomembrane liner both during and after construction. Therefore, the protective cover soil, which is installed over the geotextile or other geosynthetic component, becomes a critical component in the design of a safe and efficient landfill liner system. To date, no systematic study has been reported to determine the level of protection achieved by using various soil types and soil thicknesses as protective cover soils (Ruetten et al. 1995). A wide variety of soils are currently being used as protective cover soils and thus it is essential to evaluate their performance (Reddy et al. 1995).

3 FIELD TESTING PROCEDURE

The structural integrity of a geomembrane liner during construction is crucial for its intended purpose of effective leachate containment. In this study, a field investigation was performed to evaluate different protective cover soils and to determine the most efficient cover soil system that provides the maximum level of geomembrane liner protection during construction.

3.1 Test Variables

The field testing procedure followed in this study included preparation of the subgrade and placement of the geomembrane liner on the prepared subgrade. Next, a protective cover soil layer was constructed on the geomembrane liner in the same manner as it would be done during a regular drainage layer placement operation. This procedure involved pushing the soil with a dozer and performing dozer maneuvers such as braking, turning and repeated travel on the protective cover soil. Several tests were performed using different cover soils, different dozers, and by either using or not using a geotextile between the soil and the geomembrane liner. The following conditions were tested:

1. medium gravel, no geotextile, CAT D4 (light dozer);
2. medium gravel, geotextile, CAT D7 (heavy dozer);
3. medium gravel, no geotextile, CAT D7;
4. fine gravel, no geotextile, CAT D4;
5. fine gravel, no geotextile, CAT D7;
6. fine gravel, geotextile, CAT D4; and
7. fine gravel, geotextile, CAT D7.

A uniform 0.3 m thick soil layer and smooth 1.5 mm thick (60 mil) high density polyethylene (HDPE) geomembrane were used in all of the above tests. The geotextile used was a nonwoven needle-punched polypropylene geotextile with a mass per unit area of 270 g/m². The two different types of dozers used for this study were a light dozer (CAT D4 model) and a heavy dozer (CAT D7 model). The specifications of both dozers are summarized in Table 1.

3.2 Field Testing Procedure

The field testing was performed at Suburban South Recycling and Disposal Facility in Brownsville, Ohio, USA. A level test area was identified, and the subgrade was prepared for the test pads. The level area was large enough to perform tests on four different pads concurrently. The subgrade, which consisted of silty clay with a stiff to very stiff consistency, was inspected for any protrusions that might damage the geomembrane during the tests. A 9.1 m wide geomembrane roll was placed along one end of the test pad and unrolled. A 6.1 m long piece was cut to form a 6.1 m × 9.1 m geomembrane test pad. The geomembrane was then visually examined for damages incurred during transportation and storage.

Six stakes were driven into the ground to provide control depths for the granular material (protective cover soil): four stakes were placed at the four corners, and two stakes were placed at the mid-point of the 9.1 m edges. A piece of flag tape was tied to the stakes at a height of 0.3 m from the ground surface to assist the dozer operator with the placement of the 0.3 m granular soil layer. Figure 4 shows the geomembrane test pad immediately before placement of the granular soil. Granular drainage soil was piled along the 6.1 m edge of the test pad. When sufficient material was placed for the dozer to operate, the operator pushed the soil onto the geomembrane to form a relatively uniform 0.3 m thick layer over a portion of the geomembrane. Additional granular soil was then placed along the edge, and the operation was repeated until the entire geomembrane was covered with the granular soil. The operator then used the dozer blade to level and adjust the soil thickness to 0.3 m. The photographs in Figure 5 show the granular drainage soil being pushed onto the geomembrane.

Table 1. Specifications of the dozers used in this study.

