September 6, 2024

Mr. Clay McDaniel via email: clay.mcdaniel@arkansas.gov
Engineer
Arkansas Department of Energy and Environment, Division of Environmental Quality
Office of Land Resources — Assessment and Remediation
5301 Northshore Drive
North Little Rock, Arkansas 72118-5317

Re: Landfill Assessment
NABORS Landfill (AFIN 03-00051)
1320 Landfill Road, Mountain Home, Arkansas 72653
Contract No.: 4600043737

Dear Mr. McDaniel:

The Arkansas Department of Energy and Environment, Division of Environmental Quality (ADEE-DEQ) requested EnSafe Inc. evaluate the current conditions of the NABORS Landfill, located north of Mountain Home, Arkansas. EnSafe understands the NABORS Landfill (Permit Number 0249-S1-R2) is a Class 1 Landfill that was closed in place in 2019. The final cover design included 12-inches of intermediate soil cover over the waste, overlaid with a geomembrane and a synthetic grass turf. The design also required a half-inch of granular material to be placed on top of the turf liner. ADEE-DEQ requested EnSafe to evaluate three specific items: 1) wrinkles in the landfill's turf liner, 2) erosion in the access road between wells LCS-4 and LCS-5, and 3) potential issues with settlement of a storm water inlet structure near well LCS-4.

EnSafe visited the NABORS Landfill with ADEE-DEQ on August 2, 2024, to evaluate the items listed above. The following provides EnSafe observations, EnSafe's understanding of the root cause, and potential solutions to resolve the issues.

TURF LINER WRINKLES

During the site visit, EnSafe personnel observed, as previously noted, wrinkles in turf liner. Photos are included in the photo log in Attachment A. Most of the wrinkles were at the bottom of the landfill slopes, but some wrinkles were also observed on the landfill slopes. EnSafe personnel also observed in some locations wrinkling of the geomembrane liner, and tears in the turf liner, some of which had been previously repaired. The wrinkles and tears appeared to be more prevalent on the longer, steeper slopes, where the weight of the liner and granular fill on the liner appear to be overcoming the internal friction angle between the turf and geomembrane liners.

Wrinkles in the turf liner themselves do not present a problem. However, the wrinkles are causing an issue with storm water drainage and conveyance. The liner wrinkles are accumulating at the bottom of the landfill slopes, where the storm water is conveyed around the landfill. The accumulated wrinkles are starting to block storm water from being conveyed to the drainage conveyances. Over time, as more wrinkles form at the bottom of the slopes, this will become a major problem, and deeper pools of storm water will form along the toe of the landfill. The accumulation of storm water at the toe of the landfill cap will contribute to additional weight pulling on the turf cap and potentially causing tears and additional major slippage of the turf from the slopes as described below.

The presence of the wrinkles at the bottom of the landfill indicates there is a more significant problem. The turf liner is sliding from the weight of the turf liner and granular ballast, on the liner, and exerting a downward force which causing tears in the turf liner along the top of the slope. Based on project information provided by ADEE-DEQ, the turf liner is a ClosureTurf (standard turf) liner, which is underlaid with a geomembrane, AGRU MicroSpike liner. Based on the manufacture's documentation for this project, the internal angle of friction between the two liners is 21 degrees, see manufacturer's documents in Attachment B. For the landfill slopes that are 3 horizontals to 1 vertical (3:1) or flatter, the weight of the turf liner and granular ballast is not enough to overcome the internal friction force. However, based on readily available data and site observations, many of the slopes are steeper than 3:1. In the areas where steeper slopes were identified to be at or greater than 2.5/1, with slopes longer than 250 feet, a greater accumulation of wrinkles were observed at the bottom of the landfill slopes and more repaired tears were observed at the top of the slopes. Basically, the long-steeper slopes, combined with the weight of the turf and ballast are overcoming the internal friction force between the turf and underlying liner.

In a few areas, the geomembrane is bowing. This could be caused by the wrinkles in the turf liner and accumulated storm water adding additional weight and pulling the geomembrane down. If this is the case, the geomembrane could tear in the future and cause a major issue with the landfill cover's stability.

Based on the manufacturer's documentation, the AGRU MicroSpike should be replaced with an AGRU Super GripNet under the turf liner for slopes greater than 3:1 that are longer than 250 feet, which would increase the internal friction force between the liners enough to prevent sliding. Another option would be to reduce the length of the slope by installing terraces mid-way down the slope, which would reduce the weight on the liner.

EROSION IN ACCESS ROAD

EnSafe personnel observed erosion of the access road and the grassy area between the road and the fence line between wells LCS-4 and LCS-5, see photos in Attachment A. The access road at this location is adjacent to a steep slope, which leads to an onsite retention pond. The adjacent steep slope is allowing storm water runoff to concentrate in this area and head-cut the grassy area and access road. This is typical for areas where water flows over a steep slope, without something in place to prevent erosion.

EnSafe recommends repairing the road by installing a non-woven (or woven) geotextile overlaid with a minimum of 6-inches of dense graded aggregate. The channel created by the erosion, in the grassy area, should be shaped into a uniformed swale and concrete matting, like Flexamat, be installed from the roads edge to just beyond the fence line. The concrete matting, adjacent to the road, should be toed into the ground, at least 1.5 feet, and grout installed over the toed in matting, see example detail in Attachment C. The concrete matting should extend at least 2 feet over the top bank of the swale.

INLET STRUCTURE

EnSafe personnel observed cracks in the concrete headwall around the corrugated metal storm water pipes near well LCS-4. The cracks appeared to be caused by differential settlement under the headwall and the absence of reinforcement in the concrete. Over time the cracks will continue to get wider and spread. However, the loads on the headwall are minimum, and do not require immediate action. However, the cracks are allowing storm water to seep through the headwall and could potentially seep along the pipe under the access road at this location. The seepage over time could cause voids in the access road, which could cause the road to collapse. To prevent the potential seepage issues, the headwall should be removed, anti-seep collars installed around the pipes, the soils under the headwall recompacted, and a reinforced concrete headwall installed to replace the existing headwall.

If you have any questions regarding this letter's content, please contact me by phone at 901-937-4349 or by email at ctripeltt@ensafe.com.

Sincerely,

EnSafe Inc.

Chris Triplett

By: Chris Triplett, PE, PM
Director of Engineering Design

Attachments:
- Attachment A — Photo Log
- Attachment B — Turf Liner Manufacture's Documentation
- Attachment C — Example Detail

ENSAFE

Attachment A
Photo Log

Turf Wrinkles at Bottom of Landfill Slope

Turf Wrinkles in Landfill Slope

Turf Liner Previous Repairs

Bowing geomembrane

Headwall Cracks

Road and Grassy Area Erosion

Grassy Area Erosion

Attachment B
Turf Liner Manufacture’s Documentation

DESIGN GUIDANCE MANUAL

ClosureTurf® Final Cover System

June 3rd, 2024

Version History

Version Number	Date	Description of Major Changes
v.23041	10 February 2023	Issued for Publication
v.24155	03 June 2024	• Added CT HF (high-friction engineered turf) • Changed the term “Sand Infill” to “Aggregate Infill” • Updated Sections 1.2, 2.4, 4.1, 5.2, 6.2, 10.2, and Appendices A, B and F

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1. Introduction

ClosureTurf®, illustrated below in Figure 1-1, is a three-component system patented by Watershed Geosynthetics, LLC (Watershed Geo®) that consists of, from bottom to top, a structured geomembrane, an engineered turf, and a specified infill. ClosureTurf is primarily used as a final cover system at landfills and other waste containment facilities undergoing closure. As described herein, ClosureTurf offers a variety of benefits over traditional soil cover systems.

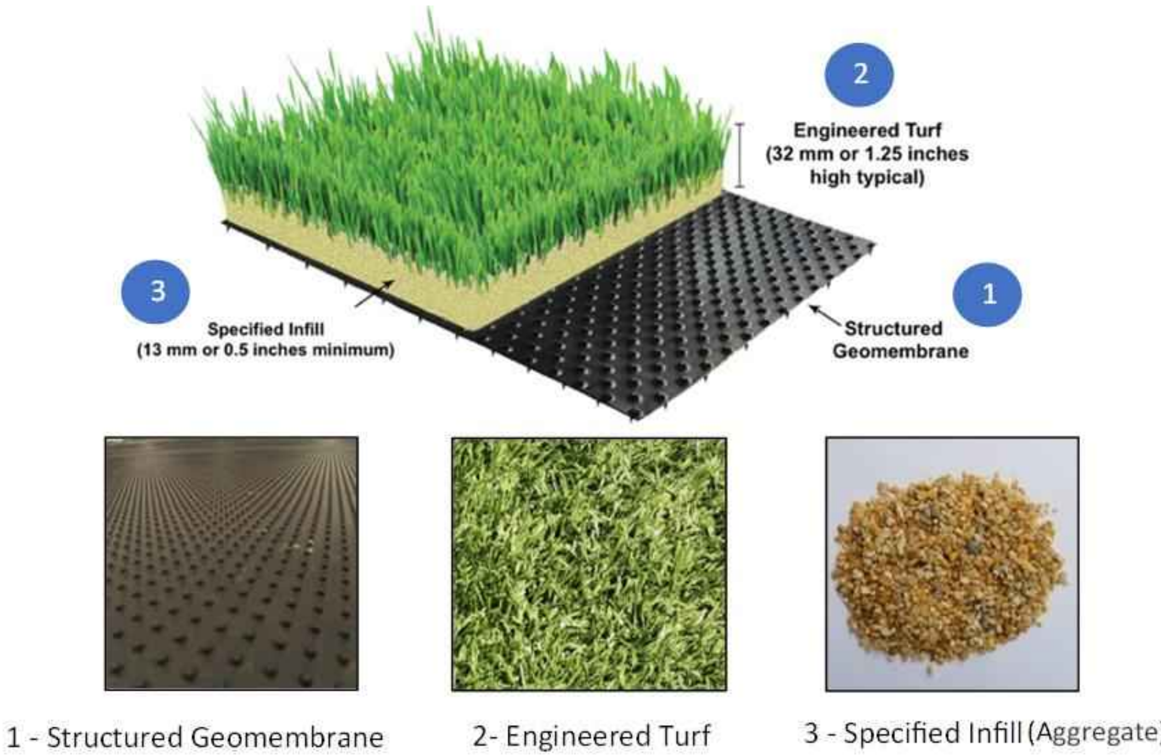

Figure 1-1. ClosureTurf Components

1.1. Purpose and Scope of Design Guidance Manual

This design guidance manual, referred to as the Design Guidance, was developed to guide the engineering design of landfill and waste containment facility closures using ClosureTurf. The Design Guidance is an update to the ClosureTurf Design Guidance Manual dated February 2023.

The Design Guidance describes technical factors relevant to ClosureTurf that are frequently considered during landfill closure design and provides guidance on how to address these factors.

Each project will require the design engineer to tailor the ClosureTurf system design to project requirements as well as the site and facility conditions. Furthermore, it may be necessary to adjust the design to address field conditions encountered during installation. Watershed Geo cannot anticipate all the possible ways that this product may be designed; therefore, this Design Guidance should be considered as guidance only.

Watershed Geo maintains an online technical library to provide the latest product information and technical documents for ClosureTurf, including the product data sheets, design guidance manual, installation guidance, technical specifications, construction details, etc. Instructions on how to access the technical library can be found on Watershed Geo's website through this link: https://watershedgeo.com/downloads/ct-technical/. The design engineer is encouraged to contact Watershed Geo if additional information or assistance on ClosureTurf design is needed. Contact information can be found at: https://watershedgeo.com/contact/.

1.2. Components of ClosureTurf

As illustrated in Figure 1-1, the bottom component of ClosureTurf is a structured geomembrane that serves as the hydraulic barrier to minimize rainfall infiltration. The structured geomembrane is made with either a high-density polyethylene (HDPE) or linear low-density polyethylene (LLDPE) formulation. The engineered turf overlying the structured geomembrane is made of HDPE synthetic grass blades tufted into a double-layer polypropylene (PP) woven geotextile backing. The engineered turf provides the appearance and texture of natural grass for the cover system, while also protecting the geomembrane from weathering. The infill component is usually a specified aggregate material placed between the blades of the engineered turf. It provides additional protection of ClosureTurf from wind uplift and weathering, while improving trafficability of the cover system by people, vehicles, and equipment. In areas with concentrated flows (e.g., drainage swales and perimeter channels), the cementitious HydroBinder® infill is recommended instead of the specified aggregate infill (further discussed in Section 5).

The components of ClosureTurf can be selected from available product options to address specific site conditions. Three types of structured geomembranes are currently available for use in ClosureTurf: MicroSpike®, MicroDrain®, and Super GripNet® manufactured by Agru America. All three types are available in HDPE and LLDPE formulations. The structured geomembrane should be selected based on factors including slope angle, interface shear strength, drainage of stormwater, and construction costs. The three types of structured geomembranes shown on Figure 1-2 are described below:

- MicroSpike consists of both top and bottom surfaces having consistent texturing patterns.
- MicroDrain has studs on its top face to create a transmissive drainage layer, thereby eliminating the need for a separate geonet or geocomposite drainage layer. The bottom face of the geomembrane uses the same texturing pattern as MicroSpike.
- Super GripNet also has studs on the top face to create a transmissive drainage layer. The bottom of Super GripNet has a spiked surface to increase the interface shear strength between ClosureTurf and subgrade for cover stability on steep slopes.

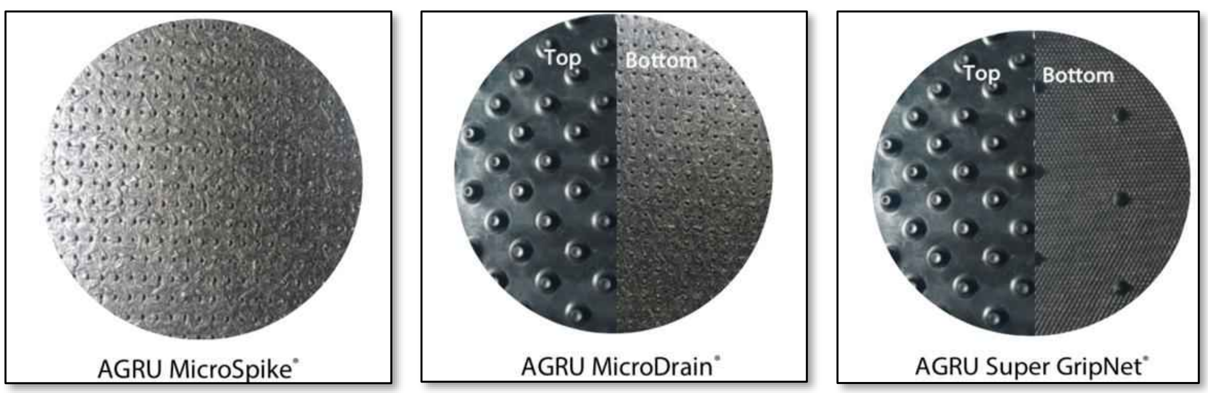

Figure 1-2. Structured Geomembranes Available for ClosureTurf

Four types of engineered turf are available for the ClosureTurf system: CT, CT X, CT HD, and CT HF. The types differ by the tufting gauge (i.e., turf fiber density), tufting pattern, and color. CT is the standard turf commonly used for closure applications. It is generally available in two colors: olive green and tan. CT X is the blended turf that contains a mixture of both olive green and tan turf fibers. It has a similar turf fiber density to CT. It can be customized for aesthetic purposes to better blend with surrounding landscapes. CT HD is the high-density turf that has a higher turf fiber density approximately twice of CT. CT HD provides higher seam strength, wind uplift resistance, and hydraulic shear resistance against potential aggregate infill movement, which results in less post-closure maintenance. CT HD is also generally available in olive green and tan colors. CT HF is the high-friction turf with an offset tufting pattern. It has a similar turf fiber density to CT. Because of the alternating turf stitch pattern, CT HF provides a higher interface friction against the geomembrane than the other types of engineered turf. CT HF is available in olive green and tan colors, too.

The specified aggregate infill is typically a coarse, angular sand. Watershed Geo recommends that the aggregate infill should meet Watershed Geo's technical specification to achieve adequate hydraulic shear resistance and minimize potential movement in the field. Hydraulic stability of the aggregate infill is discussed in detail in Chapter 6. Watershed Geo evaluates potential sources of locally available aggregate infill and maintains a database of appropriate sources to assist customers and installers in identifying a material source. Contact Watershed Geo for potential aggregate infill sources near a project location, as needed.

1.3. Benefits of ClosureTurf

ClosureTurf has been developed to address long-standing challenges with traditional soil cover systems, including the following:

- Sites where suitable soil materials are unavailable or where it is expensive to import from an off-site source;
- Performance issues stemming from erosion of the soil cover and/or difficulty in sustaining healthy vegetation;
- Problems with slope instability caused by cracking and veneer-type sliding that adversely affect the integrity of the traditional soil cover system; and
- Need for frequent and sometimes extensive post-closure maintenance.

With the engineered turf and a specified aggregate infill layer, ClosureTurf overcomes the above challenges and provides the following advantages and benefits:

- ClosureTurf requires minimal soil (i.e., only the thin layer of aggregate infill). Sites with limited available soil can avoid purchasing and importing large quantities of soil required for a traditional soil cover system.
- For sites that would otherwise require large quantities of soil to be imported, the elimination of these materials benefits neighbors and local communities by reducing nuisance caused by truck traffic, dust, mud tracked onto public roads, chances of vehicle accidents, and noise during construction.
- At landfills, depending on permits, it is possible that the elimination of the soil layers in a traditional soil cover system can provide additional capacity (airspace) for waste disposal, which represents an opportunity to increase site life as well as landfill revenue.
- In general, ClosureTurf can be constructed faster than traditional soil cover systems.

- Upon completion of installation, ClosureTurf is fully functional and able to perform as designed. Traditional soil cover systems take one or more growing seasons to establish vegetation. The soil cover is particularly vulnerable to erosion problems during this interim period.
- As a manufactured product in accordance with stringent industrial standards and procedures, ClosureTurf properties are consistent and verifiable. This results in a reliable finished product that performs more predictably and consistently than traditional soil cover systems.
- Because the specified aggregate infill layer used in ClosureTurf is thin, the probability of a veneer-type soil cover failure above the geomembrane is negligible. With relatively high interface shear strength, the ClosureTurf system is inherently more stable than traditional soil covers from a geotechnical engineering perspective.
- Compared with traditional soil cover systems, ClosureTurf is more tolerant of differential settlement because of the flexible geosynthetic components.
- Stormwater runoff quality is significantly improved at sites using ClosureTurf compared to sites with traditional soil cover systems.
- Significantly lower post-closure maintenance costs are expected for ClosureTurf than for a traditional soil cover system because no mowing, fertilization, or revegetation is required.
- Site maintenance and system repairs are easier with ClosureTurf compared to traditional soil cover systems, as no soil excavation is required for ClosureTurf.
- Installation of ClosureTurf conserves water and natural soil and requires fewer truck trips and less heavy equipment; therefore, the environmental impact is much smaller. A study has shown that approximately 65% to 75% reduction in carbon emissions can be achieved when using ClosureTurf instead of a traditional soil cover system (Joshi 2023).
- ClosureTurf provides an improved base for solar arrays at closed landfills than traditional soil cover systems due to elimination of soil erosion and reduction in post-closure maintenance.

1.4. <u>ClosureTurf Applications</u>

Engineered specifically for waste containment facilities, ClosureTurf has been used at sites ranging from local municipalities to large industrial, utility, and United States Environmental

Protection Agency (USEPA) Superfund sites. The waste types in those facilities include municipal solid waste (MSW), construction and demolition debris, industrial sludge and byproducts, coal combustion residuals (CCR), hazardous waste, and contaminated materials. ClosureTurf has been installed successfully in differing climatic regions that experience heavy rainfall, hurricane-force winds, and extreme temperatures, as well as areas with seismic activity. A map of ClosureTurf project sites can be found at: https://watershedgeo.com/.

2. Final Cover Slope Stability

This chapter addresses slope stability considerations associated with the use of ClosureTurf for final closure of landfills and other waste containment facilities.

2.1. Potential Failure Modes

Veneer-type slope instability is the propensity of the cover layer (or veneer) of a final cover system to slide. Veneer-type sliding failures have occurred with soil-geosynthetic cover systems placed over steep slopes of landfills, especially after major storm events (Koerner and Soong 1998), resulting in rupture, tearing, or cracking of the cover system components. In such cases, sliding of the cover system occurred along the weakest interface between the cover system components (e.g., soil-geosynthetic or geosynthetic-geosynthetic interface).

