DESIGN AND TESTING OF A NWNP GEOTEXTILE GAS PRESSURE RELIEF LAYER BELOW A GEOMEMBRANE COVER TO IMPROVE SLOPE STABILITY

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SUMMARY: Pore pressures generated by landfill gas can cause instability for final cover systems incorporating geomembranes. To address this issue, designers often incorporate a gas-relief layer below the final cover system. Recent testing, described in this paper, indicates that specialized nonwoven-needlepunched geotextiles may be an appropriate medium for the gas-relief layer, replacing more traditional materials such as sand. Gas transmissivity is very sensitive to the presence of capillary water, which can be expected under almost all real-world situations.

1. INTRODUCTION

Pore pressures generated by landfill gas can create excess pore pressures beneath a final landfill cover. Landfill covers incorporating a geomembrane cannot be expected to relieve this pressure transverse to the geomembrane. In this case, the gas must be transmitted laterally to point outlets. If the gas is not adequately vented, excess pore pressures may cause enough uplift below the geomembrane to cause the cover-veneer system to be unstable and slide down-slope. A design methodology for providing a blanket gas-relief layer with regularly spaced highly-permeable strip drains has been previously developed by Thiel (1998). A schematic of the design elements is presented in Figure 1. The steps proposed in the methodology are as follows:

- Step 1: Perform a cover slope-stability analysis to determine the maximum allowable gas pressure that results in an acceptable factor of safety.
- Step 2: Estimate the maximum gas flux that may need to be removed from below the landfill cover.
- Step 3: Design a gas-relief system, consisting of a transmissive blanket gas-relief layer and intermittent highly-permeable strip drains that will remove the gas at the estimated design flux rate. The following equation is used to specify the required gas transmissivity of the gas-relief layer, and the spacing of the strip drains:

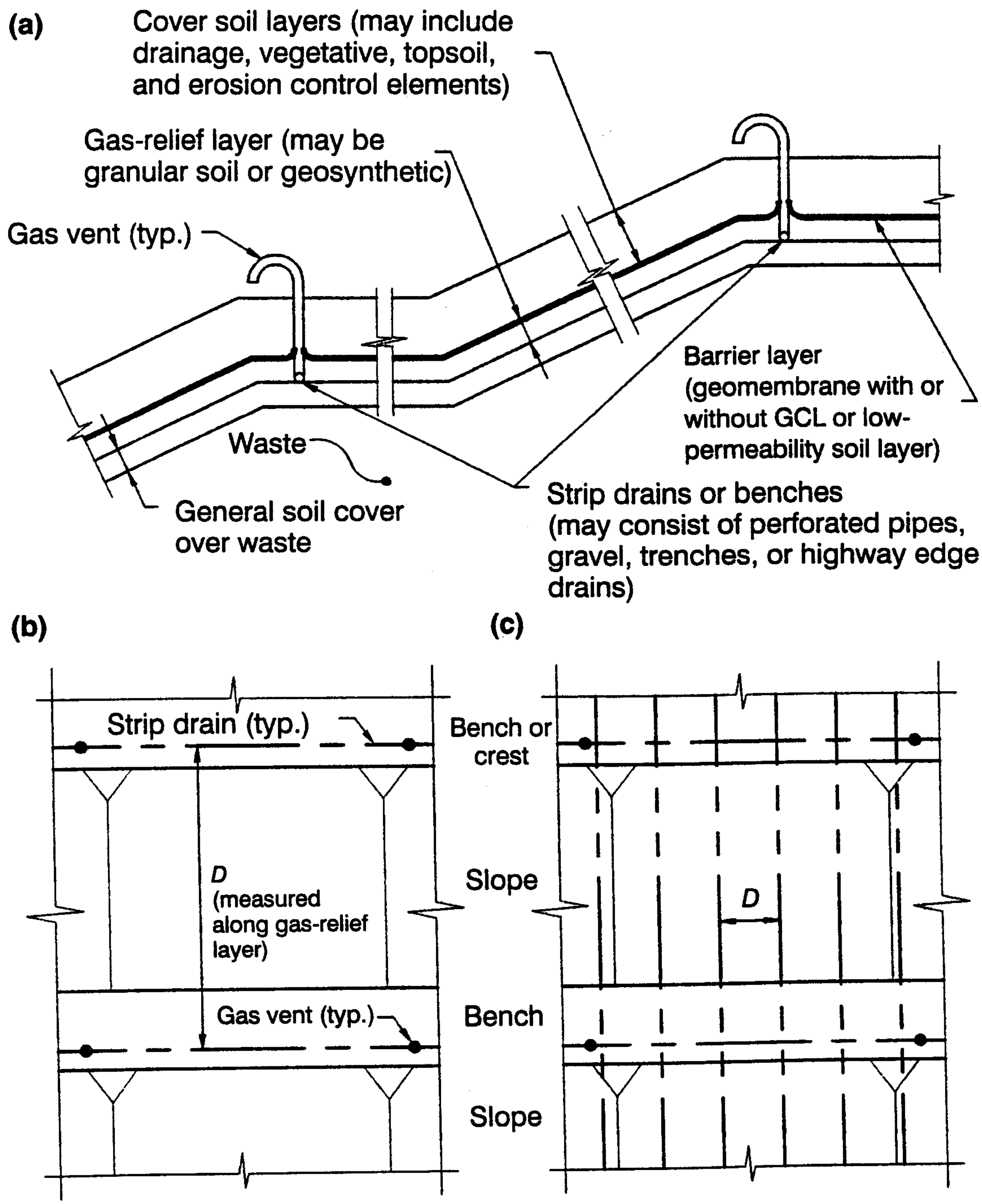


Figure 1. Schematic showing design elements of gas-relief layer: (a) Side view of final cover with gas-relief layer and strip drains; (b) Plan view of strip drain layout on benches only; (c) Plan view of strip drain layout on slopes and benches.

$$u_{max} = \frac{\Phi_g \gamma_g}{\Psi_g}\left(\frac{D^2}{8}\right) \quad (1)$$

where: u_{max} = maximum gas pressure (kPa); Φ_g = gas flux from landfill surface ($m^3/s/m^2$); Ψ_g = in-plane gas transmissivity of the gas-relief layer under field conditions (m^2/s); γ_g = density of the gas (kN/m^3); and D = distance between strip drains (m).

Equation (1) implies a trade-off between the transmissivity of the gas-relief layer and the strip-drain spacing, for a given assumed gas flux rate and maximum allowable gas pressure. The most difficult parameter to estimate is the gas flux. Limited guidance is provided in Thiel (1998) that suggests a gas generation rate, r_g, of $6.24\text{x}10^{-3}$ cubic meters of gas per wet kilogram of waste per year ($m^3/kg/yr$) (=$1.98\text{x}10^{-10}$ $m^3/kg/s$) might be a reasonable basis for estimating the gas flux. The author cautions, however, that estimation of a gas flux is very site-specific, and can vary by over one order of magnitude.

Example 1. Design of a Gas-Relief System.

Given the following design parameters for a landfill cover: slope angle (β)= 18.4°; interface friction angle on the bottom of the geomembrane (ϕ') = 30°, with adhesion (a') = 0; unit weight of drainage layer cover soils (γ) = 15.7 kN/ m^3, with a thickness (h) normal to the slope = 0.3 m during construction; an average waste depth under the final cover = 30 m; a waste density (γ_{waste}) = 800 kg/m^3; a landfill gas generation rate (r_g) = $1.98\text{x}10^{-10}$ $m^3/kg/s$; and a minimum desirable factor of safety (FS) = 1.5. What would be a reasonable specification for a gas-relief system? Assume the strip drains will be connected to a slight vacuum such that there is no backpressure in the strip drains.