<table>
<thead>
<tr>
<th>Dozer properties</th>
<th>Dozer D4</th>
<th>Dozer D7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass (kg)</td>
<td>7,726</td>
<td>27,125</td>
</tr>
<tr>
<td>Width of tracks (m)</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Length of tracks (m)</td>
<td>2.0</td>
<td>3.2</td>
</tr>
<tr>
<td>Surface area of tracks in contact with soil (m²)</td>
<td>2.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Average contact pressure between tracks and soil (kPa)</td>
<td>29</td>
<td>46</td>
</tr>
</tbody>
</table>
Figure 4. Photograph of field test pad with the geomembrane.

(a)

(b)

Figure 5. Photographs of the placement of the protective cover soil on the geomembrane: (a) soil placement on the geomembrane; (b) dozer traversing over soil on the geomembrane.
The dozer then traversed the granular soil layer in both the forward and reverse directions, proceeding five times in each direction (Figure 6). This action was performed to simulate normal dozer traffic on the granular soil layer during actual construction. The dozer was then turned 180° on the granular soil layer by maneuvering back and forth. This action also simulates normal dozer operations during placement of materials. Finally, the dozer traversed back and forth on the test pad five more times to complete the testing. At the end of each motion, break forces were applied to simulate braking operations during placement of protective cover materials. A few sampling locations on the test pad where the dozer traversed the most were selected. The first few inches of the granular material were removed at these locations using a backhoe with a rubber lined bucket edge. A side swipe motion of the backhoe was used to remove the gravel. The final few centimeters of the granular material were carefully removed with a shovel. An approximate area of 0.9 m × 0.9 m was cleared using this method. Once the geomembrane surface was exposed, it was cleaned using a cloth and visually examined for damage. A 0.6 m × 0.6 m sample was cut and labelled. The underside of the sample was examined for damage that occurred due to protrusions at the subgrade surface. Samples of the granular material were collected before and after testing. All geomembrane and soil samples were carefully transported to the laboratory for testing.

### 3.3 Damage Assessment Tests

#### 3.3.1 Soil Testing

Samples of medium and fine gravel were obtained before and after field testing to evaluate their particle size distributions and hydraulic conductivity values. The particle size distributions of these protective cover soils are shown in Figure 7, and the hydraulic conductivity values were determined to be $1.3 \times 10^{-2}$ m/s and $6.6 \times 10^{-3}$ m/s for the medium and fine gravels, respectively. The differences in the particle size distributions and the hydraulic conductivity values for the soils before and after field testing were insig-
significant. These results show that the protective cover soils did not undergo significant changes due to construction operations.

3.3.2 Geomembrane Testing

In order to quantify the change in geomembrane properties due to the placement of the protective cover soils and construction loading, several laboratory tests were conducted on the geomembrane samples taken after field testing. These tests included water vapor transmission (WVT) tests, multi-axial tension tests, and wide strip tensile tests. The procedures followed for these tests are briefly described in the following sections.

Water Vapor Transmission Tests. The WVT test was selected to provide information on the changes in the permeability of the geomembrane due to damage. A WVT test can detect minute cracks in the geomembrane that may not be visible to the naked eye. Theoretically, a damaged geomembrane should have a higher vapor transmission capability than a geomembrane that is not damaged.

The WVT tests were performed in accordance with ASTM E 96 (Procedure B). Three 108 mm diameter circular specimens were cut from each of the exhumed geomembrane samples and from a virgin geomembrane sample. The thickness of each geomembrane specimen was recorded as the average of five thickness measurements. Using wax, the geomembrane specimens were attached to aluminum cups that contained distilled water. The wax sealed the junction between the geomembrane specimen and the cup. A flange was fitted over the geomembrane specimen and tightened against the cup to hold...
the geomembrane securely in place. This apparatus left a geomembrane area of 0.0071 m² through which the water contained in the cup could migrate. In addition, a control specimen that consisted of an aluminum disc sealed to an aluminum cup in the same manner as the geomembrane specimens was used. The cups were stored under a Plexiglass hood in standard laboratory conditions. Air was continually circulated through the hood with a sufficient velocity to maintain uniform conditions at all test locations. The temperature and relative humidity were recorded and changed less than 0.6°C and 2%, respectively, for all of the tests. Periodically, the dishes were removed from the hood and weighed on a scale readable to 0.001 g. The positions of the specimens in the hood were rotated at each weighing. The ambient temperature and relative humidity were recorded when the specimens were weighed.