The stability of ClosureTurf on side slopes should be evaluated by calculating the factor of safety (FS) against veneer slope instability. The critical slip surface for ClosureTurf is along either the interface between the engineered turf and geomembrane or the interface between the geomembrane and subgrade (i.e., foundation layer of the cover system). Hence, this chapter focuses on the method for evaluating the veneer stability of these interfaces.

In addition to veneer stability, the design engineer should evaluate other potential modes of slope instability (e.g., global waste slope stability) that do not necessarily pertain to ClosureTurf. Those potential modes are beyond the scope of this Design Guidance.

2.2. Veneer Stability Analysis Method

The static and pseudo-static (i.e., seismic) veneer stability of ClosureTurf on a slope can be evaluated using methods based on limit equilibrium, such as closed-form equations developed for both finite and infinite slope configurations. In practice, closed-form equations are widely used because they are simple, practical, technically-sound, and can be easily coded in a spreadsheet. Examples of these equations include Giroud et al. (1995a) and Matasovic (1991). The design engineer is responsible for selecting an appropriate method for analyzing the stability of a particular slope or set of slopes.

Inputs to a veneer slope stability analysis include, but are not limited to, the unit weight of ClosureTurf, interface shear strength between the engineered turf and geomembrane, interface shear strength between the geomembrane and subgrade material, and the hydraulic head acting on the geomembrane component of ClosureTurf. The hydraulic head on the geomembrane can be estimated using equations presented in the literature (e.g., Thiel and Stewart 1993) or using the Hydrologic Evaluation of Landfill Performance (HELP) software developed by the USEPA (Schroeder et al. 1994a and 1994b; Tolaymat and Krause 2020). Inputs for the hydraulic head calculation include weather data and characteristics of the ClosureTurf (i.e., transmissivity, slope, and length of the drainage layer). Additionally, external loading (e.g., vehicular loading) may need to be included in a veneer stability analysis, if applicable.

The design engineer should review technical guidance and state and federal solid waste regulations to understand if there are any specific methods or target FSs required by the regulations for the veneer slope stability of a landfill final cover system.

2.3. ClosureTurf Interface Shear Strength

As stated above, inputs to a ClosureTurf veneer stability analysis require information on shear strengths along two interfaces (i.e., between the engineered turf and geomembrane and between the geomembrane and subgrade material). Watershed Geo conducted interface shear testing in accordance with ASTM D5321 to evaluate the interface shear strength of the engineered turf layer against the underlying geomembrane. Appendix A provides the results of interface shear strength tests between the different types of engineered turf and structured geomembrane used in ClosureTurf. Test results indicate peak interface friction angles are 34 degrees for the CT HD turf, 36 degrees for the CT turf, and greater than 45 degrees for the CT HF turf, when using the Super GripNet geomembrane (or the MicroDrain geomembrane that has the same studded top surface); and 19 degrees for the CT HD turf, 23 degrees for the CT turf, and 40 degrees for the CT HF turf, when using the MicroSpike geomembrane. Measured large displacement shear strengths were lower than the peak interface strengths reported above (i.e., strain-softening).

The interface shear strength between the geomembrane and the subgrade material depends on the subgrade material at the site. Therefore, when selecting the appropriate interface friction angle for the veneer stability analysis, it is recommended that project-specific interface shear testing be conducted using samples of subgrade material collected from the site.

The design engineer should use the selected interface shear strength parameters to perform a veneer stability analysis of ClosureTurf to evaluate whether the calculated FS meets or exceeds the target FS. Alternatively, the design engineer may back-calculate the minimum required interface shear strength parameters to achieve the target FS. These values can then be incorporated into the technical specifications as minimum required parameters; and the project specifications would require the contractor to perform interface shear testing to verify that the construction materials supplied to the project have adequate interface shear strengths to meet the target FS.

2.4. General Guidance on Maximum Slope

Table 2-1 provides the design engineer with general guidance on the maximum allowable slope at which each ClosureTurf system can be constructed. This table was developed by Watershed Geo based on results of interface shear testing conducted between the engineered turf and geomembrane and assumed typical values of interface shear strength between the geomembrane and subgrade material. Therefore, it is important to note that this table should be used for preliminary design purposes only. The design engineer should conduct project-specific interface shear testing to evaluate the critical interface (i.e., the interface with the lowest interface shear strength) and perform detailed slope stability analyses for the site-specific design.

Table 2-1. Maximum Allowable Slope for Preliminary Design of ClosureTurf (1) (2) (3) (4) (5) (6)

Geomembrane	Engineered Turf		
	CT HD (High-Density Turf)	CT (Standard Turf)	CT HF (High-Friction Turf)
MicroSpike	5H:1V	4H:1V	3H:1V
MicroDrain	3H:1V	3H:1V	2.5H:1V
Super GripNet	3H:1V	2.5H:1V	2H:1V(2)

Notes:

1. The table above is used for preliminary design purposes only. Site-specific slope stability analysis should be performed for the final design with an adequate safety factor by the project design engineer.
2. For slopes steeper than 2H:1V, additional measures (e.g., additional anchor trench or ballast) may be required to improve veneer stability, as determined by the design engineer to account for site-specific conditions. Contact Watershed Geo for more guidance, if needed.
3. The interface shear strength between the engineered turf and geomembrane has been tested by SGI Testing Services, LLC and the test results are provided in Appendix A.
4. The interface shear strength between the geomembrane and subgrade is dependent on the site subgrade materials. For the purpose of developing Table 2-1, the peak interface friction angle

between the geomembrane and subgrade was assumed to be 31 degrees for MicroSpike and MicroDrain and 37 degrees for Super GripNet. Site-specific interface shear testing should be conducted to obtain the interface friction angle for the detailed slope stability analyses.

5. Table 2-1 does not account for seismic conditions. If the site is in a seismic impact zone, additional slope stability analyses should be performed to evaluate the slope stability under the design earthquake event.
6. If PowerCap™, Watershed Geo's patented solar energy generation system, is considered for future beneficial site use, MicroSpike is recommended for use only on the landfill top deck with a slope equal to or less than 10 percent (%) when CT and CT HD are used; and on a maximum slope of 3H:1V when CT HF is used. Otherwise, Super GripNet or MicroDrain should be considered. Contact Watershed Geo for more guidance on maximum allowable slopes associated with PowerCap installation.

2.5. Example Calculation

Appendix B provides an example calculation for final cover veneer slope stability of ClosureTurf.

3. Wind Uplift Resistance

Exposed geomembranes can be lifted by wind, causing the geomembrane to be torn or pulled from the anchor trench. ClosureTurf is not an exposed geomembrane system. Unlike an exposed geomembrane system, the engineered turf and aggregate infill above the structured geomembrane provide resistance against wind uplift.

This chapter presents a wind uplift calculation method for ClosureTurf. The pressure necessary to cause an exposed geomembrane to lift is typically calculated based on the negative pressure relative to atmospheric pressure (suction) induced by wind and the resulting strain on the geomembrane. The calculation method for exposed geomembranes developed by Giroud et al. (1995b) and Giroud and Zornberg (1997) is used in this Design Guidance. Because ClosureTurf is not an exposed geomembrane, additional steps are needed to analyze the system's resistance to wind uplift that involve the engineered turf and aggregate infill.

3.1. Analysis Method

When wind flows over obstacles, local air pressure increases or decreases depending on the geometry of the obstacles that the flow encounters. If the air pressure becomes negative (relative to atmospheric pressure), suction (or uplift pressure) occurs. If the suction is strong enough, geomembrane cover systems can be lifted by wind. For ClosureTurf, the weight of the geomembrane, engineered turf, and aggregate infill is intended to counteract this wind uplift pressure.

Wind uplift pressure acting on ClosureTurf can be calculated using Equation 3-1 (Dedrick 1973; Wayne and Koerner 1988; Giroud et al. 1995b):

$$P = \frac{1}{2} C_p \rho U(H)^2 \cdot K_d \cdot K_e \qquad (3\text{-}1)$$

In this equation, P is the wind-generated uplift pressure normal to the surface in pounds per square foot, C_p is a wind pressure coefficient, ρ is the air density (= 0.0024 slug per cubic foot at 59 degrees Fahrenheit [°F] and sea level), $U(H)$ is the mean upstream wind speed in feet per second at the height of the slope, K_d is the wind directionality factor (= 1.10), and K_e is the ground elevation factor.

The ground elevation factor can be calculated using Equation 3-2 (ASCE 2022):

$$K_e = e^{-0.000362 \cdot Z_e} \tag{3-2}$$

In the above equation, Z_e is the ground elevation above sea level in feet.

3.2. Wind Tunnel Test Results

Watershed Geo has conducted extensive wind tunnel testing of ClosureTurf at the Iowa State University Aerodynamic and Atmospheric Boundary Layer Wind and Gust Tunnel. The key observations made during the wind tunnel testing are as follows:

- The wind-induced uplift pressures varied along the side slopes and top deck. Uplift pressures were observed approximately from the middle of windward (i.e., slopes facing the wind) slope extending along the top deck to the leeward side slopes.
- The maximum uplift pressure occurred near the crest of the windward slope.
- Windward slopes experienced higher wind uplift pressures than leeward slopes.
- The measured maximum wind uplift pressures were larger for a 3H:1V slope than those for a 4H:1V slope.
- For the given test conditions, the wind uplift pressure experienced by ClosureTurf is about 70% lower than the wind uplift pressure experienced by an exposed smooth geomembrane cover. This lower uplift pressure appears to be associated with turbulence created by the engineered turf.
- For the given test conditions, the maximum uplift pressure experienced by a high-density turf (CT HD) is lower than that experienced by a standard density turf (CT). On a 4H:1V slope, the maximum wind uplift pressure of CT HD is 17% lower than that of CT; and on a 3H:1V slope, the maximum wind uplift pressure of CT HD is 24% lower than that of CT.

The wind tunnel test results are presented in the form of wind pressure coefficients, C_p. Figures 3-1 and 3-2 show the wind pressure coefficient distributions for 3H:1V and 4H:1V slopes, respectively, with two types of engineered turfs, CT and CT HD. No wind tunnel tests have been conducted for the blended turf CT X or high-friction turf CT HF. Since CT X and CT HF have similar turf density to CT, the wind pressure coefficients of CT can be applied to CT X and CT HF.

It is noted that positive wind pressure coefficients correspond to downward pressure (or compression) and negative wind pressure coefficients correspond to upward pressure (or uplift). The horizontal locations of the measurement points, *x*, are normalized by the length of the model, *L*, in Figures 3-1 and 3-2.

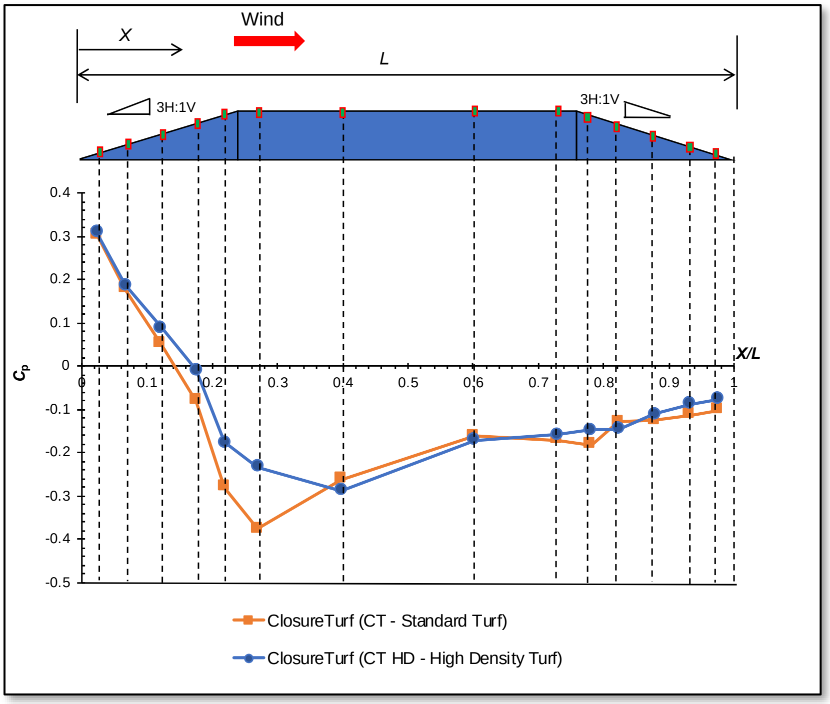

Figure 3-1. Wind Pressure Coefficients for ClosureTurf on a 3H:1V Slope

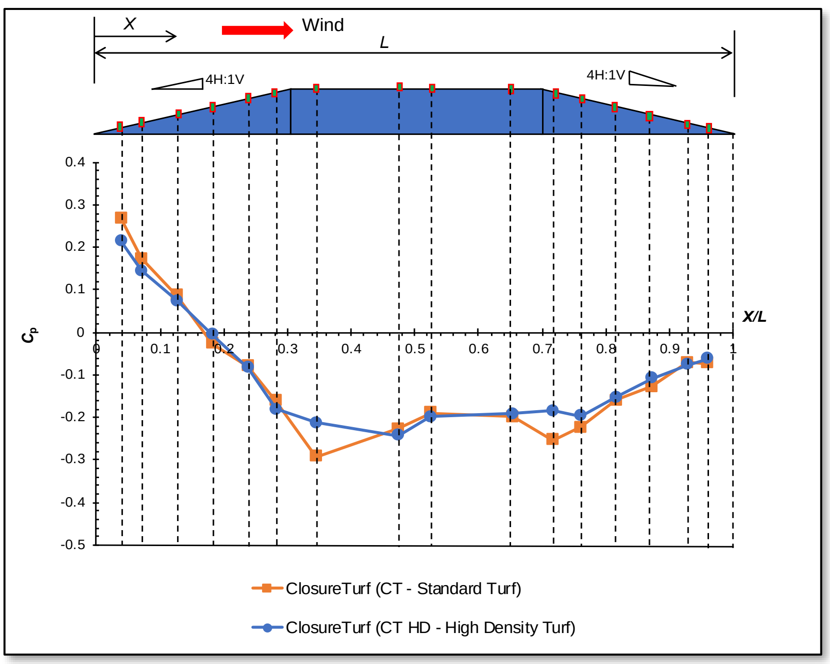

Figure 3-2. Wind Pressure Coefficients for ClosureTurf on a 4H:1V Slope

3.3. Wind Uplift Analysis Procedure

The procedure for wind uplift analysis of ClosureTurf consists of the following steps (see Appendix C for more details):

1. Select the maximum absolute value of the negative wind pressure coefficient, C_p, based on the results of wind tunnel testing and the landfill slope configuration.
2. Select the appropriate design wind speed for the location of the project. The basic wind speed, corresponding to a 3-second gust at 32.8 feet above ground, at locations in the United States can be obtained from an online database (https://asce7hazardtool.online/) based on recommendations in ASCE 7-22 (ASCE 2022).
3. Calculate the mean hourly design wind speed at the top of the landfill from the basic wind speed.
4. Calculate the maximum wind uplift pressure using Equation 3-1. The critical location is usually at or near the windward crest.
5. Calculate the weight of ClosureTurf on a per square foot basis.
6. Calculate an FS against the maximum wind uplift pressure by dividing the weight of ClosureTurf by the wind uplift pressure. A minimum FS in the range of 1.1 to 1.2 is considered adequate for purposes of design against the maximum wind uplift pressure. The basis for these minimum FS values is given in Appendix C to this Design Guidance.
7. If the target FS is not met, a tension strain analysis is performed to evaluate whether the wind-induced tension in the ClosureTurf system is acceptable, as discussed in Appendix C.

3.4. Example Calculations

Appendix C presents example wind uplift calculations for ClosureTurf using the procedures presented above.

4. Puncture and Tearing Loads and Resistance

This chapter presents a summary of design considerations regarding the puncture and tearing loads induced on ClosureTurf and the resistance of the system to these loads.

4.1. <u>Design Considerations</u>

Potential sources for puncture and tearing stresses applied to ClosureTurf are similar to sources considered for traditional cover systems with geomembranes. The geomembrane component of ClosureTurf can potentially be punctured by large or sharp objects in the subgrade. Puncture can be induced by equipment loads on top of ClosureTurf. In addition, equipment traveling on slopes induce static and dynamic loads (e.g., equipment weight, acceleration, and braking), which may cause the cover system to slide or components of the system to tear.

To avoid puncturing the ClosureTurf geomembrane, the following should be taken into consideration:

- The subgrade should be prepared such that it:
    - has relatively uniform and smooth surface; and
    - is free of sharp objects, oversized particles, and other deleterious materials that could damage the geomembrane.
- Subgrade soil should conform to the requirements of the project technical specifications.
- Anchor trenches should be free of sharp objects and other deleterious materials.
- Construction stakes and hubs in the subgrade should be removed and resulting holes backfilled.
- Any potentially damaging particles, including stones, construction debris, and soil clods that accumulate on the exposed geomembrane during ClosureTurf installation should be removed before placing the engineered turf on the geomembrane.

The maximum particle size of the subgrade material should be determined by the design engineer based on the anticipated equipment loading and puncture resistance properties of the geomembrane.

With the subgrade meeting the requirements described above, the following should be taken into consideration regarding equipment loads to prevent ClosureTurf from tearing:

- Do not allow equipment with ground contact pressures exceeding 5 pounds per square inch (psi) on the partially constructed system until aggregate infill has been installed.
- Do not allow equipment with ground contact pressure greater than 35 psi on slopes steeper than 15% or ground contact pressure greater than 85 psi on slopes less than 15%, after ClosureTurf installation is complete.

It should be noted that the above-mentioned limits on equipment loading are for the general guidance purposes only and based on assumptions that: (1) the subgrade is firm and unyielding and able to support the equipment without creating rutting or bearing capacity issues; and (2) the subgrade is free of sharp rock fragments or stones, large stones and other deleterious matter such as tree roots, construction debris and metallic objects that could cause damage to ClosureTurf, as previously discussed. The design or construction quality assurance (CQA) engineer should specify the maximum allowed equipment loading limits based on site-specific conditions.

The contractor should use rubber-tired or -tracked equipment and limit the speed of equipment traveling on ClosureTurf. The equipment is not allowed to make sharp turns, sudden acceleration/deceleration, or repetitive passes on ClosureTurf. The design engineer should evaluate the maximum allowable equipment speed on ClosureTurf. Appendix B presents an example ClosureTurf veneer slope stability analysis considering equipment loading.

A puncture resistance analysis of the geomembrane can be performed by the engineer, as needed, using commonly accepted approaches (e.g., Wilson-Fahmy et al. 1997, Narejo et al. 1997, and Koerner et al. 1997).

4.2. <u>Puncture Resistance Test Summary</u>

To examine puncture resistance, Watershed Geo had SGI Testing Services conduct tests on samples of the engineered turf and structured geomembrane. The specific geomembrane used in the testing was 40-mil HDPE MicroSpike. Testing was conducted in accordance with the *Standard Test Method for Large-Scale Hydrostatic Puncture Testing of Geosynthetics* (ASTM D5514) using Virginia Department of Transportation #57 aggregate. For a maximum loading of 85 psi, the geomembrane component was deformed but not punctured. Because no punctures were observed in the geomembrane component for the loading of 85 psi, the ultimate static puncture strength of the system is expected to be greater than 85 psi. Additional details on the hydrostatic puncture testing are provided in Appendix D.

5. Surface Water Management

This chapter provides guidance on the design of open channels with ClosureTurf to manage surface water. The chapter addresses landfill hydrology, final cover conveyance channels, infill materials, and downstream considerations related to energy dissipation systems and sediment storage volumes in ponds.

5.1. Hydrology, Channel Sizing, and Channel Infill Selection

Table 5-1 presents parameters for defining site hydrology when applying the Rational Method or the Soil Conservation Service Unit Hydrograph Method to evaluate hydrologic performance of ClosureTurf. These parameters are used for sizing conveyance channels using Manning's Equation and selecting infill materials as a function of permissible and computed flow velocities.