Step 1: Determine maximum allowable gas pressure. Using the infinite-slope equation as presented in Thiel (1998), u_{max} can be determined as follows:

$$u_{max} = h\gamma\cos\beta - \frac{[FS \cdot h\gamma \sin\beta - a']}{\tan\phi'} \quad (2)$$

$$u_{max} = 0.3\times15.7\times\cos(18.4) - \frac{[1.5\times0.3\times15.7\times\sin(18.4)-0]}{\tan(30)} = 0.61 \text{ kPa}$$

Step 2: Estimate the gas flux as:

$$\Phi_g = r_g\left(\frac{V_{waste}}{A_{cover}}\right)\gamma_{waste} \quad (3)$$

$$\Phi_g = \frac{1.98\times10^{-10}\ \text{m}^3}{\text{kg}\cdot\text{s}}\times\frac{30\text{m}^3}{\text{m}^2}\times\frac{800\ \text{kg}}{\text{m}^3} = 4.75\times10^{-6}\ \text{m}^3/\text{s}/\text{m}^2$$

Step 3: Using the results from steps 1 and 2, calculate the required transmissivity, Ψ_g, for the gas-relief layer, and the required spacing, D, for the strip drains using Equation (1). A graph of the results showing the range of solutions for Ψ_g vs. D is presented in Figure 2.

END OF EXAMPLE 1

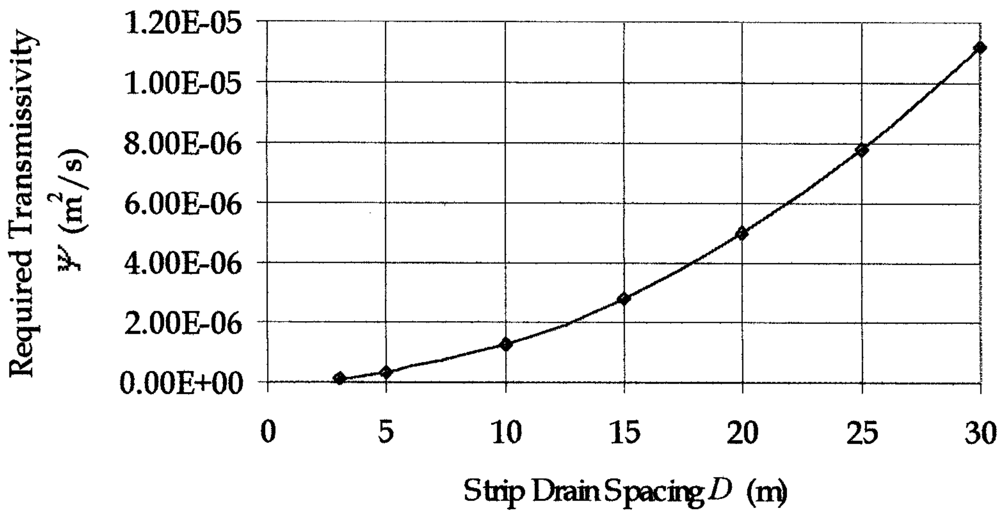


Figure 2. Solution for Example 1: Required gas transmissivity vs. strip-drain spacing.

The graphical solution presented in Figure 2 indicates, for example, that for a strip-drain spacing of 15 m, the required gas transmissivity is approximately 3×10^{-6} m^2/s. It is not common, however, to specify materials in terms of their gas transmissivity. For one thing, there are no standard test procedures available to measure gas transmissivity. Some insights into how to convert between gas and water transmissivity are provided in Thiel (1998), which proves that the landfill gas transmissivity of a dry, porous medium under laminar flow conditions is almost exactly 10 times lower than the hydraulic transmissivity. In addition to performing a direct conversion based on the theory of intrinsic permeability, however, it is also important to take into account that field gas transmissivity is greatly affected by the presence of capillary moisture. For example, limited testing indicates that sands may lose 50-90% of their gas transmissivity due to the presence of interstitial capillary water. The implications of this are that to achieve a field gas transmissivity of 3×10^{-6} m^2/s might require a 30-cm thick layer of sand having a hydraulic conductivity (i.e. coefficient of permeability) of 0.05-0.1 cm/s. If a good source of coarse, clean sand is not available, the designer could specify a geonet-composite. Standard geonet composites are often reported having a hydraulic transmissivity under low normal load of 1×10^{-3} m^2/s, which would translate to a dry-gas transmissivity of 1×10^{-4} m^2/s. Even allowing for some reduction due to the presence of field moisture, one would expect a standard geonet composite to meet the Example 1 gas-transmissivity requirement of 3×10^{-6} m^2/s.