Water vapor transmission is defined as the slope of the regression line on a weight versus time plot divided by the exposed area of the test specimens. When the plots of weight versus time were constructed, adjustments were made using the control specimens to compensate for variability in the test conditions and water vapor that may have escaped through the seal. Compensations were made by subtracting the initial weight of the control specimen from the weight of the control specimen at each weighing interval and then subtracting this value from the weight of each geomembrane specimen for a given interval. Plots of the modified weight versus time data were made for each geomembrane specimen, and a line was fit to the data using the least-squares method. The slope of each line was calculated and divided by the exposed area of the geomembrane test specimens to give the water vapor transmission rate.

Geomembrane permeance is defined as the water vapor transmission divided by the vapor pressure differential across the geomembrane liner, which is the driving force of the water vapor transmission, and is calculated using the following equation:

$$\text{Permeance} = \frac{WVT}{S(R_1 - R_2)}$$

where: $WVT =$ water vapor transmission (g/day-m²); $S =$ saturation vapor pressure (Pa); $R_1 =$ relative humidity inside the cup; and $R_2 =$ relative humidity outside the cup. The geomembrane permeance was calculated for this test using the average recorded temperatures and relative humidities which were 23.1°C and 35.9%, respectively. Thus, the following values were used: $S = 64,329$ Pa, $R_1 = 1.0$ (100%) and $R_2 = 0.359$.

Permeability is defined in ASTM E 96 as the permeance multiplied by the geomembrane liner thickness. This definition of permeability is a property of the geomembrane and would be unchanged by the geomembrane thickness; however, the terms permeability and permeance are often used interchangeably. By convention, the permeability of the geomembrane is reported in units of cm/s-Pa by dividing the permeance of the geomembrane by the density of water (1 g/cm³). This “permeability” is actually the permeance of the geomembrane and will decrease with increasing thickness of the geomembrane.

Multi-Axial Tension Tests. The multi-axial tension test was selected because the test results do not significantly depend on the orientation of nicks, cuts or indentations in the geomembrane. This test was performed in accordance with ASTM D 5617. The test uses a 0.3 m or 0.6 m diameter specimen attached to a pressure vessel. The specimen
undergoes out-of-plane deformation when the chamber pressure is increased. The pressure is increased until the specimen is ruptured, which is associated with a sudden loss in pressure. The deformation versus pressure data is used to calculate the stress and strain experienced by the geomembrane specimen. The stress-strain values obtained are used to evaluate the performance of geomembrane liners during placement of the granular drainage layer. A detailed description of the test procedure and data reduction procedure is given in ASTM D 5617.

Wide Strip Tensile Tests. The wide strip tensile test was selected because it is simple and widely used. This test was performed in accordance to ASTM D 4885 and was selected to provide a comparison of the tensile properties of geomembrane samples taken from the field after testing with those of virgin geomembrane samples in order to assess the damage to the geomembrane samples under different protective cover conditions. By comparing the wide strip tensile test results with the multi-axial test results, the suitability of each testing method for geomembrane damage assessment can be evaluated. A detailed description of the wide strip tensile test procedure and data reduction procedure is given in ASTM D 4885. It should be noted that the test standard recommends expressing the tensile strength in force per unit width; however, for the purpose of this paper it is expressed as stress, i.e. force per unit cross sectional area.

4 RESULTS AND DISCUSSION

As mentioned in Section 3.3.1, the soils did not undergo significant changes in physical and hydraulic properties. The results of the multi-axial tension tests and wide strip tensile tests performed on the geomembrane specimens are summarized in Table 2. These test results are used to assess the damage to the geomembrane liner. The results of the WVT tests are also discussed below.