Table 5-1. Hydrology and Hydraulics Parameter Recommendations for ClosureTurf-lined Areas

Runoff Process	Parameter	Value
Rainfall to Runoff	Curve Number	92 - 95, or as selected by the design engineer
	Rational "C"	0.74 - 0.78, or as selected by the design engineer
Sheet Flow	Manning's Roughness	0.22 (when slope $\leq$ 10%) 0.12 (when slope > 10%)
	Maximum Flow Length	Selected such that flow depth is $\leq$ 0.1 foot, or as required
Shallow Concentrated Flow	Average Velocity (1) (feet/second)	TR-55 unpaved condition (calculated as $16.135 \times (S)^{0.5}$, where S is the surface slope in feet/foot), or as selected by the design engineer
Concentrated Flow (2)	Manning's Roughness	0.02 (when using HydroBinder)

Notes:

1. The suggested value is based on Part 630 Hydrology, National Engineering Handbook (NRCS 2010) for shallow concentrated flow over an unpaved surface or grassed waterway of a given slope. Check local requirements for suitability.
2. Hydraulically stable stone (gravel/riprap) or HydroBinder other than the aggregate infill should be used in concentrated flow locations.

The terminology in Table 5-1 is based on Hydraulic Engineering Circular Number 22 (HEC-22), *Urban Drainage Design Manual* (FHWA 2009). Only the parameters that are influenced by the selection of ClosureTurf over traditional cover systems are discussed herein. For example, many state or local agencies require that a design storm event be selected from Atlas 14 Point Precipitation Frequency Estimates published by the National Oceanic and Atmospheric Administration (NOAA 2022). However, because this design requirement is applicable for all cover systems, it is not addressed in this Design Guidance. It is also recommended that the design engineer consider applicable federal (e.g., *Urban Drainage Design Manual*, FHWA 2009) and state (e.g., *Georgia Stormwater Management Manual*, ARC 2016) design guidelines, as appropriate for the site location and standards of practice, during the design process.

5.2. General Design Considerations

5.2.1. Hydrology

Because longer drainage lengths are typically possible with ClosureTurf compared to traditional soil cover systems, the need for drainage benches to intercept and manage runoff may be eliminated or the spacing of benches, if still needed, can be increased. The ability to maintain sheet flow for extended distances is a significant advantage to ClosureTurf.

Due to the relative impermeability of the underlying geomembrane and small thickness of the aggregate infill layer, curve numbers for ClosureTurf tend to be higher than those of traditional soil cover systems. This may affect the runoff volumes and rates to be managed by stormwater ponds and other downstream features, which are discussed in Section 5.2.5.

5.2.2. Typical ClosureTurf Stormwater Management Features

Regulatory requirements generally specify that a network of final cover channels be designed to route runoff generated within a final cover area so that this runoff does not increase peak discharge rates and total runoff volumes associated with any predevelopment outfalls of a site. Typical landfill or other site development regulations for channel sizing will also require conveyance of specific design storms, such as the 25-year/24-hour storm event, or the 100-year/24-hour storm event with some degree of freeboard, or both. Note that, for reasons to be described in Chapter 6, storm events selected to size drainage benches and channels may differ from those selected for evaluating hydraulic stability of the ClosureTurf aggregate infill.

Typical final cover drainage features include benches, berms, swales, downchutes, perimeter channels, etc. Relevant standard details are provided in Watershed Geo's online technical library.

5.2.3. Channel Infill Selection for ClosureTurf Stormwater Management Features

Stone (gravel or riprap) or HydroBinder is recommended as a ClosureTurf infill option within channels rather than aggregate infill. The relative costs and advantages of HydroBinder versus stone depend on site-specific conditions.

When stone is used, the design engineer should assess whether a nonwoven geotextile cushion should be placed between the stone and ClosureTurf to reduce the potential for damage to the ClosureTurf system including puncture of the ClosureTurf geomembrane component.

When HydroBinder or other low permeability binder infill is used, water relief vents (e.g., a slit cut into the HydroBinder layer with an insert to maintain water flow, i.e., a piece of geocomposite, geonet, studded geomembrane such as Agru's MicroDrain®, etc.) should be considered to relieve hydraulic pressure within the ClosureTurf drainage layer at locations where the internal drainage capacity is decreased or restricted (e.g., upstream of riprap check dams, sharp decreases in slope, grade breaks at downchutes, terminations/connections to concrete structures, such as headwalls and drop inlets, etc.)

The spacing of water relief vents is site-specific, depending on multiple variables (e.g., channel slope, drainage area to the channel, location of structures, etc.). A spacing of approximately 200 ft can be used as a general guidance for a HydroBinder-lined drainage swale or channel and should be adjusted by the design engineer based on site-specific conditions. It is also suggested that vents be installed immediately upstream of any location in the drainage swale or channel that restricts flow within the internal drainage layer (e.g., concrete headwalls, drop inlets, or cross stream check dams). For a HydroBinder-lined downchute, water relief vents are suggested at locations immediately above the benches, if any, and toe of the slope. The width of the vent is suggested to be approximately 1/3 of the channel or downchute bottom width.

Also, as is standard practice for the design of any channel lining system, the calculated flow velocity for the selected design storm should be compared to the permissible flow velocity of the ClosureTurf with the HydroBinder infill within channels, which is considered to be 29 ft/s, if a FS of 2.0 is desired.

5.2.4. Energy Dissipation

Similar to any surface water conveyance terminating and transitioning flow direction at the toe of a slope, proper energy dissipation is necessary at the base of downslope channels using ClosureTurf and around any relatively sharp changes in flow direction. Proper energy dissipation techniques can be found in HEC 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels* (FHWA 2006).

Where concrete energy dissipators are required, polyethylene (PE) embedment strips can be cured into the concrete dissipators and later welded to the geomembrane component of ClosureTurf to maintain a continuous closure system. Alternatively, batten strips with concrete anchors may be used. Where stone energy dissipators are used, placement of HydroBinder around the footprint of stone is suggested to minimize loss of aggregate infill placed in the vicinity of the energy dissipators.

5.2.5. Stormwater Pond Design

Because runoff from ClosureTurf may generate greater peak discharge rates and volumes compared to those from traditional soil cover systems, projects using stormwater ponds to attenuate flows prior to discharge may need an increased stormwater pond size. However, this potential increase to pond size can be at least partially offset by a reduction or elimination of the required sediment storage volume that must be managed (i.e., the volume of ClosureTurf aggregate infill transported by runoff will typically be small and often negligible relative to the volume of sediment transported by runoff from a traditional soil cover system). As a reference, Appendix E presents a parametric study comparing pond design for traditional soil cover versus the ClosureTurf final cover system.

6. Hydraulic Stability of Aggregate Infill

The specified aggregate infill is one of the three components of ClosureTurf. The infill serves as a protective layer for the turf and geomembrane components. While the turf and geomembrane components are not directly sensitive to hydraulic forces, washout of the aggregate infill layer can increase exposure of the turf and geomembrane to puncture stresses, ultraviolet (UV) degradation, and wind uplift.

Washout of the aggregate infill can occur when raindrops dislodge individual aggregate particles (i.e., splash erosion), when planar flow concentrations during a storm impose hydraulic shear stresses high enough to mobilize the infill (i.e., sheet erosion), or when a combination of the two mechanisms occurs.

This chapter presents evaluation methods and performance requirements for the aggregate infill based on an extensive testing program to establish allowable shear stresses, material specification requirements, recommended design methods to compare calculated shear stresses with allowable ones, and the selection of an alternative infill in case calculated shear stresses exceed allowable ones.

This chapter is limited in scope to areas of a ClosureTurf installation that receive sheet flow or shallow concentrated flow. It is considered best practice to use supplemental/alternative infill materials in ClosureTurf concentrated flow channels, as discussed in Section 5.2.3.

6.1. <u>Hydraulic Testing and Performance Specifications</u>

Hydraulic stability of aggregate infill has been independently tested by TRI Environmental (TRI) and the Civil Infrastructure Testing and Evaluation Lab (CITEL), two third-party laboratories, in general accordance with ASTM D 6460, *Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion*, and ASTM D 6459, *Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall-Induced Erosion.* A summary of the aggregate infill testing program and results and the development of the aggregate infill specification based on the test results is provided as Appendix F.

The ClosureTurf Aggregate Infill Specification is available at Watershed Geo's online technical library. The aggregate infill must meet criteria for fine aggregate angularity, specific gravity, and particle size distribution. When the aggregate infill meets material specifications, the permissible hydraulic shear stress of the aggregate infill is suggested to be 0.8 psf for standard density turf (i.e. CT, CT X and CT HF) or 1.5 psf for high density turf (CT HD).

6.2. Suggested Method for Calculating Hydraulic Shear Stress

For design, the calculated hydraulic shear stresses for a ClosureTurf installation should be less than the suggested permissible hydraulic stresses for the aggregate infill, as indicated above. The example calculations included as Appendix G provide a suggested method to estimate the hydraulic shear stress on ClosureTurf using widely accepted engineering methods such as those presented in HEC 22, Urban Drainage Design Manual (FHWA 2009). Two different hydraulic shear stress calculations are presented in the appendix, differentiated by location and the choice of geomembrane used in ClosureTurf. Typically, multiple drainage paths are evaluated to establish a maximum anticipated hydraulic shear stress for design. If the calculated maximum hydraulic shear stress exceeds the permissible value, mitigation options include flattening the slope, shortening drainage lengths (e.g., addition of a drainage bench), and using infill with a higher permissible shear stress (e.g., HydroBinder, as discussed in Chapter 5).

Based on Watershed Geo's experience, it is suggested that the maximum drainage length on a typical landfill slope (e.g., 3H:1V or 4H:1V) be limited to the drainage length calculated using the permissible aggregate infill hydraulic shear stress of 0.8 psf for CT, CT X and CT HF (1.5 psf for CT HD) or 350 ft, whichever is smaller, or an alternative length as determined appropriate by the design engineer. Depending on the size of drainage area of the landfill top deck, a stormwater diversion berm is also suggested to separate top deck runoff and the runoff from the side slope. The diversion berm is intended to reduce the amount of runoff on the side slope, as well as mitigate potential localized aggregate infill movement resulting from geometry change and surface irregularities due to imperfections during construction and differential landfill settlement along the crest line.

7. Landfill Gas Management

For waste containment facilities that contain organic waste materials and generate gas (e.g., MSW landfills), a landfill gas management system should be considered to control gas emissions from these facilities in accordance with regulatory requirements on landfill closure and gas emissions. This chapter provides general design considerations of the landfill gas management system associated with ClosureTurf.

7.1. ClosureTurf Gas Management

Due to the light weight of ClosureTurf compared to a soil cover, ClosureTurf is susceptible to uplift caused by landfill gas pressure buildup underneath the cover system. The design of a gas-generating landfill closed with ClosureTurf should include a landfill gas management plan to prevent gas uplift of ClosureTurf. The design engineer should evaluate the site conditions and regulatory requirements to determine whether a passive landfill gas venting system or an active landfill gas collection and control system (GCCS) is required. For landfills that allow free venting of gas, passive gas vents (PGVs) should be considered to relieve gas pressure under ClosureTurf. For landfills where an active gas collection system is required, pressure relief valves (PRVs) should be considered in combination with the active gas collection system to provide gas pressure relief in case of system malfunction, such as a flare shutdown. Details of the PGV and PRV developed by Watershed Geo for use with ClosureTurf can be found at Watershed Geo's online technical library. Figure 7-1 is a photo of a ClosureTurf PRV installed in the field.

Figure 7-1. ClosureTurf Pressure Relief Valve (PRV) Installed in Field

The ClosureTurf PRV is designed with an internal one-way check valve that closes under the vacuum applied to the GCCS and opens under positive gas pressure accumulated beneath the geomembrane of ClosureTurf. Based on laboratory flow test results, the suggested design maximum gas flow rate for each PRV is 50 standard cubic feet per minute (scfm) under a pressure differential equal to one inch of water column.

PRVs are typically installed at a minimum density of one per acre of installed ClosureTurf. However, the design engineer should evaluate whether additional PRVs are necessary based on a site-specific landfill gas generation rate analysis, for example, using the Landfill Gas Emissions Model (LandGEM) developed by USEPA (USEPA 2005) and taking into account the field measurements of landfill gas flow rates, if available.

7.2. Integration with Gas Management System

A conventional active landfill GCCS consists of vertical gas extraction wells, gas collection wellheads, lateral and header gas collection pipes, condensate sumps, gas blowers, and flare stations. ClosureTurf has been installed at landfills with the conventional active GCCS, as shown in Figure 7-2.

Figure 7-2. ClosureTurf Integrated with Landfill Gas Collection System

Geomembrane boots are used to seal penetrations around gas collection wellheads and pipes. An example pipe penetration detail is available at Watershed Geo's online technical library. Gas collection pipes can be installed either above or below the ClosureTurf cover system. Table 7-1 summarizes the advantages and disadvantages of these two installation options for the design engineer to consider.

Table 7-1. Advantages and Disadvantages of GCCS Pipe Installation Options

Above ClosureTurf System		Below ClosureTurf System	
Advantages	Disadvantages	Advantages	Disadvantages
No or fewer pipe penetrations	Pipes exposed to weather, including freeze-thaw and thermal expansion/ contraction	Pipes protected from weather by the ClosureTurf system	Possible leak points created by pipe penetrations
Increased ability to inspect, repair, or upgrade piping	More visible; aesthetics may be a consideration	Pipes concealed beneath the ClosureTurf system	More difficult to inspect, repair, or upgrade pipes
Less expensive to install	Potential damage due to external loads (e.g., traffic)	Less susceptible to damage due to external loads (e.g., traffic)	More expensive to install

7.3. Surficial Gas Collection System

Watershed Geo has developed a surficial gas collection system to use with ClosureTurf installations (Figure 7-3). This system consists of surficial gas collection wellheads, gas collection strips, and PRVs. The collection strips may consist of Super GripNet, single-sided geocomposite, or other materials that facilitate the lateral flow of gas. The system allows a vacuum to be applied to the wellhead to extract the gas from the surface below the geomembrane of ClosureTurf.

The locations of the surficial gas collection strips and wellheads should be established by the design engineer in the landfill gas management plan. If the surficial gas collection system is connected to a conventional GCCS with vertical gas extraction wells, it is recommended that automatic isolation of the surficial gas collection system be incorporated in the design to prevent potential backflow of landfill gas during a flare shutdown event.

Details of the surficial gas collection system, including the surficial gas collection wellhead detail not shown on Figure 7-3, are available at Watershed Geo's online technical library.

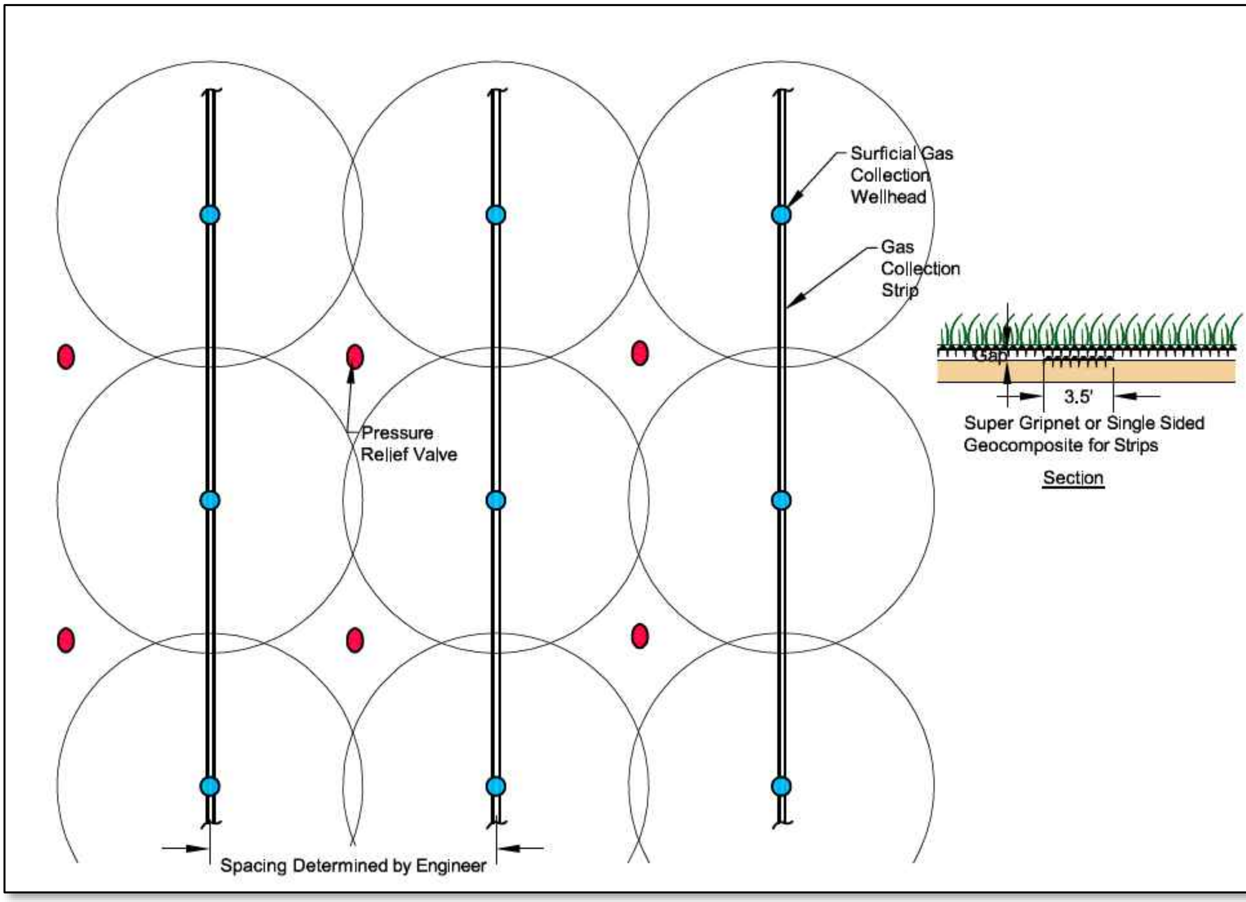

Figure 7-3. Illustration of ClosureTurf Surficial Gas Collection System

8. ClosureTurf Performance Equivalency

This chapter compares the performance of ClosureTurf with USEPA-prescribed minimum design requirements for final cover systems at MSW landfills and coal combustion residuals (CCR) units. This comparison is presented in terms of reduction in infiltration through the cover system and erosion resistance.

8.1. Regulatory Requirements

USEPA has established minimum requirements for the management of MSW landfills through Title 40 Code of Federal Regulations (CFR) Part 258, commonly referred to as Resource Conservation and Recovery Act (RCRA) Subtitle D requirements. 40 CFR §258.60(a) requires that the final cover system be designed and constructed to meet the following criteria:

(1) *Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} centimeters per second (cm/sec), whichever is less, and*

(2) *Minimize infiltration through the closed MSW landfill unit by the use of an infiltration layer that contains a minimum of 18 inches of earthen material, and*

(3) *Minimize erosion of the final cover by the use of an erosion layer that contains a minimum of 6 inches of earthen material that is capable of sustaining native plant growth.*

For closure of coal combustion residuals (CCR) units (e.g., CCR landfills and surface impoundments), the USEPA prescribes minimum final cover system requirements under 40 CFR §257.102(d)(3)(i), which are similar to those for MSW landfills.

Many state regulations adopt the federal requirements for final cover systems. Furthermore, the Federal and state regulations allow for the use of alternative final cover systems, provided it can be demonstrated that the performance of the alternative system is equivalent to or better than the prescriptive final cover system, for example, as stated under 40 CFR §258.60(b) and 40 CFR §257.102(d)(3)(ii). The following sections present methods to demonstrate that ClosureTurf is equivalent to the final cover systems prescribed by the regulations, both in terms of reduction of infiltration through the cover system and erosion resistance.

8.2. Infiltration Reduction Equivalency

The hydrologic performance of ClosureTurf has been evaluated using the HELP model to demonstrate its equivalency to the prescribed minimum design requirements in federal regulations and similar state regulations. Table 8-1 provides typical parameters for modeling the components of ClosureTurf in the HELP model.