Recent laboratory testing, such as presented in the remainder of this paper, indicates that specialized nonwoven-needlepunched (NWNP) geotextiles may also provide adequate gas-transmissivity under moist field conditions to satisfy gas-relief requirements such as those indicated in Example 1. There are several advantages to considering the use of a single NWNP geotextile instead of either a granular soil or geonet composite. Examples include the ease and speed of installation, potential cost savings, less airspace occupied than soils, and the potential to laminate the NWNP geotextile to final-cover geomembranes to provide a single unit for installation as a barrier layer and gas transmission layer.

2. LABORATORY TESTING PROGRAM

2.1 Geotextile Sample

The geotextile sample used for the test program consisted of two NWNP geotextile layers that were needlepunched together. Physical characteristics of the two layers are described as follows:

- Top layer: nominal 200 g/m^2, 6-denier NWNP polyester geotextile. The purpose of this layer was to provide a surface for applying the heat-bonding agent that would be used to bond the geotextile to a PVC geomembrane. In other applications this layer could serve as a filter, or be deleted if not needed.
- Bottom layer: nominal 950 g/m^2, 45-denier NWNP polyester geotextile. The purpose of this layer was to provide gas transmissivity. This layer was lightly to moderately needled during production to encourage maximum void space without compromising the material integrity or shear strength. The staple fibers were manufactured from recycled PET bottles, and produced with a trilobal spinneret followed by water quenching. The purpose of this manufacturing technique was to provide fibers with a high bending modulus that would spring back after application of a transient load.

The overall thickness of the sample under a 24 kPa normal load was 1.02 cm, and the mass per area of the dry sample was 1,176 g/m^2.

2.2 Laboratory Test Equipment and Procedures

A series of transmissivity tests were performed on specimens of the geotextile sample using both air and water. Two test methods were used for the water testing: a linear-flow device as specified by ASTM D4716, and an experimental radial-flow device. For tests using air, only the radial-flow device was used.

2.2.1 Linear-flow testing

The linear-flow test is an approved ASTM method (ASTM D4716) for measuring the transmissivity (in-plane flow) of geotextiles to water. The test method is not appropriate, however, for measuring transmissivity to gases. The purpose of performing linear-flow tests was to provide a correlation of the results with the radial-flow device.

2.2.2 Radial-flow testing

There is not an approved test method published for a radial flow device, although the ASTM committee on geosynthetics in the USA is currently evaluating this test method for adoption into its standards. Some of the advantages of the radial-flow device over the linear-flow device are that it is not as susceptible to leakage along the sides of the specimen, and it is amenable to testing with gases in addition to liquids. Descriptions of the radial-flow test device design, operations, and data reduction are presented by Weggel and Gontar (1993), and Koerner et al (1984). In general, a circular specimen of the geotextile is placed between two circular steel platens, and the platens are loaded with a specified normal load. The lower platen contains an inner concentric hole into which the test fluid is introduced under a controlled pressure. The fluid flows radially through the specimen and exits at the perimeter of the platens. For water tests, the exit pressure at the perimeter is controlled. For air tests, the exit pressure is atmospheric pressure. The variables that enter into the equation for calculating transmissivity in this test are the inner and outer diameter of the test device, the inlet and exit pressures of the fluid, the fluid density, and the fluid flow rate. The test device used for this study had inner and outer diameters of 5.08 cm and 30.48 cm, respectively.

2.2.3 Test program

Transmissivity testing was performed at two normal loads, 4.8 kPa and 24 kPa, which covers the typical range of landfill final cover loading. Separate specimens from the same sample were used for the linear- and radial-flow devices. In the radial-flow tests, the following sequence of testing was observed: a) dry sample with air, b) saturated testing with water, and c) wet sample with air immediately after the water test. In this manner, the final test with the wet sample was intended to simulate field conditions for transmitting gas.