4.1 Water Vapor Transmission Tests

A total of 24 WVT tests were performed, including three tests on virgin specimens. Figure 8 shows the average permeance values of geomembrane specimens for different protective cover conditions. These results show that the differences between the specimens are too small to be detected by this test. The apparent variation in the test results is due to the fact that the WVT rate was so low (on average each specimen only lost approximately 4 mg of water over the duration of the test) that even small errors in weight measurements are significant. The overall average permeance of the exhumed geomembrane specimens is $6.34 \times 10^{-15}$ cm/s-Pa which agreed well with the average permeance of $7.70 \times 10^{-15}$ cm/s-Pa for the virgin geomembrane specimens. These test results show that the permeability of the geomembrane did not change due to the different protective cover conditions used in this study.
Table 2. Summary of multi-axial and wide strip tensile test results for the geomembrane field specimens.

<table>
<thead>
<tr>
<th>Test condition for 1.5 mm thick smooth HDPE geomembrane</th>
<th>Multi-axial tension testing</th>
<th>Wide strip tensile testing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elongation at burst (%)</td>
<td>Tensile stress at burst (MPa)</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>Change (%)</td>
</tr>
<tr>
<td>Virgin geomembrane</td>
<td>25.33</td>
<td>N/A</td>
</tr>
<tr>
<td>After field test with medium gravel, no geotextile and light dozer</td>
<td>19.1</td>
<td>-24.6</td>
</tr>
<tr>
<td>After field test with medium gravel, no geotextile, heavy dozer</td>
<td>15.16</td>
<td>-46.7</td>
</tr>
<tr>
<td>After field test with medium gravel, geotextile, light dozer</td>
<td>26.9</td>
<td>6.2</td>
</tr>
<tr>
<td>After field test with fine gravel, no geotextile, light dozer</td>
<td>20.13</td>
<td>-20.5</td>
</tr>
<tr>
<td>After field test with fine gravel, no geotextile, heavy dozer</td>
<td>18.25</td>
<td>-28.0</td>
</tr>
<tr>
<td>After field test with fine gravel, geotextile, light dozer</td>
<td>30.12</td>
<td>18.9</td>
</tr>
<tr>
<td>After field test with fine gravel, geotextile, heavy dozer</td>
<td>29.2</td>
<td>15.3</td>
</tr>
</tbody>
</table>

Note: N/A = not applicable.
4.2 Multi-Axial Tension Tests

A total of 24 multi-axial tension tests were conducted on geomembrane specimens obtained from the field including three tests on virgin geomembrane specimens. Out of these, 15 tests were performed using 0.3 m diameter specimens and 9 tests were conducted using 0.6 m diameter specimens. The test results for the 0.3 and 0.6 m diameter specimens from the same geomembrane field sample, and a virgin geomembrane sample are compared in Figures 9a and 9b. Figure 9a is a plot of geomembrane tensile stress at burst while Figure 9b is a plot of geomembrane elongation at burst. This data indicates that the results obtained using 0.3 and 0.6 m diameter specimens are in close agreement.

Figure 10a is a plot of the average geomembrane specimen tensile stress at burst for all of the protective cover conditions used in this study. The average geomembrane tensile stress at burst for the virgin geomembrane specimen is also plotted in Figure 10a for comparison purposes. Figure 10a shows that the average geomembrane tensile stresses for the field specimens are approximately the same as those values for the virgin geomembrane specimens. The geomembrane specimens from field samples that were tested without a geotextile as protection failed at slightly higher tensile stresses than the virgin geomembrane specimens, whereas the geomembrane specimens from field samples that were tested with a geotextile as protection failed at slightly lower tensile stresses than the virgin geomembrane specimen. These slight differences in geomem-
Figure 9. Multi-axial tension test results showing the effect of geomembrane specimen size on: (a) tensile stress at burst; (b) elongation at burst.

Note: Fine gravel was used in these field tests.

The tensile stress at burst may be attributed to the more brittle or stiffer condition of the geomembrane in the absence of a geotextile.