Table 8-1. Typical Material Properties for ClosureTurf Used in HELP Model

Component	Thickness	HELP Material Texture # (1)	Hydraulic Conductivity	HELP Layer Type
Engineered Turf (2)	0.5 in (2)	2	2.5×10^{-2} cm/sec (3)	Vertical Percolation Layer
Studded Drainage Layer for Geomembrane	130 mil (0.13 in)	20	Varies (4,5)	Lateral Drainage Layer
Geomembrane	40 to 50 mil (0.04 to 0.05 in)	35	2.0×10^{-13} cm/sec (6)	Flexible Membrane Liner

Notes:

1. The HELP material texture numbers are typically used in the HELP model for the default values of total porosity, field capacity, and wilting point.
2. The engineered turf component and thickness represent the combination of the synthetic turf and aggregate infill. A larger thickness of 0.6 in may also be used to consider the approximate thickness of the geotextile backing.
3. The hydraulic conductivity is based on a typical value for sand.
4. The hydraulic conductivity of the drainage layer is calculated using the transmissivity of the studded geomembrane divided by its thickness. Based on the laboratory test results included in Appendix G, the transmissivity of the studded geomembrane (MicroDrain or Super Gripnet) is a function of hydraulic gradient: $\theta = 2.542 \times 10^{-3}/i^{0.376}$, m^2/sec, where i is the hydraulic gradient, for example, for a 3H:1V slope, i ≈ 33% or 0.33. To calculate the hydraulic conductivity of the drainage layer in the unit of cm/sec, the calculated transmissivity needs to be converted to cm^2/sec and the thickness of the studs needs to be converted to cm (i.e., from 0.13 in to 0.33 cm).
5. The hydraulic conductivity of the drainage layer may be reduced to account for creep, intrusion, and/or clogging expected under long-term conditions.
6. The hydraulic conductivity of the geomembrane represents a typical value from manufacturers.

A commonly used approach to demonstrate a reduction in infiltration rates is to evaluate the ratio of the calculated annual infiltration rate through ClosureTurf to the rate through the prescriptive final cover system. Multiple case studies examined by Carlson et al. (2019) have demonstrated the infiltration rate through ClosureTurf is much less than or equivalent to the calculated infiltration rates through final cover systems meeting the prescriptive minimum design requirements. A similar infiltration equivalency demonstration for ClosureTurf can be performed for a landfill site based on the site-specific conditions and the prescriptive soil cover requirements by the state where the landfill is located, as a part of the permit application package.

8.3. Erosion Resistance Equivalency

The prescribed final cover systems rely on establishing and maintaining vegetative cover to provide erosion resistance. When adequate vegetation is not established, either during the period soon after closure completion or on a seasonal/long-term basis (e.g., droughts, etc.), maintenance is necessary to repair and reseed the eroded area; and this could result in poor runoff water quality and dusty conditions until proper vegetation is established.

ClosureTurf is different from vegetated soil covers because its manufactured/specified properties have been developed to be inherently erosion-resistant, and the system is effective upon completion of installation, without a lengthy period to establish vegetation. The synthetic engineered turf and aggregate infill have been shown through laboratory testing (and verified by field performance) to provide excellent resistance to wind and water erosion. When ClosureTurf is designed in accordance with the recommendations provided in this Design Guidance (e.g., related to hydraulic and wind uplift considerations) and installed properly, it is expected to provide equivalent or superior water and wind erosion resistance to vegetated final cover systems, thus reducing the need for post-closure maintenance and repairs.

As another indicator of superior erosional performance in terms of runoff quality, the lack of fine-grained soil materials in the ClosureTurf infill makes the system less susceptible to erosion-induced suspension of solids and related migration of sediment particles. For example, a case study from De Abreu and Franklin (2014) measured a turbidity of 11 nephelometric turbidity units (NTU) for the runoff from ClosureTurf, whereas runoff generated from a clayey cover soil at the same site produced a turbidity of 371 NTU.

9. ClosureTurf Design Life

This chapter discusses the UV longevity and the projected design life of ClosureTurf.

9.1. Longevity of System Components

Longevity of ClosureTurf depends on the longevity of individual components (i.e., structured geomembrane, engineered turf, and specified aggregate infill). Because the geomembrane is covered by the engineered turf and specified infill, the unexposed geomembrane has an anticipated service life of at least 200 years under most climate conditions (Koerner et al. 2011; Scholl et al. 2023). The engineered turf geotextile backing has an expected service life greater than 100 years, provided it remains covered with the specified infill (Gobla 2014; Scholl et al. 2023). The specified infill will not degrade appreciably from weathering for centuries. The most critical ClosureTurf component with respect to longevity is the exposed engineered turf fibers forming the “grass” matrix that hold the specified infill in place.

9.2. Service Life Projection of Turf Fibers

A multi-year testing program was instituted to evaluate the service life of the engineered turf fibers. Outdoor weathering testing was initially conducted on samples of turf fibers placed at the test field of Atlas Material Testing Solutions located in New River, Arizona. Samples of the weathered turf fibers after approximately 1, 5, 7 and 10 years of exposure were sent to a geosynthetics laboratory and tested for remaining tensile strength. The results were independently reviewed by a third-party consulting firm (Geosyntec 2015) and the evaluation report is provided in Appendix H. Based on the evaluation results, the half-life of the turf fibers was projected based on semi-log linear extrapolation to be more than 100 years (Figure 9-1). As noted in the report, the service life of the turf fibers was expected to be much longer than the projected half-life.

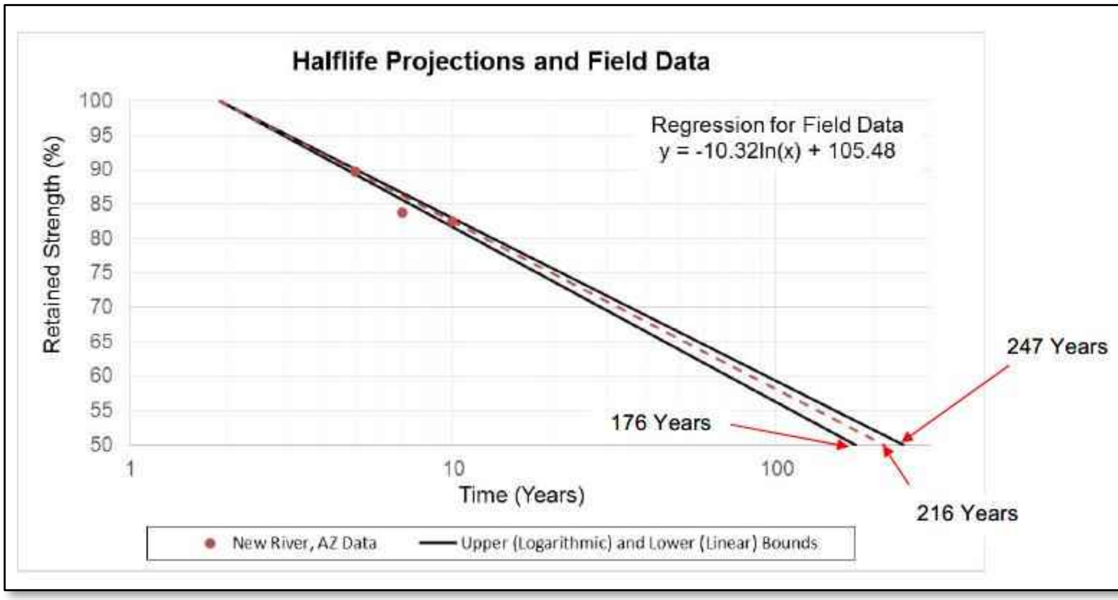

Figure 9-1. Half-Life Projection of Turf Fibers of ClosureTurf (Geosyntec 2015)

Subsequently, field samples of the turf fibers were collected from multiple sites to evaluate the real-world performance. In addition, an accelerated natural weathering program has been undertaken on samples of the turf fibers at the same Atlas facility in Arizona using Fresnel Solar Collectors. The accelerated results equivalent up to 21 years of UV exposure have been obtained to date. The 2015 UV longevity evaluation report has been updated to incorporate the new test results (Geosyntec 2022). The updated evaluation report is provided in Appendix H.

The new data from the real-world field and accelerated weathering test results are plotted in Figure 9-2, along with the data points from the initial 10-year weathering test and projected trend lines. The new data points clearly support the projected half-life of more than 100 years for the turf fibers, as most of them are above the projected trend lines.

The accelerated weathering testing is still ongoing. The projection plot will be updated once additional data points beyond the equivalent 21-year become available.

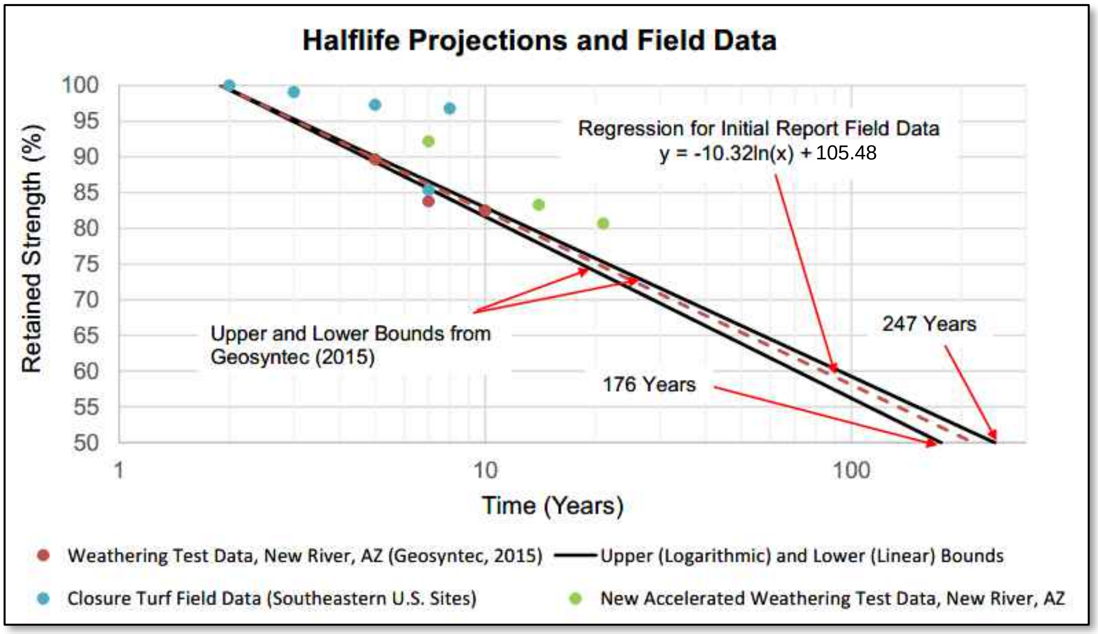

Figure 9-2. Half-Life Projection of Turf Fibers of ClosureTurf with Additional Field and Accelerated Weathering Data (Geosyntec 2022)

9.3. Summary

Based on the results of field samples and weathering test results, ClosureTurf is projected to have a design life, represented by the service life, of 100 years or longer, provided it is installed and maintained appropriately in accordance with engineering design drawings, technical specifications, and post-closure care procedures.

10. Other Considerations

This chapter addresses several considerations for design of ClosureTurf cover systems not discussed in previous chapters. These other considerations are:

- Settlement
- Thermal effects
- Impact of animals
- Resistance to fire and lightning
- Measures to prevent vandalism
- Post-closure care
- Beneficial use for solar development

10.1. Settlement

ClosureTurf is a light-weight cover system with an average weight on a unit area of approximately 5 psf, compared to approximately 240 psf or more for a typical soil cover system. As a result, installation of ClosureTurf induces significantly less additional settlement of the underlying waste mass than installation of the traditional soil cover system. Since the waste is usually inhomogeneous, differential settlement may occur over time after the landfill is closed. The differential settlement may result in tension in the final cover system, causing a soil cover to crack. Unlike the soil cover, ClosureTurf is made of flexible geosynthetic materials, which can tolerate relatively large differential settlements. The settlement can be estimated during the design using one-dimensional consolidation equations coded in a calculation spreadsheet or commercially available computer software.

The differential settlement may cause grade reversal and hence, localized ponding of rainwater, which needs to be repaired as part of post-closure maintenance. Repair of depressions is straightforward for ClosureTurf because there is no excavation of thick soil layers. One repair approach with ClosureTurf is to cut one or more holes at the location of the depression. Flowable backfill (usually a mix of fly ash, cement, and water) is then pumped into the depressed area to raise “subgrade” for the ClosureTurf to its original grade. After mitigating settlements, the holes in the geomembrane are patched and seamed with new pieces of geomembrane; the engineered turf is repaired using a heat-bonded seam; and aggregate infill is replaced to cover the repaired area.

10.2. Thermal Effects

Stress cracks of geomembrane can result from relatively large temperature changes over a brief duration and from other causes. Stress cracking of the structured geomembrane component of ClosureTurf was evaluated using the *Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test* (ASTM D5397). For example, the product specification sheets for 50-mil HDPE Super GripNet and MicroDrain report stress crack resistance at more than 500 hours based on testing in accordance with ASTM D5397, which meets the minimum acceptable resistance for geomembranes per GRI-GM13 (GSI 2016).

Results of freeze-thaw tests ranging from -20 to +30 degrees Celsius (°C) (Comer et al. 1996) indicated "neither geomembrane sheets nor their associated seams were adversely affected." The performance of the geomembrane component of ClosureTurf with respect to freeze-thaw cycling is expected to be similar to the performance of geomembranes in the Comer et al. (1996) study.

Similar to other HDPE and LLDPE geomembranes, ClosureTurf should typically not be installed at ambient temperatures below 35°F or above 104°F. If ClosureTurf is planned for installation outside the above-mentioned temperature range, it should be demonstrated before installation that the integrity of the geomembrane is not affected by the weather conditions (USBR 2014).

Wrinkles could form during installation of ClosureTurf due to thermal expansion. HDPE geomembranes typically have a higher coefficient of thermal expansion than LLDPE geomembranes (Scheirs 2009). Best wrinkle management practices, including but not limited to acclimation of geomembrane to ambient temperatures and "snapping" of geomembrane to reduce excess slack, should be implemented during installation to minimize wrinkles.

Wrinkling is a dynamic process and may continue due to temperature fluctuations after installation of ClosureTurf. Small wrinkles may migrate downslope due to gravity and thermal cycling over time, forming larger wrinkles in or near drainage swales on side slopes, if any, and perimeter channels at the toe of side slopes. Wrinkles may affect the aesthetics of ClosureTurf; however, wrinkles themselves generally do not have adverse impacts on the overall performance of ClosureTurf in terms of infiltration reduction, erosion resistance, and final cover structural integrity. Therefore, wrinkles of ClosureTurf observed after closure usually do not require repairs, unless desired by the site owner for aesthetic reasons. If the aggregate infill is displaced from the top of a wrinkle, resulting in exposed geotextile backing, new aggregate infill should be placed to cover the exposed geotextile backing. A binding agent, such as the cementitious HydroBinder® or the polyurethane-based DuraGuard™ can be used to keep the aggregate infill in place on top of a wrinkle.

After installation, temperature changes may cause the ClosureTurf system to contract and develop tensile stresses. Calculations of factors of safety against pull-out can be performed, as determined by the design engineer, to evaluate whether these tensile stresses may cause the cover system to pull out of perimeter anchor trenches. Appendix I provides an example calculation for pull-out resistance for one potential design scenario.

In cold climate regions, freezing temperatures may cause ClosureTurf to bridge over the concave-shaped bottom of stormwater drainage swales and channels due to thermal contraction. Adding dead weight, such as crushed stone (e.g., gravel or riprap), on ClosureTurf can mitigate the bridging (also known as trampolining) effect. The drainage stone should be sized by the design engineer such that it will not be displaced by the hydraulic shear force from the concentrated flow. The properly sized and hydraulically stable drainage stone can then be used in lieu of the HydroBinder infill in the design. Best management practices, including ballasting with sandbags, should be used to help temporarily control potential bridging or trampolining during ClosureTurf installation in cold climate regions.

Watershed Geo worked with GSI to test the integrity of ClosureTurf under deep freeze conditions. No tears or punctures were observed in the structured geomembrane or engineered turf component of ClosureTurf during the deep freeze test. Appendix J presents the details of the deep freeze test. Additionally, there have been no reported observations of damage to installed ClosureTurf as a result of freezing temperatures in field conditions.

10.3. Impact of Animals

Traditional vegetated soil cover systems can provide suitable habitats for burrowing animals and birds. Burrowing animals can pose problems to the integrity and performance of traditional cover systems (Lutton et al. 1979). ClosureTurf does not include soil layers that can provide a suitable habitat for burrowing animals. Watershed Geo has not observed evidence of burrowing animal activities to date. Nonetheless, should evidence of burrowing ever be discovered, the disturbed area of ClosureTurf can be easily repaired. ClosureTurf has little attraction for birds because it does not provide a suitable habitat. However, bird damages to ClosureTurf have been observed at landfill sites where there is a working phase with food sources. The damages often occurred in localized areas around landfill gas wellheads and drainage berms, where the bird could perch. Birds appear to target the black geotextile backing of the engineered turf, not the geomembrane. For sites with a bird nuisance, the damaged turf can be repaired and infilled with HydroBinder for additional protection. Bird droppings may cause some grasses or weeds to grow on ClosureTurf in limited areas, usually in drainage swales and perimeter channels where ponded water is present due to subgrade depression. Observed grass or weeds growing at the ClosureTurf site can be readily addressed as part of site maintenance.

Hoofed animals (e.g., deer or elk) have been observed at ClosureTurf sites, but they do not inhabit these areas because no food source is present. Furthermore, there have been no reports of damage to ClosureTurf trampled by animal hoofs at these sites. The aggregate infill and engineered turf prevent direct contact of the hoofs with the underlying geomembrane and dissipate contact pressures. Estimates of maximum ground contact pressure for a typical adult hoofed animals are less than the allowable loading limits of ClosureTurf suggested by Watershed Geo. Should the geomembrane be damaged from hoofed animals, it can be repaired by replacing the geomembrane in patches and seaming.

10.4. Resistance to Fires

Grasses used on traditional cover systems are composed of organic matter that is combustible under certain climatic and seasonal conditions. Fires on vegetated covers can be ignited by natural or human-induced causes, and once started, can rapidly spread. Unlike natural grass, ClosureTurf is a synthetic product that is unlikely to propagate fires under field conditions.

To further evaluate the fire resistance of ClosureTurf, Watershed Geo conducted tests using the *Standard Test Methods for Fire Tests of Roof Coverings* (ASTM E108). When exposed to flame as prescribed by the test conditions, some damage to ClosureTurf was observed in the form of melting of the engineered turf. The underside of the Super GripNet also displayed some effects from the fire. Despite the observed damages, the geomembrane component of the cover system was not breached by fire. Furthermore, the damaged area observed during the fire resistance test was confined and the fire didn’t spread. Additional details on the setup and results of the fire resistance tests are provided in Appendix K.

10.5. Resistance to Lightning

ClosureTurf is not a conductor of electricity and therefore, is unlikely to be hit by lightning strikes. However, if lightning does strike the system and causes a fire, the damage is expected to be localized based on the observations during the fire resistance tests. Damage from lightning strikes can be repaired by patching the damaged geomembrane and engineered turf and replacing the aggregate infill.

10.6. Measures to Prevent Vandalism

Geosynthetic materials are susceptible to damage from vandalism. Although vandalism has not been observed at any ClosureTurf installation, it could potentially be vandalized, thereby affecting the performance of the system during the post-closure care period. Measures should be taken to prevent or discourage vandalism during the post-closure care period, which may include the following, as necessary:

- Use of a chain-link fence or other suitable fence along the property boundary;
- Posting of appropriate signs (e.g., no trespassing) on the fence at the entrance and within the property boundary; and/or
- Use of cameras, video surveillance, and/or motion sensors at key locations at the facility.

10.7. Post-Closure Care

Landfill post-closure care (e.g., final cover system maintenance) is required by the federal and state regulations for a minimum period of 30 years. ClosureTurf does not require significant maintenance activities in comparison to traditional soil cover systems, i.e., no mowing, fertilizing, revegetation, etc. However, regular inspection of ClosureTurf is still required to identify any damages or aggregate infill movement, followed by repairs, as necessary. The ClosureTurf Post-Closure Care Manual is available at Watershed Geo's online technical library.

10.8. Beneficial Use for Solar Development

Several landfills closed with ClosureTurf have been beneficially reused to develop solar fields for electricity generation. Compared with a traditional landfill soil cover system, the ClosureTurf system provides a stable foundation for a solar field for the following reasons:

- Less maintenance is required with ClosureTurf, which lowers the risk of damage to the solar panels from personnel and equipment.
- No vegetation overgrowth is present that may block sunlight and negatively impact power generation efficiency of the solar panels.
- Dust, which can lower the efficiency of a solar array, is less likely to be generated.
- Rainwater from the drip edge of solar panels is less likely to erode the cover system.