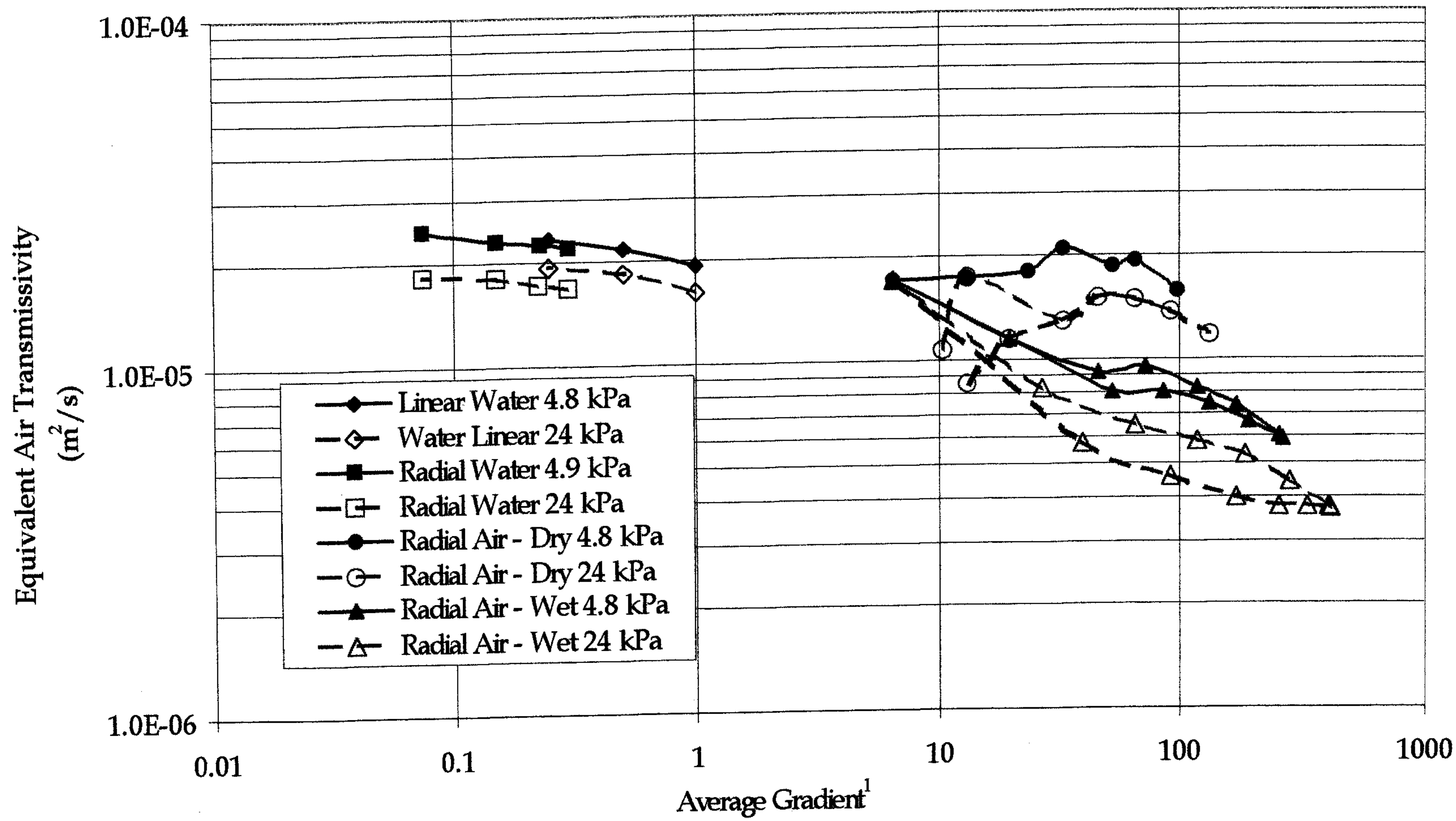
2.2.4 Test results

Figure 3 graphically presents the results of all the transmissivity tests. Note that the results of the water-transmissivity tests were converted to air-transmissivity using the theory of intrinsic permeability so that the results could be compared. The following observations can be made from the results:

a) The results were very similar between the two normal loads, with the 24 kPa normal load giving slightly lower transmissivity results, as one would expect.
b) The standard ASTM D4716 linear water-transmissivity test results, when converted to air transmissivity by the theory of intrinsic permeability, result in an equivalent air transmissivity of approximately 2×10^{-5} m^2/s.
c) The radial-water test results, converted to equivalent air transmissivity, are very close to the linear test results. This validates the test method compared to the standard ASTM test method.
d) The dry-air transmissivity test results, conducted at a higher average gradient because of the sensitivity limits on the flow-measuring devices, show transmissivity values very close to the water test results. This validates the theory of intrinsic permeability as applied to this study, which in turn lends support to the overall design methodology.
e) The wet-air transmissivity tests were conducted by passing air through the specimens after they had been tested for saturated water transmissivity. The results show a pattern of decreasing transmissivity with increasing gradient. The reasons for the shape of the curve are not understood at this time, but the results are quite encouraging. The decrease in transmissivity with increasing gradient indicates a complex interference of the interstitial water affecting air flow through the sample, possibly causing a more turbulent air flow.

3. IMPLICATIONS OF TEST RESULTS FOR DESIGN

The test results presented in Figure 3 indicate that, under wet conditions, the NWNP geotextile used in this study would meet the minimum gas-transmissivity requirements from Example 1. Even at the highest gradients of over 400 under wet conditions, the tested air transmissivity of approximately 4×10^{-6} m^2/s is greater than the minimum requirement in Example 1 of 3×10^{-6} m^2/s for a strip-drain spacing of 15 m. In fact, the maximum gas gradient calculated by the author for the design situation in Example 1 would be less than 10. If the measured wet-air transmissivity is taken from Figure 3 at a gradient of 10, the value would be greater than 1×10^{-5} m^2/s, which would provide a factor of safety of over 3 on the required transmissivity. To obtain an even greater factor of safety, the designer could choose to move the strip drains closer together.



[1] In a radial-flow device the gradient varies inversely with the distance from the center. The radial-test gradients reported in this study are the average gradient calculated by dividing the total head loss, by the distance between the inner and outer radii.

Figure 3. Equivalent air transmissivity measurements conducted with different test devices and fluids for a specialized NWNP geotextile.

4. CONCLUSIONS AND RECOMMENDATIONS

Slope stability of landfill covers incorporating geomembrane barriers can be compromised by pore pressures caused by landfill gas. This has been demonstrated by field failures in which gas pressures appeared to play a significant role.

Standard geotechnical and fluid mechanics engineering principles can be used to design final cover systems to accommodate potential landfill gas pressures. However, as is typical with many geotechnical problems, the basic input of field parameters to the analysis (in this case an estimation of the field gas pressures and volumes) is not an exact science, and involves educated assumptions and experience.

An analytical and design approach has been proposed that incorporates a gas-relief layer with intermittent strip drains to control landfill gas pressures below covers. The gas-relief layer can consist of a coarse sand, geonet-composite, or possibly a coarse, heavy NWNP geotextile. Design practitioners need to be aware of the high sensitivity of gas transmissivity to the presence of water.

The test results presented in this paper indicate that specialized NWNP geotextiles may be an appropriate material for a gas-relief layer. Unique manufacturing characteristics of the NWNP geotextile selected for this study, designed to improve gas transmissivity, were coarse fibers, trilobal water-quenched fibers to provide a high bending modulus, and a thick final product that was not heavily needled during production.

The industry is in need of well-documented test data for gas transmissivity. The testing should be performed at relatively low pressure gradients representative of landfill gas collection requirements. The testing should be performed not only for dry geotextiles, but also on wet geotextiles at a simulated field moisture capacity. When possible, it would be useful to provide side-by-side testing of air and water transmissivity in the laminar flow region to verify that the concept of intrinsic permeability can be applied to geotextiles. The geotextiles being tested should be fully described in terms of their mass per unit area, fiber size, initial thickness, and polymer type. This will also require standardization of a test method.

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