Figure 10b shows a comparison of the average geomembrane specimen elongation at burst for all of the protective cover conditions used in this study. The average geomembrane elongation at burst for the virgin geomembrane specimens is also given for
Figure 10. Multi-axial tension test results for geomembrane specimens showing:
(a) average tensile stress at burst; (b) average elongation at burst.

Comparison purposes. These results show that the differences in geomembrane elongation at failure for different protective cover conditions are quite significant. The geomembrane specimen elongation at failure decreased with increasing soil particle size and the use of a heavier dozer. However, when protected by a geotextile, the geomembrane specimen elongation at burst significantly increased, and in fact was more than
that of the virgin geomembrane specimens. These results clearly reflect the protection provided by using a geotextile in the protective cover system. The geomembrane specimen elongation at burst is the lowest at 15.2% for the case of medium gravel and a heavier dozer, and the highest at 32.1% for the case of fine gravel, a lighter dozer and a 270 g/m² geotextile. Although no visible physical damage occurred, the protective cover system consisting of a medium gravel layer constructed directly on the geomembrane using a heavy dozer caused significant changes in the multi-axial tensile properties of the geomembrane liner.

4.3 Wide Strip Tensile Tests

A total of 21 wide strip tensile tests were conducted on geomembrane specimens obtained from the field. In addition, three tests were conducted on virgin geomembrane specimens. Based on the stress-strain data, the following values were calculated: (i) yield stress; (ii) yield strain; (iii) 10% secant modulus; (iv) stress at break; (v) strain at break; and, (vi) load/width at break. The average values of these different parameters are plotted in Figures 11 through 16, respectively, for the various protective cover conditions. The test results for the virgin geomembrane specimens are also shown on these plots for comparison purposes.

Figure 11 is a plot of the yield stresses for the geomembrane specimens tested under different protective cover conditions. Figure 11 shows that the yield stress for geomembrane specimens under different protective cover conditions is approximately equal to the yield stress for the virgin geomembrane specimens. The same observation is also made for the yield strain and the 10% secant modulus plots in Figures 12 and 13, respect-
Figure 12. Average geomembrane specimen percent strain at yield based on wide strip tensile tests.

Figure 13. Average geomembrane specimen 10% secant modulus based on wide strip tensile tests.
tively. This result indicates that the geomembrane specimen yield stress and strain do not change for different protective cover systems tested in this study.

Figures 14 and 15 present the values of the average geomembrane specimen stress and strain at break, respectively, obtained from wide strip tensile tests performed on geomembrane field specimens under different protective cover conditions. The average stress and strain at break for the virgin geomembrane specimens are also shown in Figures 14 and 15. From Figure 14, it is observed that all of the geomembrane field specimens experienced less stress at break as compared to the virgin geomembrane specimens. The difference in the stress at break between the virgin geomembrane specimens and the geomembrane field specimens was less for geomembrane field specimens that had a protective cover with a geotextile as compared to the geomembrane field specimens that had a protective cover without a geotextile. The maximum difference in geomembrane stress occurs when the protective cover consists of medium gravel as compared to fine gravel. The use of either a light or heavy dozer during construction appears to have no significant influence on the geomembrane stress at break. Similar trends also occur for both geomembrane strain at break and geomembrane load/width at break (Figures 15 and 16, respectively). The wide strip tensile test results demonstrate that damage caused to the geomembrane liners is not reflected in the geomembrane ultimate or break stresses and strains; however, the damage potential is reflected in the geomembrane ultimate or break stresses and strains.

5 SUMMARY AND CONCLUSIONS

This research investigated the performance of different protective covers for landfill geomembrane liners under construction loading conditions. Both medium and fine gravels were used as the protective cover soils and were tested with and without the presence of a geotextile over the geomembrane liner. Field testing was performed at a landfill site using both light and heavy dozers. After field testing, geomembrane samples were exhumed and visually inspected. None of the geomembrane samples had apparent damage in the form of tears or holes; however, all of the geomembrane samples that were tested without a geotextile had surficial scratches and dents.