Watershed Geo has developed a patented solar power generation system, PowerCap™, specifically for installation on ClosureTurf. No penetrations through or mechanical connections to the ClosureTurf final cover system are required for this system. The system can be installed on landfill side slopes and top deck, maximizing power generation at the site.

More information on solar development can be found at Watershed Geo's website: https://watershedgeo.com/products/powercap/.

It should be noted that if future solar development is planned during the landfill closure, potential impact of the solar arrays on the final cover system (e.g., access roads, stormwater management, slope stability, final cover settlement, etc.) should be evaluated and incorporated into the landfill closure design.

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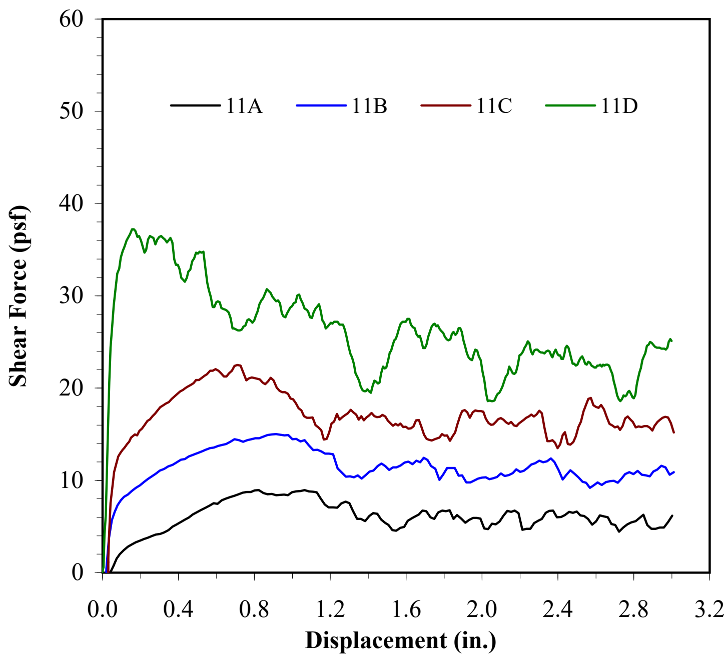
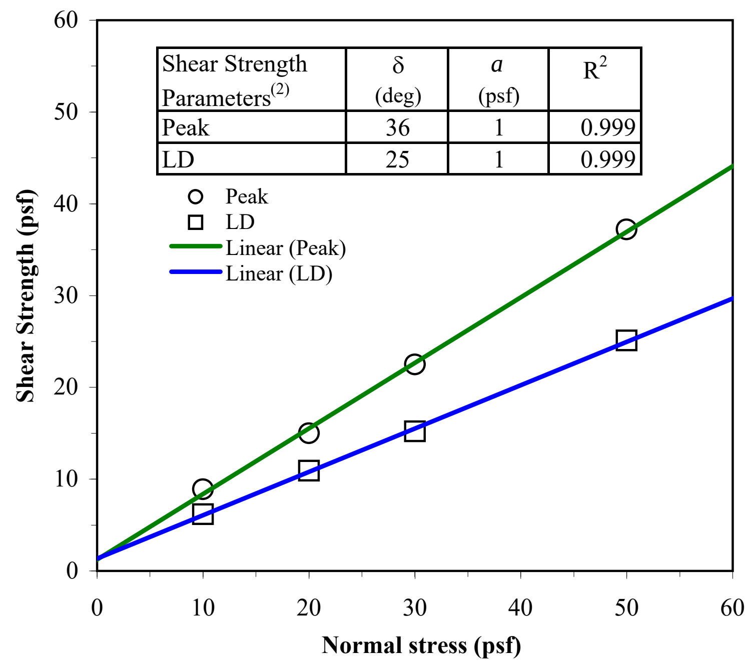
Appendix A
ClosureTurf Interface Shear Strength Test Results

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
CT32 Synthetic Turf with base geotextile side down against
Agru 50-mil Super Gripnet LLDPE geomembrane with stud side up
Lower Shear Box: Concrete sand

Note: The CT turf is denoted as the “CT32 Synthetic Turf” in this test report.





Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Soil Shear Strength ϕ (deg)	Soil Shear Strength c (psf)	Shear Strengths τ_P (psf)	Shear Strengths τ_{LD} (psf)	Failure Mode
11A	12 x 12	10	0.04	10	24	-	-	-	-	-	-	-	-	-	-	8.9	6.2	(1)
11B	12 x 12	20	0.04	20	24	-	-	-	-	-	-	-	-	-	-	15.0	10.9	(1)
11C	12 x 12	30	0.04	30	24	-	-	-	-	-	-	-	-	-	-	22.5	15.2	(1)
11D	12 x 12	50	0.04	50	24	-	-	-	-	-	-	-	-	-	-	37.2	25.1	(1)

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the geotextile side of the turf and the stud side of Agru 50-mil Super Gripnet.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

SGI TESTING SERVICES, LLC

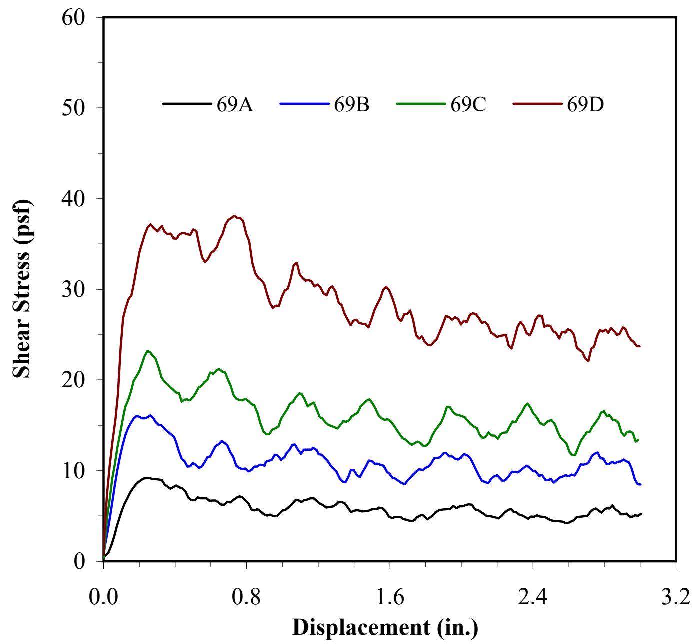
DATE OF TEST:	5/28/2019
FIGURE NO.	1
PROJECT NO.	SGI19014
DOCUMENT NO.	
FILE NO.	

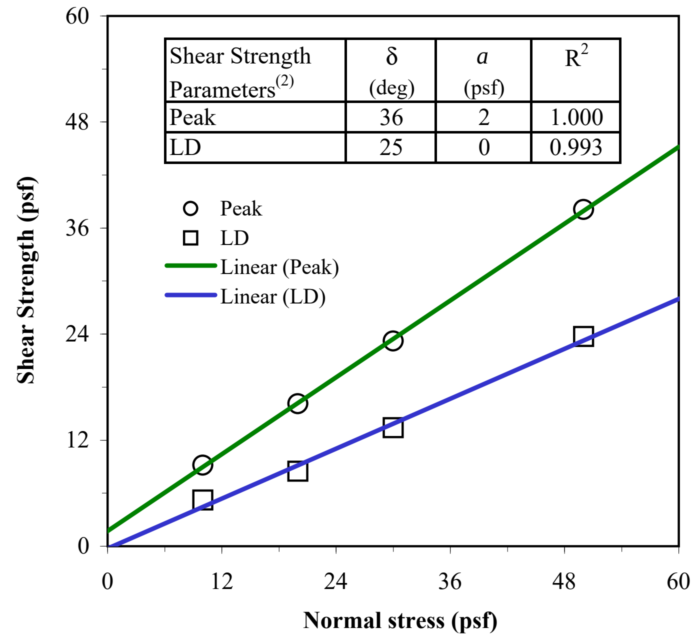
S19014-011RRRR.ds.xls

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
Synthetic turf CT-32 with base geotextile side down against
Agru 50-mil MicroDrain LLDPE geomembrane #GTA0127680003 with stud side up
Lower Shear Box: Concrete sand

Note: The CT turf is denoted as the "CT32 Synthetic Turf" in this test report.





Shear Strength Parameters[2]	δ (deg)	*a* (psf)	R^2
Peak	36	2	1.000
LD	25	0	0.993

Test No.	Shear Box Size (in x in)	Normal Stress (psf)	Shear Rate (in/min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	GCL ω_i (%)	GCL ω_f (%)	Shear Strength τ_P (psf)	Shear Strength τ_{LD} (psf)	Secant Angle δ_P (deg)	Secant Angle δ_{LD} (deg)	Failure Mode
69A	12 x 12	10	0.04	-	-	-	-	-	-	-	-	-	-	-	-	9.2	5.2	43	28	(1)
69B	12 x 12	20	0.04	-	-	-	-	-	-	-	-	-	-	-	-	16.1	8.5	39	23	(1)
69C	12 x 12	30	0.04	-	-	-	-	-	-	-	-	-	-	-	-	23.2	13.4	38	24	(1)
69D	12 x 12	50	0.04	-	-	-	-	-	-	-	-	-	-	-	-	38.1	23.7	37	25	(1)

NOTES:
(1) Sliding (i.e., shear failure) forced to occurr at the interface between the bsae geotextile side of synthetic turf and the stud side of geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test .

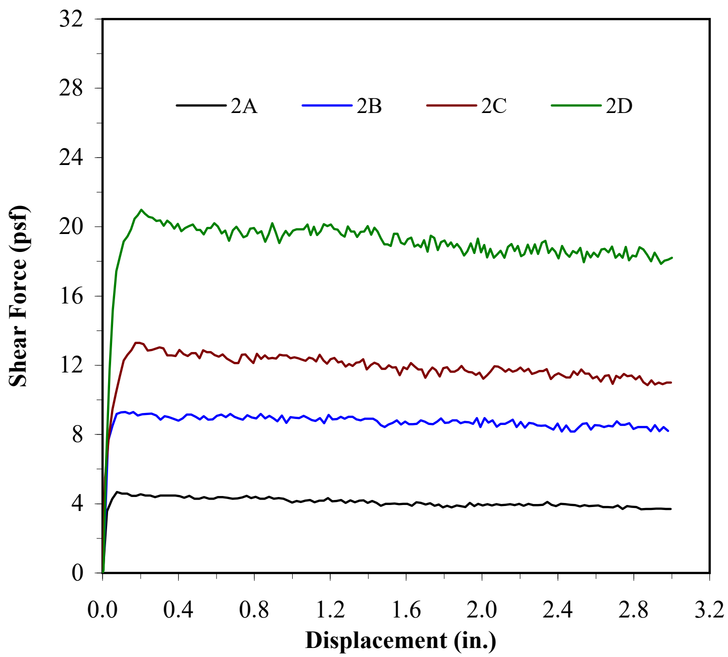
DATE OF REPORT:	12/27/2023
FIGURE NO.	1
PROJECT NO.	SGI23014
DOCUMENT NO.	
FILE NO.	

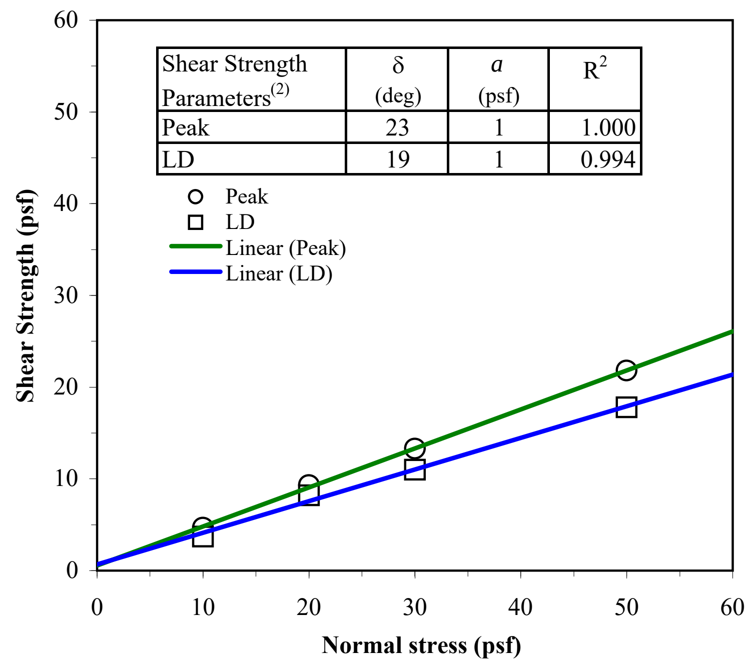
SGI TESTING SERVICES, LLC

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
CT32 Synthetic Turf with base geotextile side down against
Agru 40-mil Microspike LLDPE geomembrane with dull side up
Lower Shear Box: Concrete sand

Note: The CT turf is denoted as the “CT32 Synthetic Turf” in this test report.





Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Soil Shear Strength ϕ (deg)	Soil Shear Strength c (psf)	Shear Strengths τ_P (psf)	Shear Strengths τ_{LD} (psf)	Failure Mode
2A	12 x 12	10	0.04	10	24	-	-	-	-	-	-	-	-	-	-	4.7	3.7	(1)
2B	12 x 12	20	0.04	20	24	-	-	-	-	-	-	-	-	-	-	9.3	8.2	(1)
2C	12 x 12	30	0.04	30	24	-	-	-	-	-	-	-	-	-	-	13.3	11.0	(1)
2D	12 x 12	50	0.04	50	24	-	-	-	-	-	-	-	-	-	-	21.8	17.8	(1)

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the geotextile side of heavy closure turf and the dull side of agru 40-mil microspike LLDPE geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

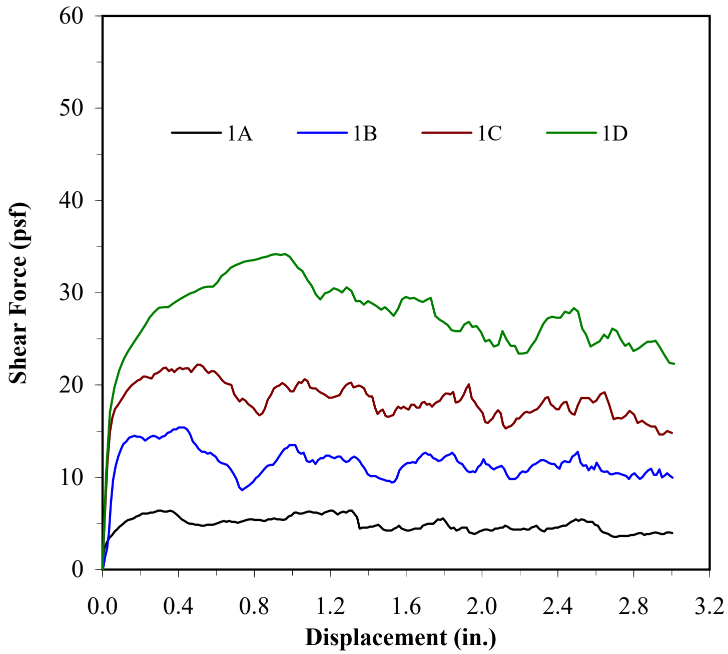
DATE OF TEST:	5/6/2019
FIGURE NO.	1
PROJECT NO.	SGI19014
DOCUMENT NO.	
FILE NO.	

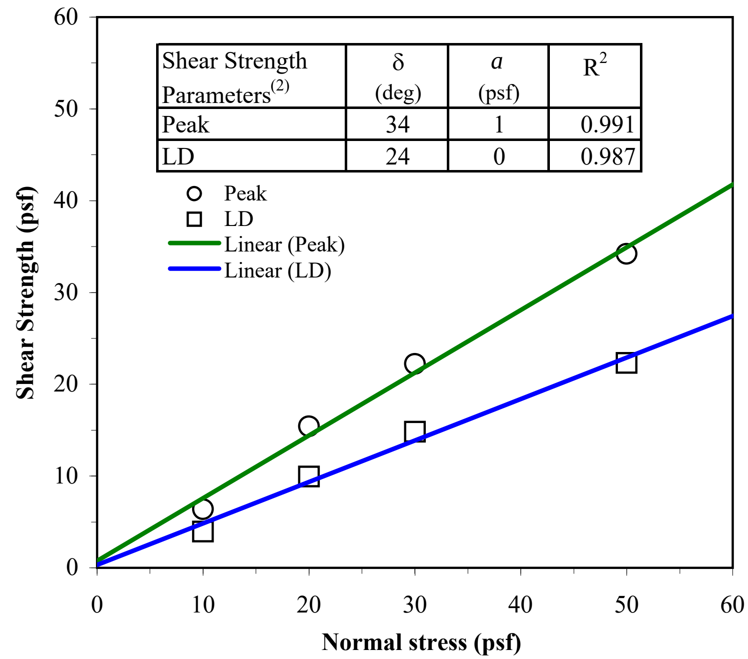
SGI TESTING SERVICES, LLC

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand /
New ClosureTurf with geotextile side down /
Agru 50-mil SuperGripnet with studs side up /
Lower Shear Box: Concrete sand

Note: The CT HD turf is denoted as the “New ClosureTurf” in this test report.





Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Soil Shear Strength ϕ (deg)	Soil Shear Strength c (psf)	Shear Strengths τ_P (psf)	Shear Strengths τ_{LD} (psf)	Failure Mode
1A	12 x 12	10	0.04					-	-	-						6.4	3.9	(1)
1B	12 x 12	20	0.04					-	-	-						15.4	9.9	(1)
1C	12 x 12	30	0.04					-	-	-						22.2	14.8	(1)
1D	12 x 12	50	0.04					-	-	-						34.2	22.3	(1)

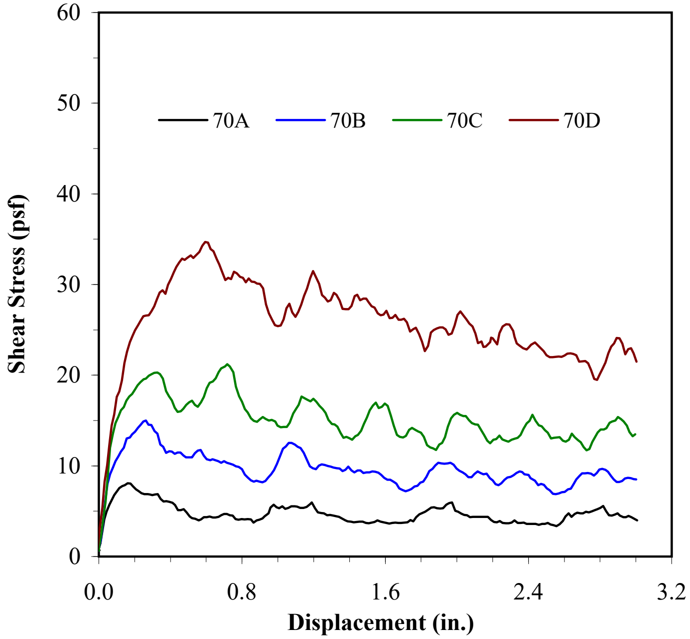
NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the base geotextile of ClosureTurf and studs side of Agru SuperGripnet geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

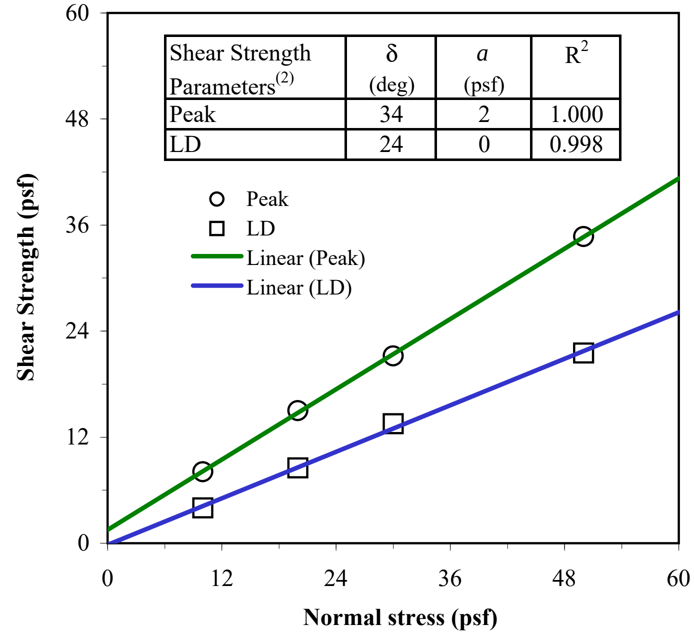
SGI TESTING SERVICES, LLC

DATE OF TEST:	6/7/2018
FIGURE NO.	1
PROJECT NO.	SGI18014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
Synthetic turf CT-HD (CT43) with base geotextile side down against
Agru 50-mil MicroDrain LLDPE geomembrane #GTA0127680003 with stud side up
Lower Shear Box: Concrete sand





Shear Strength Parameters[2]	δ (deg)	a (psf)	R^2
Peak	34	2	1.000
LD	24	0	0.998

Test No.	Shear Box Size (in x in)	Normal Stress (psf)	Shear Rate (in/min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	GCL ω_i (%)	GCL ω_f (%)	Shear Strength τ_P (psf)	Shear Strength τ_{LD} (psf)	Secant Angle δ_P (deg)	Secant Angle δ_{LD} (deg)	Failure Mode
70A	12 x 12	10	0.04	-	-	-	-	-	-	-	-	-	-	-	-	8.1	4.0	39	22	(1)
70B	12 x 12	20	0.04	-	-	-	-	-	-	-	-	-	-	-	-	15.0	8.5	37	23	(1)
70C	12 x 12	30	0.04	-	-	-	-	-	-	-	-	-	-	-	-	21.2	13.5	35	24	(1)
70D	12 x 12	50	0.04	-	-	-	-	-	-	-	-	-	-	-	-	34.7	21.5	35	23	(1)

NOTES:
(1) Sliding (i.e., shear failure) forced to occurr at the interface between the bsae geotextile side of Synthetic turf and the stud side of geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

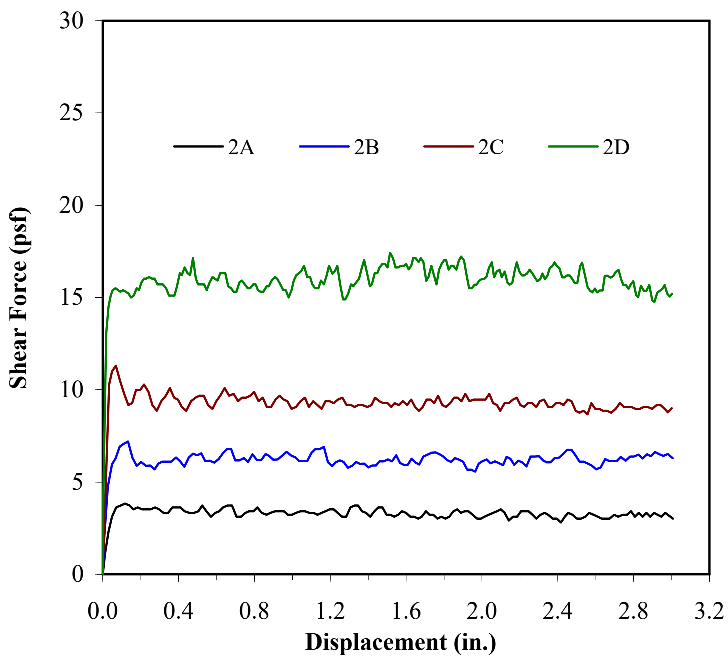
SGI TESTING SERVICES, LLC

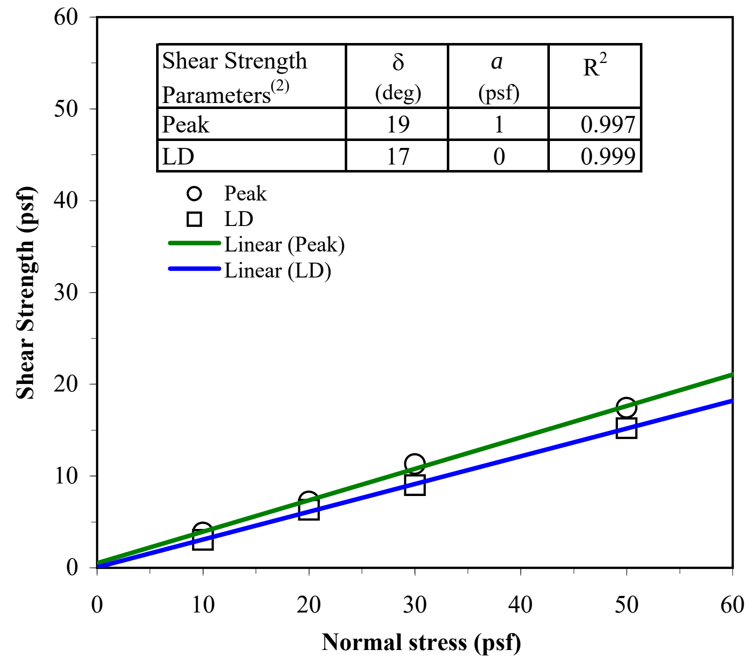
DATE OF REPORT:	12/27/2023
FIGURE NO.	2
PROJECT NO.	SGI23014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand/
New ClosureTurf with geotextile side down /
Agru 40-mil Microspike HDPE geomembrane with dull side up and shiny side down/
Lower Shear Box: Concrete sand

Note: The CT HD turf is denoted as the "New ClosureTurf" in this test report.





Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Soil Shear Strength ϕ (deg)	Soil Shear Strength c (psf)	Shear Strengths τ_P (psf)	Shear Strengths τ_{LD} (psf)	Failure Mode
2A	12 x 12	10	0.04					-	-	-						3.8	3.0	(1)
2B	12 x 12	20	0.04					-	-	-						7.2	6.3	(1)
2C	12 x 12	30	0.04					-	-	-						11.3	9.0	(1)
2D	12 x 12	50	0.04					-	-	-						17.4	15.2	(1)

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the base geotextile of ClosureTurf and dull side of Agru Microspike HDPE geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

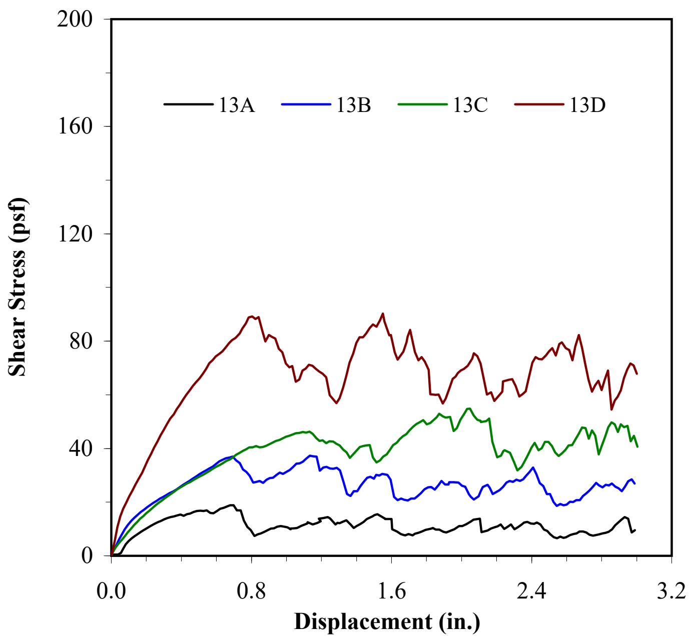
SGI TESTING SERVICES, LLC

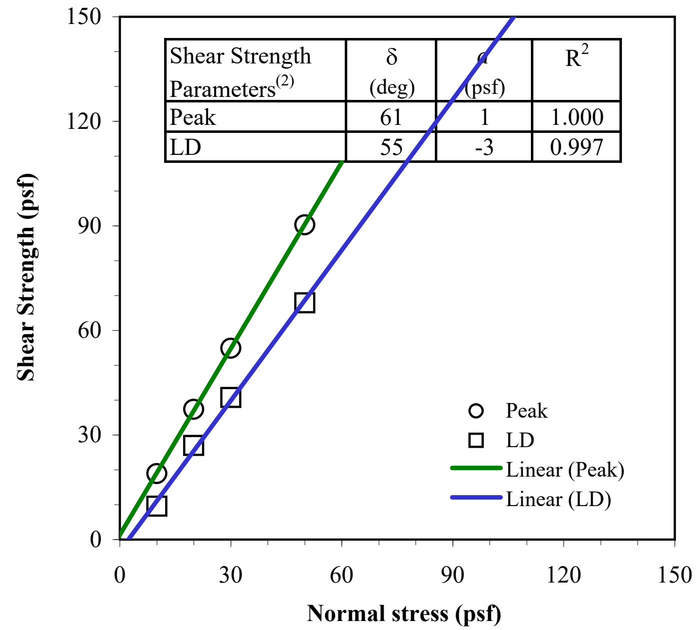
DATE OF TEST:	6/28/2018
FIGURE NO.	2
PROJECT NO.	SGI18014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
100% Vv stitch turf with approximately a 0.5" thick sand layer on top and base geotextile side down against Agru 50-mil Super Gripnet LLDPE geomembrane with stud side up
Lower Shear Box: Concrete sand

Note: The CT HF turf is denoted as the “Vv stitch turf” in this test report.





Test No.	Shear Box Size (in x in)	Normal Stress (psf)	Shear Rate (in/min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Target Soil Compaction γ_d (pcf)	Target Soil Compaction ω_i (%)	Target Soil Compaction ω_f (%)	GCL ω_i (%)	GCL ω_f (%)	Shear Strength τ_P (psf)	Shear Strength τ_{LD} (psf)	Secant Angle δ_P (deg)	Secant Angle δ_{LD} (deg)	Failure Mode
13A	12 x 12	10	0.04	-	-	-	-	-	-	-	-	-	-	-	-	18.9	9.5	62	44	(1)
13B	12 x 12	20	0.04	-	-	-	-	-	-	-				-	-	37.3	27.0	62	53	(1)
13C	12 x 12	30	0.04	-	-	-	-	-	-	-				-	-	54.9	40.7	61	54	(1)
13D	12 x 12	50	0.04	-	-	-	-	-	-	-				-	-	90.3	67.9	61	54	(1)

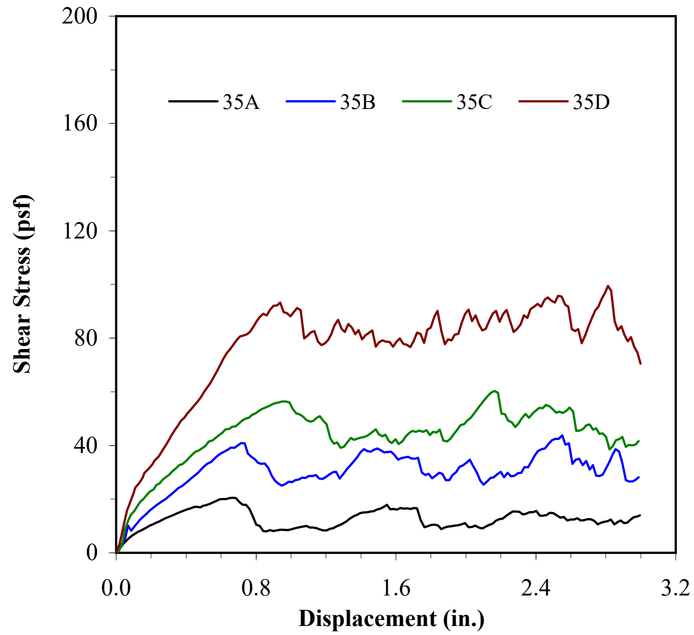
NOTES:
(1) Sliding (i.e., shear failure) forced to occurr at the interface between the base geotextile side of Synthetic turf and the stud side of Super Gripnet geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test .

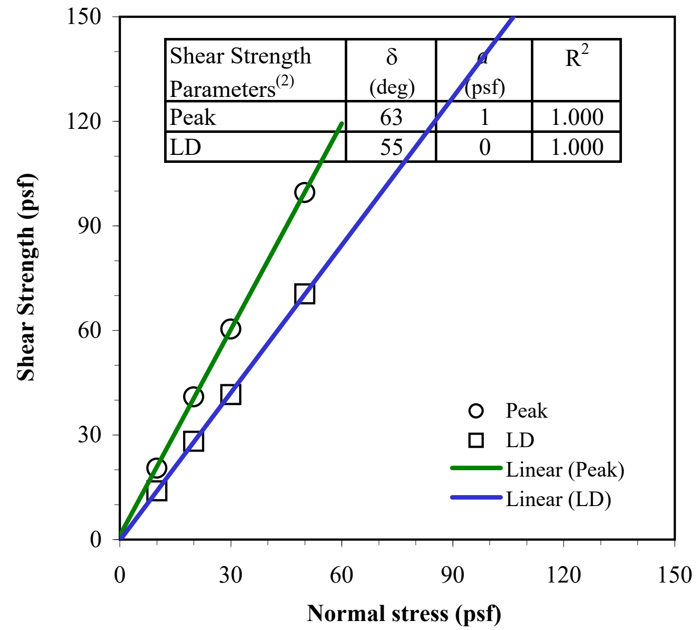
SGI TESTING SERVICES, LLC

DATE OF REPORT:	3/20/2024
FIGURE NO.	3
PROJECT NO.	SGI24014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
CT-HF turf with approximately a 0.5" thick sand layer on top and base geotextile side down against
Agru 50-mil MicroDrain LLDPE geomembrane #GTA0127680003 with stud side up
Lower Shear Box: Concrete sand





Test No.	Shear Box Size (in x in)	Normal Stress (psf)	Shear Rate (in/min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Target Soil Compaction γ_d (pcf)	Target Soil Compaction ω_i (%)	Target Soil Compaction ω_f (%)	GCL ω_i (%)	GCL ω_f (%)	Shear Strength τ_P (psf)	Shear Strength τ_{LD} (psf)	Secant Angle δ_P (deg)	Secant Angle δ_{LD} (deg)	Failure Mode
35A	12 x 12	10	0.04	-	-	-	-	-	-	-	-	-	-	-	-	20.5	13.9	64	54	(1)
35B	12 x 12	20	0.04	-	-	-	-	-	-	-				-	-	40.9	28.2	64	55	(1)
35C	12 x 12	30	0.04	-	-	-	-	-	-	-				-	-	60.4	41.6	64	54	(1)
35D	12 x 12	50	0.04	-	-	-	-	-	-	-				-	-	99.5	70.5	63	55	(1)

NOTES:
(1) Sliding (i.e., shear failure) forced to occurr at the interface between the base geotextile side of Synthetic turf and the stud side of MicroDrain geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test .

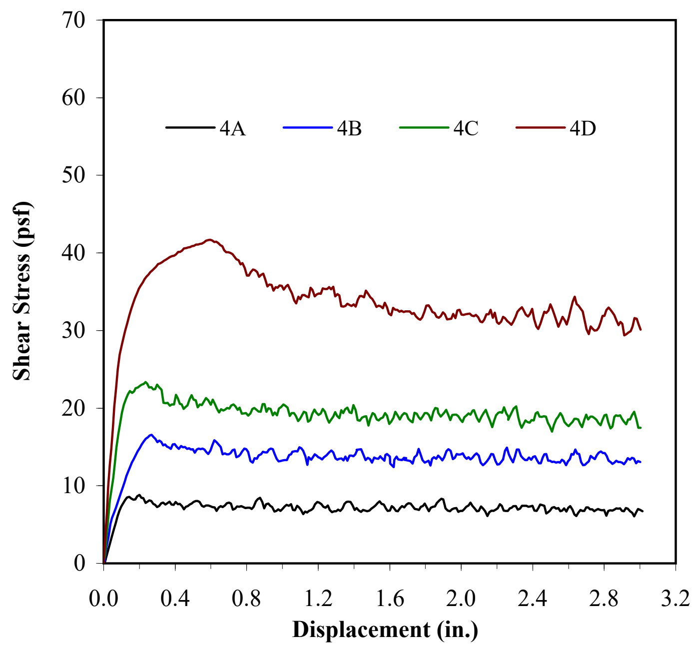
SGI TESTING SERVICES, LLC

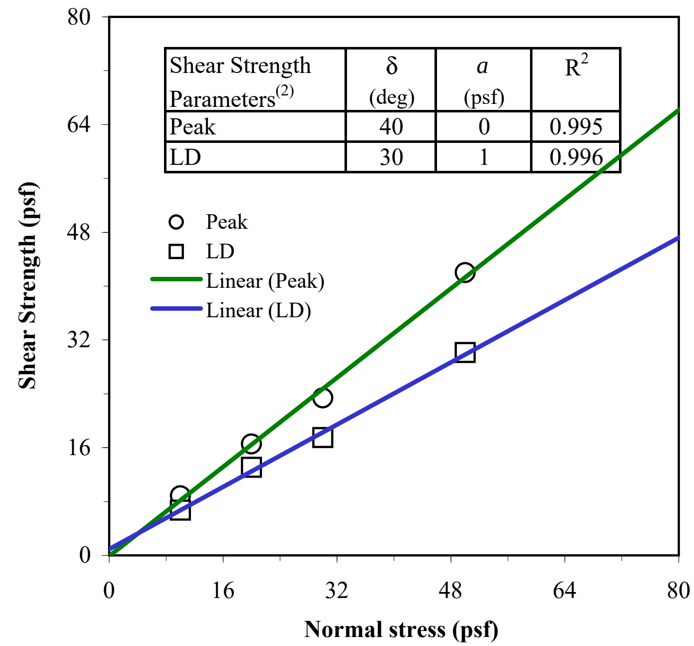
DATE OF REPORT:	3/28/2024
FIGURE NO.	1
PROJECT NO.	SGI24014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC
INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
Synthetic turf (VV Stitch) with base GT side down against
Agru 40-mil Microspike LLDPE GM with dull side up (shear in the weak direction)
Lower Shear Box: Concrete sand

Note: The CT HF turf is denoted as the "Synthetic Turf (VV Stitch)" in this test report.





Test No.	Shear Box Size (in x in)	Normal Stress (psf)	Shear Rate (in/min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	GCL ω_i (%)	GCL ω_f (%)	Shear Strength(2) τ_P (psf)	Shear Strength(2) τ_{LD} (psf)	Secant Angle δ_P (deg)	Secant Angle δ_{LD} (deg)	Failure Mode
4A	12 x 12	10	0.04	-	-	-	-	-	-	-	-	-	-	-	-	8.8	6.7	41.4	33.8	(1)
4B	12 x 12	20	0.04	-	-	-	-	-	-	-	-	-	-	-	-	16.6	13.1	39.6	33.2	(1)
4C	12 x 12	30	0.04	-	-	-	-	-	-	-	-	-	-	-	-	23.4	17.5	37.9	30.2	(1)
4D	12 x 12	50	0.04	-	-	-	-	-	-	-	-	-	-	-	-	42.0	30.1	40.0	31.0	(1)

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the base geotextile of synthetic turf and the dull side of microspike geomembrane.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test .

SGI TESTING SERVICES, LLC

DATE OF REPORT:	3/30/2021
FIGURE NO.	2
PROJECT NO.	SGI21014
DOCUMENT NO.	
FILE NO.	

Appendix B
Example Calculation for ClosureTurf Veneer Slope Stability

EXAMPLE CALCULATION FOR CLOSURETURF VENEER SLOPE STABILITY

PURPOSE

This example calculation evaluates the veneer stability of a ClosureTurf installed as a final cover system for a hypothetical landfill. The analysis presented herein is based on the procedure presented in Chapter 9 of the document titled "*Geotechnical and Stability Analyses for Ohio Waste Containment Facilities*" published by the State of Ohio Environmental Protection Agency (OEPA 2004).

It is noted that the approaches presented in this appendix are for reference purposes. The design engineer may choose other commonly accepted approaches to evaluate the veneer slope stability of ClosureTurf.