Laboratory tests were performed to determine the physical properties of the protective cover soils and the geomembrane liner both before and after field testing. These test results are used to quantify the damage that occurred during construction loading. The results of the particle size distribution and hydraulic conductivity tests on the protective cover soil samples revealed that no significant changes in the properties of the soils took place under construction loading conditions.

The physical properties of the geomembrane samples were determined by water vapor transmission tests, multi-axial tension tests and wide strip tensile tests. The results of the water vapor transmission tests show that the geomembrane liner permeability values do not change by being in contact with any of the protective covers used in this investigation. The geomembrane specimen stress at burst values determined from the multi-axial tests, and the geomembrane yield stress and strain values determined from the wide strip tensile tests also do not change with the different protective cover conditions used. However, the geomembrane elongation at burst determined from the multi-axial tension tests and the geomembrane ultimate or break stress and strain determined.
Figure 14. Average geomembrane specimen ultimate stress based on wide strip tensile tests.

Figure 15. Average geomembrane specimen ultimate strain based on wide strip tensile tests.
Figure 16. Average geomembrane specimen load/width at burst based on wide strip tensile tests.

From the wide strip tensile tests, it was observed that the geomembrane samples underwent physical changes due to the construction loading. Even though these physical property values (geomembrane elongation at burst and ultimate stress and strain) decreased without the use of a geotextile, such changes may not adversely affect the performance of the geomembrane. However, the presence of a geotextile as light as 270 g/m² in the protective cover system completely protects the geomembrane from construction loading, as was determined by field testing. This study recommends that a geotextile be considered for use in the geomembrane liner protective cover system when gravel and/or heavy construction equipment are used.

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REFERENCES

REDDY, BANDI, ROHR, FINY & SIEBKEN  •  Landfill Geomembrane Liner Protective Covers


Discussions and Closure

FIELD EVALUATION OF PROTECTIVE COVERS FOR LANDFILL GEOMEMBRANE LINERS UNDER CONSTRUCTION LOADING


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Discussion by R.S. Thiel

The discusser enjoyed the authors’ paper because the discusser has also performed such field loading programs. However, one important description was missing: the angularity of the rock used for the medium and fine gravels in the test program. Certainly, there will be a difference in the damage caused to an underlying geomembrane depending on whether or not the gravel is angular or round. The discusser believes that the paper would be a much more valuable reference if the angularity of the gravels used in the test program were classified as being angular, subangular, subround, round, or flat.

Discussion by K. Badu-Tweneboah, J.P. Giroud, D.S. Carlson and G.R. Schmertmann

The authors should be commended for presenting an interesting paper that provides valuable information on the effect of granular soil layers on geomembrane performance. Granular soil layers, when subjected to loading from construction equipment or other sources, can apply high concentrated stresses to an underlying geomembrane at the locations where soil particles are in contact with the geomembrane. These high concentrated stresses can damage the geomembrane, thereby affecting its performance in two ways: (i) puncturing it, thereby causing an immediate decrease in its effectiveness as a low-permeability barrier; and (ii) weakening it, thereby making it more vulnerable to rupture under long-term service conditions. In their study, the authors used water vapor transmission (WVT) tests, multi-axial tension (hydrostatic) tests, and wide-strip tensile tests to evaluate the effects of several granular soils under a range of construction loadings on a 1.5 mm thick high density polyethylene (HDPE) geomembrane.

The authors conducted the WVT tests to detect changes in the permeability of the geomembrane resulting from punctures caused by exposure to the different soils and loadings. The WVT tests indicated that there were no detectable changes in permeability. This is an interesting finding because it suggests that HDPE geomembranes can continue to perform as effective low-permeability barriers after sustaining light to moderate mechanical damage. The WVT tests were not, however, useful for differentiating between the degree of damage caused by the different soils and loadings due to the lack of detectable changes in permeability. Accordingly, the rest of this discussion is devoted to mechanical tests, although it is recognized that the WVT test may be useful for soils and loadings more likely to puncture the geomembrane. The discussers note that the multi-axial tension test is also useful in detecting punctures because the hydrostatic pressure in the multi-axial tension test cannot be sustained with a punctured geomembrane specimen.