METHODOLOGY

Static and Seismic Veneer Slope Stability

Slope stability of a final cover system can be evaluated based on infinite slope or finite slope methods. The infinite slope method considers an infinite slope length whereby driving and resisting forces occur only parallel to an interface (i.e., slip plane). The finite slope method considers a slope of finite length and additionally accounts for the toe-buttressing effect. For this example calculation, static and seismic slope stability analyses of the ClosureTurf system is performed using an infinite slope method developed by Matasovic (1991). This method was selected because of the simplicity of its equation.

$$FS = \frac{\frac{a}{\gamma_c\, z_c\, cos^2\beta} + \tan\delta\left(1 - \frac{\gamma_w\,(z_c - d_w)}{\gamma_c\, z_c}\right) - k_s \tan\beta \tan\delta}{k_s + \tan\beta}$$

where:

FS	=	factor of safety;
β	=	slope inclination angle;
δ	=	friction angle along the critical slip surface;
a	=	adhesion intercept along the critical slip surface;
z_c	=	depth of the critical slip surface measured from the top of final cover (i.e., thickness of aggregate infill);
γ_c	=	unit weight of aggregate infill;
γ_w	=	unit weight of water = 62.4 pcf;
d_w	=	depth to water surface measured from the top of final cover (i.e., $z_c - h_{avg}$); and
k_s	=	seismic coefficient.

Target Factors of Safety

Target factors of safety of 1.5, 1.3, and 1.0 for long-term static, temporary static, and seismic conditions, respectively, are typically considered for veneer stability of a landfill final cover system. However, the design engineer should select the appropriate target factors of safety in accordance with project requirements, standard engineering practices, and/or regulatory requirements, as applicable.

Hydraulic Head on Geomembrane

The average hydraulic head acting on the geomembrane is computed using equations presented in OEPA (2004). These equations are:

$$h_{avg} = \frac{P\,(1 - RC)L\,(\cos\beta)}{k_d\,(sin\,\beta)}$$

or if $P\,(1 - RC) > k_c$, use:

$$h_{avg} = \frac{k_c\,L\,(\cos\beta)}{k_d\,(sin\,\beta)}$$

or if h_{avg} from the above calculation is greater than T_d then use: $h_{avg} = T_d + T_c$

Where:

h_{avg}	=	average hydraulic head;
P	=	precipitation;
β	=	slope inclination angle;
L	=	slope length;
T_c	=	thickness of cover soil (i.e., aggregate infill);
RC	=	runoff coefficient (SCS Runoff Curve Number/100);
k_d	=	hydraulic conductivity of drainage layer;
T_d	=	thickness of drainage layer; and
k_c	=	hydraulic conductivity of cover soil (i.e., aggregate infill).

Selection of Seismic Coefficient

The seismic coefficient (k_s) represents the seismic loading as a static horizontal destabilizing force within the pseudo-static framework. It should correspond to a design seismic hazard level satisfying regulatory seismic requirements and/or project design criteria (e.g., two percent probability of exceedance in 50 years for a landfill design). An appropriate seismic coefficient can be selected by following either a commonly accepted simplified procedure (e.g., Chapter 4 of Richardson et al. [1995] or Bray et al. [1998]) or a more technically robust procedure (e.g., using site-specific ground response analyses), as determined by the project design engineer. Note that for veneer stability of a landfill final cover, the seismic coefficient should be estimated at the final cover, which accounts for local site effects and wave propagation through waste.

Veneer Slope Stability with Equipment Load

Slope stability of the ClosureTurf system with equipment load can be evaluated using a similar approach (i.e., infinite slope method) as presented above. The weights of the ClosureTurf system and equipment as well as a dynamic load from equipment acceleration or deceleration act as driving forces, while the adhesive and frictional interface shear strengths of the ClosureTurf system provide resisting forces. The factor of safety is calculated as the ratio of the resisting forces to the driving forces:

$$FS_{equip} = \frac{F_a + F_r}{(W_s + W_v) \cdot \sin(\beta) + F_d}$$

where:

F_a	=	adhesive resistance along the critical slip surface;
F_r	=	frictional resistance along the critical slip surface;
F_d	=	dynamic equipment force along the slope surface;
W_s	=	weight of ClosureTurf;
W_v	=	weight of equipment; and
β	=	slope inclination angle.

The adhesive and frictional resistances of the ClosureTurf system interfaces are calculated using the following equations, respectively.

$$F_a = b \cdot l \cdot a$$

$$F_r = (W_s + W_v) \cdot \cos(\beta) \cdot \tan(\delta)$$

where:

b	=	equipment contact width;
l	=	equipment contact length;
a	=	interface adhesion intercept along the critical slip surface;
β	=	slope inclination angle; and
δ	=	interface friction angle along the critical slip surface.

The dynamic equipment force (F_d) can be calculated using the following equation:

$$F_d = m \cdot \frac{v}{t}$$

where:

m	=	equipment mass;
v	=	equipment velocity; and
t	=	duration of acceleration/deceleration.

INPUT PARAMETERS AND ANALYSIS ASSUMPTIONS

Veneer stability analyses are performed for a slope that is considered the longest and steepest of the design grades of the landfill final cover system. For the purpose of this example, the following input parameters were assumed:

Slope Geometry [1]

Slope inclination angle, β	= 18.43° (i.e., 3 horizontal to 1 vertical)
Slope maximum height, H	= 63 ft
Slope Length, L	= 63/sin 18.43° ≅ 200 ft = 6,096 cm

ClosureTurf

Aggregate infill thickness, z_c	= 0.5 in
Total unit weight of aggregate infill, γ_c	= 115 pcf
Critical interface friction angle, δ	= 36° (see Attachment B-1)[2]
Critical interface adhesion intercept, a	= 0 psf

Runoff curve number (CN): varies from 91 to 96 - a value of 95 was selected (Attachment B-2)

Drainage stud height, T_d	= 3.3 mm (see Attachment B-3)
Transmissivity, θ	= 3.86 x 10^{-3} m^2/sec (see Attachment B-4)

Precipitation Data [3]

Precipitation, P = 4.34 in/hour (or 11.02 cm/3600 sec = 3.06 x 10^{-3} cm/sec)

Seismic Parameters

Estimated maximum acceleration at the base of landfill = 0.10g

Equipment Parameters

Equipment weight	= 8,000 lb
Equipment mass	= 8,000 lb/32.2 ft/sec^2 = 248 lb/ft/sec^2
Equipment velocity	= 10 miles per hour = 14.7 ft/sec
Deceleration time	= 2 sec

---

[1] Slope geometry is typically obtained from the final cover system grading plan.

[2] For this example, it is assumed that the critical interface is between the CT turf and Super GripNet geomembrane. Interface shear test should be performed between the geomembrane and site-specific subgrade soils to assess the critical interface.

[3] In the Ohio EPA Procedure, the 100-yr, 1-hr storm was used to calculate the head on the interface for final slopes under the saturated static conditions.

CALCULATIONS AND RESULTS

Calculate the hydraulic head on the geomembrane

Step 1 - Calculate the Long-term Transmissivity of the ClosureTurf® Drainage Layer

$$\theta_L = \frac{\theta}{FS_I \text{ x } FS_{Cr} \text{ x } FS_{CC} \text{x } FS_B \text{ x } FS_S}$$

θ_L = long-term transmissivity;
θ = tested transmissivity;
FS_I = reduction factor to account for intrusion;
FS_{Cr} = reduction factor to account for creep;
FS_{CC} = reduction factor to account for chemical clogging;
FS_B = reduction factor to account for biological clogging; and
FS_S = reduction factor to account for clogging due to infiltration of fines.

A reduction factor FS_s of 4.0 was considered to account for potential clogging due to infiltration of fines[4]. The other reduction factors are not considered to be applicable to ClosureTurf and therefore, were assumed to be 1.0.

$$\theta_L = \frac{3.86 \text{ x } 10^{-3}}{1.0 \text{ x } 1.0 \text{ x } 1.0 \text{ x } 1.0 \text{ x } 4.0} = 9.65 \text{ x } 10^{-4}\ m^2/\text{sec} = 9.65\ cm^2/\text{sec}$$

Step 2 - Convert the Transmissivity to Hydraulic Conductivity

$$k_d = \frac{\theta_L}{T_d} = \frac{9.65}{0.33} = 29.24\ cm/sec$$

Step 3 – Calculate the Average Hydraulic Head

Check if $P(1\text{-}RC) > k_c$

$$P(1\text{-}RC) = 3.06 \text{ x } 10^{-3} \text{ x } (1 – 95/100) = 1.53 \text{ x } 10^{-4} \text{ cm/sec}$$

This value is less than the permeability of the aggregate infill, which has a typical permeability in the order of 10^{-2} cm/sec. Therefore, the following equation is used to calculate the hydraulic head:

[4] The reduction factor of 4.0 is considered for typical soil-geosynthetic cover and is conservative for ClosureTurf as there is no soil layer on top that could clog the internal drainage layer.

$$h_{avg} = \frac{P\,(1 - RC)\ \times\ L\,(\cos\beta)}{k_d(\sin\beta)} = \frac{1.53\ \times\ 10^{-4}\ \times\ 6{,}096\ \times\ (\cos 18.43^o)}{29.24\ \times\ (\sin 18.43^o)} = 0.096\ cm = 0.038\ in$$

The calculated hydraulic head is less than the thickness of the internal drainage layer (T_d), which is 0.33 cm.

Step 2 – Calculate the static and seismic FS

Depth to water surface, $d_w = z_c - h_{avg} = 0.5 - 0.038 = 0.462$ *inch*

Static Veneer Slope Stability

$$FS_{Static} = \frac{0 + \tan 36^o \left(1 - \dfrac{62.4\,(0.5 - 0.462)}{115\ \times\ 0.5}\right) - 0}{0 + \tan 18.43^o} = 2.1$$

Seismic Veneer Slope Stability

The seismic coefficient at the final cover should be used for the veneer stability analysis of ClosureTurf. In this example, the seismic coefficient is estimated using Figure B.1 (Attachment B-5) for simplicity. Using the estimated maximum acceleration at the base of landfill (the input parameter in this example) and assuming that the seismic behavior of this example landfill is similar to that with 100 ft of waste shown in Figure B.1, the seismic coefficient at the final cover surface is estimated to be 0.14g. The factor of safety of the veneer stability of ClosureTurf under seismic loading is calculated as:

$$FS_{Seismic} = \frac{0 + \tan 36^o \left(1 - \dfrac{62.4\,(0.5 - 0.462)}{115\ \times 0.5}\right) - 0.14\ \times \tan 18.43^o \times \tan 36^o}{0.14 + \tan 18.43^o} = 1.4$$

Veneer Slope Stability for ClosureTurf with Equipment Load

The following was assumed in the evaluation of slope stability for ClosureTurf with equipment load:

- No hydraulic head (i.e., equipment operation during dry weather)
- No seismic load.

The frictional resistance (F_r) and dynamic equipment load (F_d) are calculated as follows.

$$F_r \approx 8{,}000\ \times \cos 18.43^o\ \times \tan 36^o\ = 5{,}514\ \text{lb}$$

$$F_d = m \cdot \frac{v}{t} = 248 \times \frac{14.7}{2} = 1{,}823\ \text{lb}$$

Note that the weight of ClosureTurf (less than one percent of the equipment load) was ignored for simplicity. Then the factor of safety is calculated as:

$$FS_{equip} = \frac{F_a + F_r}{(W_s + W_v) \cdot \sin(\beta) + F_d} = \frac{0 + 5{,}514}{(8{,}000) \times \sin 18.43^o + 1{,}823} = 1.3$$

Note that the above calculation is to evaluate the effect of a dynamic equipment force on the veneer slope stability of the ClosureTurf final cover. The effect of equipment load on bearing capacity and settlement of the final cover subgrade should be evaluated separately by the project design engineer, as necessary.

SUMMARY AND CONCLUSIONS

The factor of safety for veneer stability was calculated for a landfill with a 3 horizontal to 1 vertical (3H:1V) slope, a typical slope for a municipal solid waste landfill. The computed factors of safety are equal to or greater than the target factors of safety of 1.5, 1.3, and 1.0 for long-term static, temporary static, and seismic conditions, respectively.

REFERENCES

Bray, J.D., Rathje, E.M., Augello, A.J., and Merry S.M. (1998), “Simplified Seismic Design Procedure for Geosynthetic-Lined, Solid-Waste Landfills.”

Matasovic, N. (1991). “Selection of Method for Seismic Slope Stability Analysis,” Proc. of the 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (2), St. Louis, MO, pp. 1057-1062.

Ohio Environmental Protection Agency (OEPA) (2004), “Geotechnical and Stability Analyses for Ohio Waste Containment Facilities”, Geotechnical Resource Group, September 14, 2004.

Richardson, G., Kavazanjian, E., and Matasovic, N. (1995). “RCRA Subtitle D (258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities,” US EPA Contract No. 68-C3-0315.

Attachment B-1

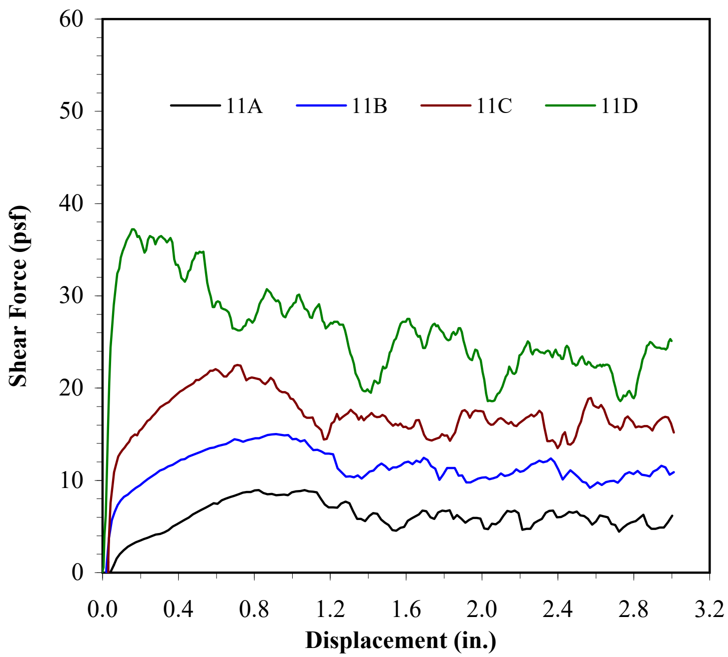
ClosureTurf Interface Shear Strength Test Report

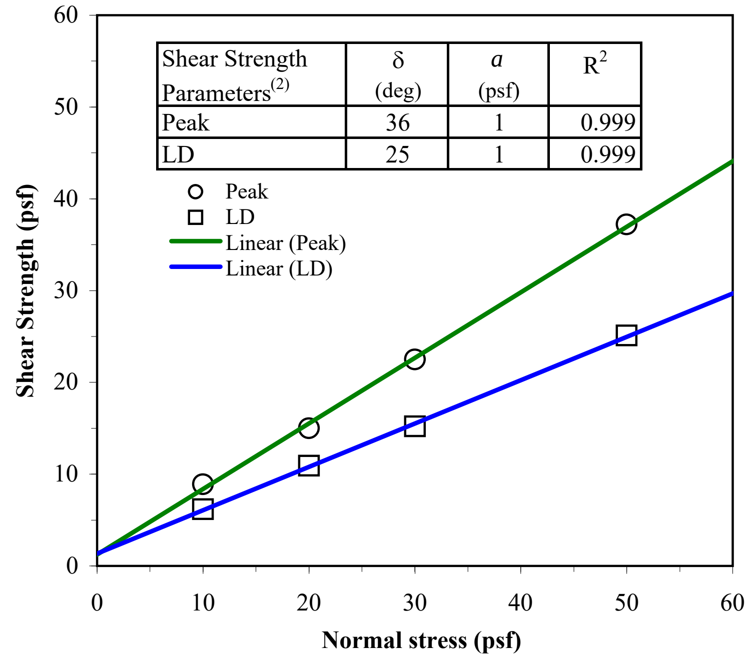
WATERSHED GEOSYNTHETICS LLC

INTERFACE DIRECT SHEAR TESTING (ASTM D 5321)

Upper Shear Box: Concrete sand
CT32 Synthetic Turf with base geotextile side down against
Agru 50-mil Super Gripnet LLDPE geomembrane with stud side up
Lower Shear Box: Concrete sand

Note: The CT turf is denoted as the "CT32 Synthetic Turf" in this test report.





Shear Strength Parameters(2)	δ (deg)	a (psf)	R^2
Peak	36	1	0.999
LD	25	1	0.999

Test No.	Shear Box Size (in. x in.)	Normal Stress (psf)	Shear Rate (in./min)	Soaking Stress (psf)	Soaking Time (hour)	Consolidation Stress (psf)	Consolidation Time (hour)	Lower Soil γ_d (pcf)	Lower Soil ω_i (%)	Lower Soil ω_f (%)	Upper Soil γ_d (pcf)	Upper Soil ω_i (%)	Upper Soil ω_f (%)	Soil Shear Strength ϕ (deg)	Soil Shear Strength c (psf)	Shear Strengths τ_P (psf)	Shear Strengths τ_{LD} (psf)	Failure Mode
11A	12 x 12	10	0.04	10	24	-	-	-	-	-	-	-	-	-	-	8.9	6.2	(1)
11B	12 x 12	20	0.04	20	24	-	-	-	-	-	-	-	-	-	-	15.0	10.9	(1)
11C	12 x 12	30	0.04	30	24	-	-	-	-	-	-	-	-	-	-	22.5	15.2	(1)
11D	12 x 12	50	0.04	50	24	-	-	-	-	-	-	-	-	-	-	37.2	25.1	(1)

NOTES:
(1) Sliding (i.e., shear failure) occurred at the interface between the geotextile side of the turf and the stud side of Agru 50-mil Super Gripnet.
(2) The reported total-stress parameters of friction angle and adhesion were determined from a best-fit line drawn through the test data. Caution should be exercised in using these strength parameters for applications involving normal stresses outside the range of the stresses covered by the test series. The large-displacement (LD) shear strength was calculated using the shear force measured at the end of the test.

SGI TESTING SERVICES, LLC

DATE OF TEST:	5/28/2019
FIGURE NO.	1
PROJECT NO.	SGI19014
DOCUMENT NO.	
FILE NO.	

Attachment B-2

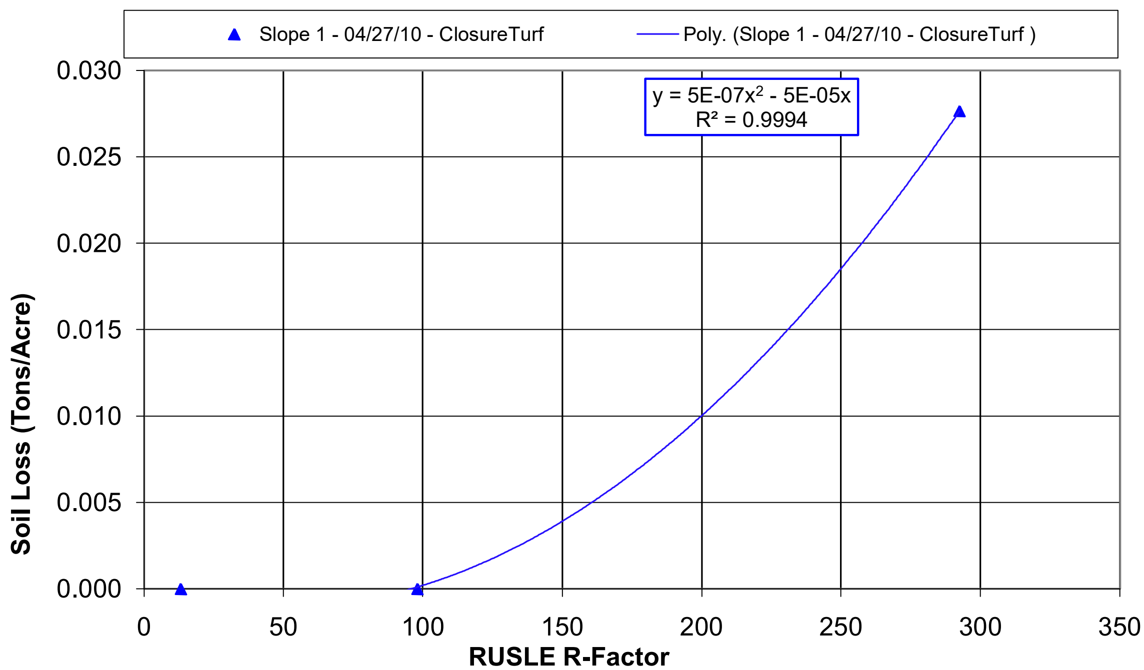
ClosureTurf Rainfall Test Report

Project: ASTM D 6459
Client: RPH
Test Date: 4/26/2010
Rainfall Rates: 2,4,6 in/hr (target); 20 minutes at each intensity (60 min. total)
Bed Size & Slope: 8-ft wide x 40-ft long; 3H:1V
Sand Ballast Layer, lbs: 1130 (approximately 1/2-inch thick, hand spread)

Plot	Intensity (in/hr)	Runoff (gallons)	Cumm. R-Factor	Soil Loss (lbs/slope)	Sediment Yield (tons/acre)	% of Ballast in Runoff/Seepage
ClosureTurf	2.36	93	13.13	0.00	0.00	0.04%
	4.65	258	97.99	0.00	0.00	
	6.57	360	292.43	0.41	0.03	

Time (min)	Cumm. Rainfall (in)	Cumm. Runoff (in)	Peak Runoff (cfs)	CN[1]	Rational "C"[2]
20	0.79	0.46	0.013	96.2	0.74
40	2.34	1.76	0.026	94.5	0.76
60	4.53	3.56	0.038	91.3	0.78

Soil Loss vs RUSLE R-Factor



1. The effective runoff curve number was determined by solving for S in the equation Q = [(P-0.2S)2/(P+0.8S)] where Q is the depth of runoff (in) and P is the rainfall depth (in). Then, CN = 1000/(S+10).