The authors used the stress-strain data from two mechanical tests, the multi-axial tension test and the wide-strip tensile test, to evaluate the relative degree of damage caused by the different soils and loadings. However, the authors did not use a criterion to determine, based on the test results, whether the level of mechanical damage undergone by a tested geomembrane specimen is acceptable. The discussers have experience in the use of the multi-axial tension test for evaluating mechanically damaged geomembranes and
have developed a simple criterion to determine if a certain type or level of mechanical damage is acceptable.

To determine if a certain type or level of mechanical damage is acceptable, one should evaluate the degree to which the geomembrane has been weakened and made more vulnerable to rupture under long-term service conditions. The ability to resist rupture depends on the deformability of the geomembrane, which is reflected in the magnitude of strain at yield and at rupture. A decrease in the geomembrane deformability results in a potential decrease in its ability to resist rupture. Based on their experience in interpreting multi-axial tension tests on mechanically damaged geomembranes, the discussers have noted that a reliable indicator of significant decrease in the deformability of an HDPE geomembrane is a change in the geomembrane rupture mode from that observed in undamaged (virgin) specimens. A virgin geomembrane with a uniform thickness must rupture at the top of the dome formed by the hydrostatically inflated geomembrane because this is the location where the tensile stresses are highest. If a geomembrane specimen ruptures at a location other than the top of the dome, this indicates that the specimen has been previously weakened at that location, for example as a result of localized mechanical damage. Indeed, the discussers have observed that: (i) HDPE geomembranes with severe mechanical damage always rupture at a location other than the top of the dome (except, of course, in cases where the location of severe geomembrane damage happens to be at the center of the specimen); and (ii) HDPE geomembranes with light mechanical damage have a mode of rupture in the multi-axial tension test that is similar to that of a virgin geomembrane. The discussers have also observed that the most significant decreases in the deformability of an HDPE geomembrane occur when geomembrane specimens rupture at locations other than the top of the dome.

From the foregoing analysis, the discussers have developed the following criterion: the mechanical damage undergone by a geomembrane is deemed unacceptable if the geomembrane specimen tested in a large diameter (e.g. \( d \geq 0.5 \text{ m} \)) multi-axial tension test exhibits rupture at a location other than the top of the dome and if this location is that of visible mechanical damage. (The requirement for a large diameter is to ensure that the specimen contains enough locations of mechanical damage to be representative.) The discussers have used the approach and the criterion described above on several occasions and they found that the proposed criterion makes it possible to clearly and objectively determine whether a certain type or level of mechanical damage is acceptable. Details on the development of the above criterion and an example from several studies to evaluate the effect of a granular soil layer on the performance of an HDPE geomembrane are presented in a paper by Badu-Tweneboah et al. (1998).

REFERENCE


The authors of the paper are thankful to the first discusser for expressing interest and facilitating discussion on the paper. The authors of the paper agree with the observation that there will be a difference in the damage caused to an underlying geomembrane depending on the shape of the soil particles. Both soils used in the field study, medium and fine gravel, are characterized as poorly graded soils with mean particle sizes of approximately 27 and 14 mm, respectively. The shape of the particles in both soils can be described as subrounded. Further laboratory investigation into the protective performance of various cover soils consisting of particles of different sizes and shapes under simulated long-term load conditions has been recently completed at the University of Illinois at Chicago and will be reported in a future publication. This recent study showed that particle size can significantly affect the performance of the cover soil in protecting the underlying HDPE geomembrane liner.

The authors of the paper are also thankful to the second set of discussers for expressing interest in the paper. The authors of the paper agree with the discussers’ assertion that an extensively damaged geomembrane when tested in a large diameter multi-axial tension test should fail away from the center and in the area of visual mechanical damage. For such situations, the elongation at burst is expected to be significantly lowered. All of these observations are pertinent and should be included in any set of damage assessment criteria. The forthcoming paper by the discussers should be interesting.

The authors of the paper agree that water vapor transmission (WVT) tests did not result in a meaningful differentiation of damage to the geomembranes caused by different soils and loadings. However, a more sensitive test may have detected the difference in WVT induced by damage to the geomembrane. Koerner and Allen (1997) suggested that the standard test method ASTM F 1249 (Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor) is a more appropriate method for determining WVT for geomembranes.

Research performed by the authors of the paper showed that the failure of the exhumed geomembrane specimens in multi-axial tension tests usually initiated in the upper portion of the dome; however, the modes of failure differed. Even virgin geomembrane specimens had different failure modes, and a summary of the observed failure modes for the virgin and exhumed geomembranes is shown in Table 1. It should be noted that a failure location at an edge indicates that either the specimen size is not adequate or there is a problem with the gripping mechanism. As seen in Table 1, none of the tests performed, even with 0.3 m diameter specimens, resulted in edge failures.

Since the modes of failure did not necessarily indicate if physical changes in the geomembrane had taken place, the degree of protection offered by the cover systems was assessed by analyzing differences in the stress and elongation at burst values of the exhumed specimens as compared to values of virgin geomembrane specimens. In addition, the ultimate or break stress and strain values determined from wide-strip tensile tests were used to describe the degree of protection offered by the cover systems. The development of criteria based on the stress and elongation at burst values from multi-axial tension tests and/or the ultimate stress and strain values from wide-strip tensile
tests would be helpful in determining if a protective cover system is acceptable or unac-
ceptable. However, further research is needed in order to determine these criteria based
on the functionality of the geomembrane (e.g. hydraulic and chemical containment)
and the site specific conditions (e.g. subgrade, liner design, construction loads, waste
loads). The most common practice has been to use the research results to select a protec-
tive cover system that offers protection such that the properties of the exhumed geo-
membrane are relatively comparable to the virgin geomembrane.

REFERENCES

American Society for Testing and Materials, West Conshohocken, Pennsylvania,
USA.

Plastic Film and Sheeting Using a Modulated Infrared Sensor”, American Society
for Testing and Materials, West Conshohocken, Pennsylvania, USA.


Table 1. Failure modes observed during multi-axial tension testing of the exhumed and
virgin 1.5 mm thick HDPE geomembranes.

<table>
<thead>
<tr>
<th>Cover soil</th>
<th>Geotextile</th>
<th>Loading</th>
<th>0.3 m diameter specimens</th>
<th>0.6 m diameter specimens</th>
<th>Failure location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium gravel</td>
<td>None</td>
<td>Heavy dozer</td>
<td>H-CAT, XD-T</td>
<td>N-EF</td>
<td></td>
</tr>
<tr>
<td>270 g/m²</td>
<td>Light dozer</td>
<td>H-CAT, TD-T</td>
<td>N-EF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine gravel</td>
<td>None</td>
<td>Heavy dozer</td>
<td>H-CAT, HOLE</td>
<td>XD-T, H-CAT</td>
<td>N-EF</td>
</tr>
<tr>
<td>270 g/m²</td>
<td>Light dozer</td>
<td>HOLE</td>
<td>HOLE, HOLE</td>
<td>N-EF</td>
<td></td>
</tr>
<tr>
<td>270 g/m²</td>
<td>Heavy dozer</td>
<td>H-CAT, H-CAT</td>
<td>MD-T, HOLE</td>
<td>N-EF</td>
<td></td>
</tr>
<tr>
<td>Virgin geomembrane</td>
<td>None</td>
<td>Light dozer</td>
<td>H-CAT, H-CAT</td>
<td>H-CAT, H-CAT</td>
<td>N-EF</td>
</tr>
<tr>
<td></td>
<td>HOLE, H-CAT</td>
<td>H-CAT</td>
<td>N-EF</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: All tests performed according to ASTM D 5617. N-EF = non-edge failure; MD-T = machine direction
tear; TD-T = transverse direction tear; XD-T = multi-directional tear; H-CAT = hole in cat eye; HOLE = circular
or elliptical hole.