2. The rational "C" coefficient was determined by solving for C in Q = C I A where Q is the peak discharge rate (cfs), I is the peak rainfall intensity (in/hr) and A is the drainage area (acre).

Note: The testing is based upon accepted industry practice as well as the test method listed. Test results reported herein do not apply to samples other than those tested. TRI neither accepts responsibility for nor makes claim as to the final use and purpose

CJS 5/5/10
Quality Review / Date

Attachment B-3

ClosureTurf Product Datasheet

ClosureTurf® w 50 mil Super Gripnet® Liner

Product Data	Test Method	LLDPE Values	HDPE Values
Thickness (nominal), mil (mm)	ASTM D5994	50 (1.25)	50 (1.25)
Thickness (min. avg.), mil (mm)	ASTM D5994	47.5 (1.19)	47.5 (1.19)
Thickness (lowest indiv.), mil (mm)	ASTM D5994	42.5 (1.06)	42.5 (1.06)
Drainage Stud Height (min. avg.), mil (mm)	ASTM D7466	130 (3.3)	130 (3.3)
Friction Spike Height (min. avg.), mil (mm)	ASTM D7466	175 (4.45)	175 (4.45)
Density, g/cc	ASTM D792, Method B	0.939 (max.)	0.94 (min.)
Tensile Properties (avg. both directions)	ASTM D6693, Type IV		
Strength @Yield (min. avg.), lb/in. width (N/mm)		N/A	110 (19.3)
Elongation @ Yield (min. avg.), % (GL=1.3 in.)		N/A	12
Strength@Break (min. avg.), lb./in. width (N/mm)		105 (18.4)	110 (19.3)
Elongation@Break (min. avg.), %(GL=2.0 in.)		300	200
Tear Resistance (min. avg.), lbs. (N)	ASTM D1004	30 (133)	38 (169)
Puncture Resistance (min. avg.) lbs. (N)	ASTM D4833	55 (245)	80 (356)
Carbon Black Content (range %)	ASTM D4218	2-3	2-3
Carbon Black Dispersion (Category)	ASTM D5596	Only near spherical agglomerates for 10 views in Cat. 1 or 2	
Stress Crack Resistance (Single Point NCTL), hours	ASTM D5397, Appendix	N/A	500
Oxidative Induction Time, minutes	ASTM D3895, 200°C, 1 atm O_2	≥140	≥140

Agru America's geomembranes are certified to pass Low Temp. Brittleness via. ASTM D746 (-80°C), and Dimensional Stability via. ASTM D1204 (± 2% @ 100°C)

ENGINEERED TURF COMPONENT (CT)

Product Data	Test Method	Values
Yarn Type	N/A	Polyethylene, Fibrillated
Yarn Color	N/A	Olive Green, Play Green, Tan
Yarn Weight (Total Product Weight)	ASTM D5261 (sample size, 1 yd²)	≥20 oz. / sq. yd. (≥ 32 oz. / sq. yd.)
Tensile Strength of Yarn	ASTM D2256	15 lbs. min.
CBR Puncture	ASTM D6241	1,500 lb. (MARV)
Tensile Product (MD/XD)	ASTM D4595	2,100 MD / 1,600 XD lb/ft (MARV)
Interface Friction between ClosureTurf CT and Super Gripnet®	ASTM D5321	35°, min. Peak*
Engineered Turf Fiber UV Stability	ASTM G147	>60% retained tensile strength at 100 yrs. (projected)
Backing System UV Stability (Exposed)	ASTM G154 Modified Cycle 1., UVA340	110 lbs./ft. retained tensile strength at 6,500 hrs (projected)
Aerodynamic Evaluation	GTRI Wind Tunnel	120 mph with max. uplift of 0.12 lb/sf
Rainfall Induced Erosion	ASTM D6459	Infill Loss 0.1% at 6 in./hr. Rainfall
Steady State Hydraulic Overtopping (ClosureTurf® w/ HydroBinder®)	ASTM D7277/D7276	5 ft. overtopping resulting in 29 ft/s velocity and 8.8 psf shear stress for Manning's *n* value of 0.02
Full Scale Wave Overtopping Test Cumulative Volume (ClosureTurf® with HydroBinder®)	Colorado State University Wave Simulator	165,000 ft³/ft
Full Scale Wave Overtopping Test Discharge (ClosureTurf® with HydroBinder®)	Colorado State University Wave Simulator	4.0 ft³/s/ft
HydroBinder® Infill Mix	ASTM C387 / ASTM C109	3/4 in. infill 5,000 psi (min. at 28 days)

*Engineered turf/geomembrane interface. Geomembrane/subgrade interface is site specific and should be evaluated per Engineer of Record's requirements.

SUPPLY INFORMATION (Standard Roll Dimensions)

	Thickness		Width		Length		Area (approx.)		Weight (avg.)	
	mil	mm	ft.	m	ft.	m	ft²	m²	lbs	kg
Super Gripnet®	50	1.25	23	7	575	175	13,225	1,225	~5,000	~2,268
Turf Component	N/A	N/A	15	4.6	300	91.44	4,500	418	~1,000	~454

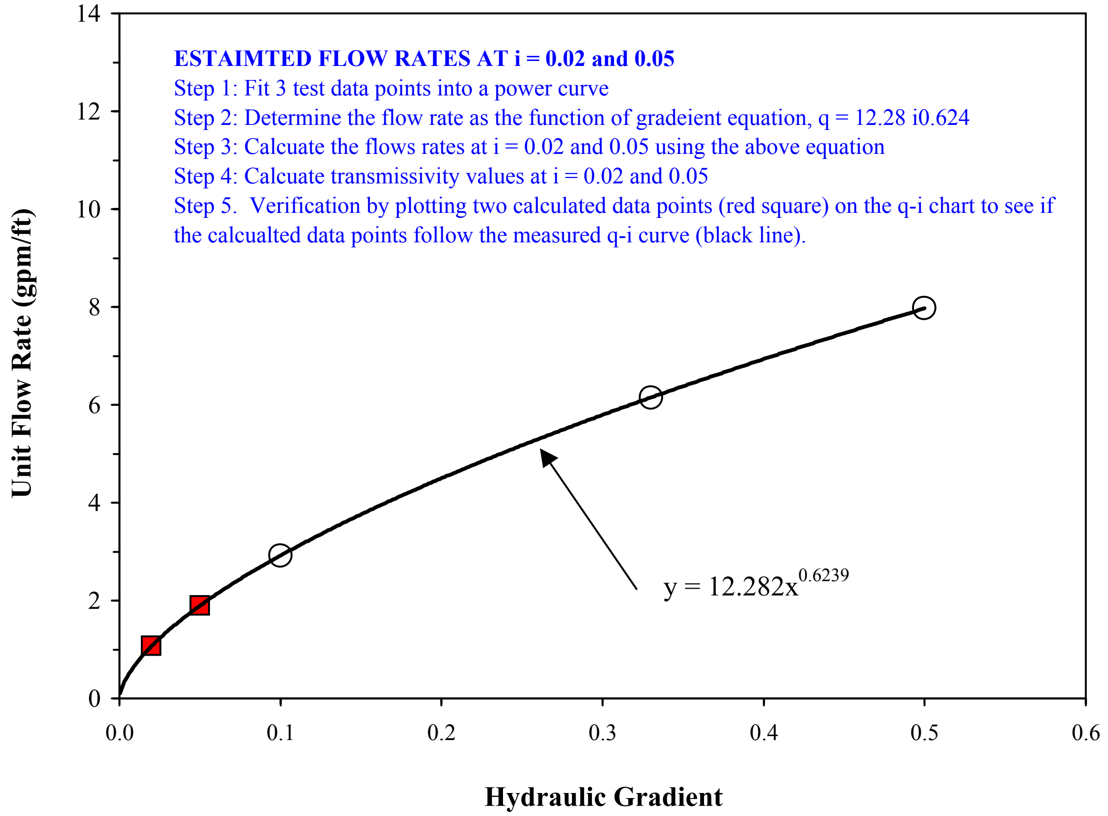
Attachment B-4

ClosureTurf Transmissivity Test Report

CLOSURETURF LLC -LANDFILL COVER SYSTEM

HYDRAULIC TRANSMISSIVITY TESTING (ASTM D 4716)

Test Configuration (from Top to Bottom): Sand Layer/Polytex Artificial Grass with Geotextile Side Down/ Agru 50-mil Super Gripnet LLDPE Geomembrane with Studs Side Up



Test No.	Flow Direction	Specimen Size Width x Length (in. x in.)	Total Normal Stress(1) σ_n (psf)	Seating Time t (hour)	Hydraulic Gradient i (-)	Transmissivity $\theta = 0.00020697\left(\frac{q}{i}\right)$ (m^2/sec)	Flow Rate $q = 12.28 i^{0.624}$ (gpm/ft)	Flow Rate q' (l/min/m)
					0.02	1.11E-02	1.07	
					0.05	7.84E-03	1.89	
1	MD	12 x12	47	0.25	0.10	6.04E-03	2.92	36.3
2	MD	12 x12	47	0.25	0.33	3.86E-03	6.15	76.4
3	MD	12 x12	47	0.25	0.50	3.30E-03	7.97	99.0

NOTE:

Total normal stress = total weight (sand + steel plate + surcharge) divided by the plan area of test specimen (1 square ft). A normal stress of 47 psf is approximately the minimum total stress required to keep the specimen from uplifting.

DATE TESTED:	1/11/2013
FIGURE NO.	A-1
PROJECT NO.	SGI10007
DOCUMENT NO.	
FILE NO.	

SGI TESTING SERVICES, LLC

Attachment B-5

Seismic Hazard Data

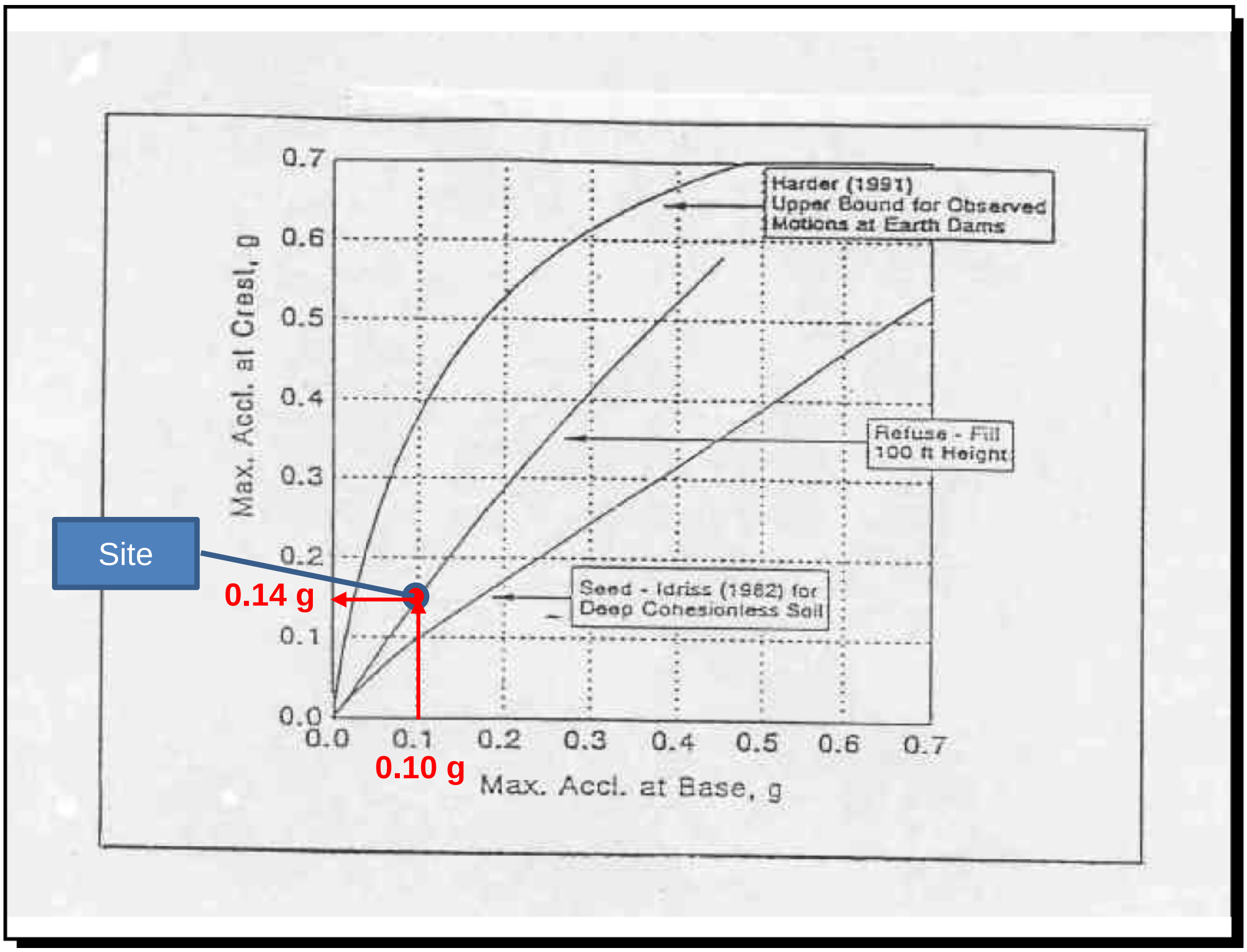


Figure B.1. The relationship between maximum horizontal seismic acceleration at the base and crest of 100 feet of refuse, on top of deep cohesionless soils, and on top of earth dams. (Singh and Sun, 1995)

Appendix C
Example Calculation for Wind Uplift of ClosureTurf

Technical Note

WIND UPLIFT ANALYSIS OF CLOSURETURF®

1. Introduction

This technical note presents design methodologies and example calculations for evaluating wind loads on ClosureTurf® final cover system (ClosureTurf). ClosureTurf consists of a structured geomembrane, an engineered turf, and a specified infill (Figure 1).

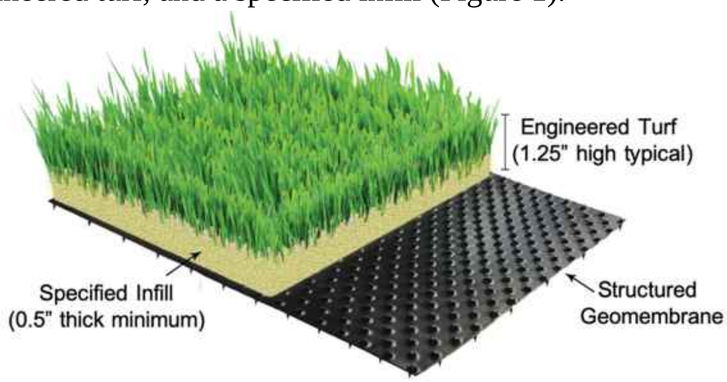


Figure 1. ClosureTurf® Final Cover System

2. Design Methodology

2.1 Wind Pressure Equation

Wind pressure acting on the ClosureTurf surface can be calculated using the following equation (e.g., Dedrick, 1973; Giroud et al., 1995; Wayne and Koerner, 1988; Zheng, et al., 2020; Zhu, et al. 2022):

$$P = \frac{1}{2} \cdot C_p \cdot \rho \cdot U(H)^2 \cdot K_e \cdot K_d$$

where,

- P = wind-generated pressure normal to the ClosureTurf surface (pounds per square foot [psf]);
- C_p = wind pressure coefficient (dimensionless);
- ρ = air density (ρ = 0.0024 slug/cubic foot [ft^3] at 59ºF and sea level);
- $U(H)$ = upstream mean wind speed (feet/second [ft/s]) at the height of slope H (feet [ft]);
- K_d = wind directionality factor (K_d = 1.1); and
- K_e, = ground elevation factor (ASCE, 2022), $K_e = e^{-0.0000362 \cdot Z_e}$, where Z_e is the ground elevation above sea level (ft).

2.2 Design Wind Speed

The design wind speed $U(H)$ at a height of slope H can be estimated from the basic wind speed following the recommendations in ASCE 7-22 (ASCE, 2022). The basic wind speed at locations in the U.S. can be obtained from the online database provided by the ASCE (https://asce7hazardtool.online/). The database can be used to search for wind speed based on location and Mean Recurrence Interval (MRI) or Risk Category. The basic wind speed corresponds to the 3-second gust speed at 32.8 ft (or 10 m) above ground in open terrain, and it is denoted as $U_3(32.8\ ft)$. An example of basic wind speeds for structures located in Atlanta, GA is shown in Figure 2. Basic wind speeds increase as the MRI increases from 10 years (i.e., MRI 10-Year) to approximately 3,000 years for Risk Category IV.

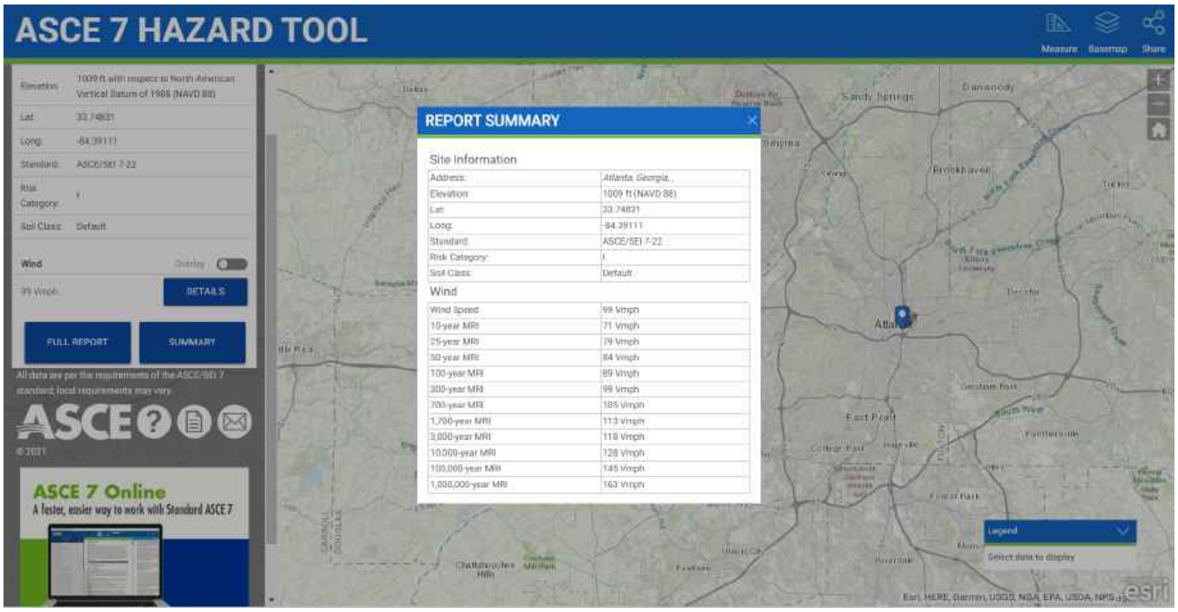


Figure 2. Basic Wind Speeds for Structures Located in Atlanta, GA based on ASCE Database

The professional engineer designing the ClosureTurf should consult with the site owner/operator to select a basic wind speed for design that corresponds to an appropriate MRI, based on any applicable federal, state, or local regulations, industry standards, historical wind records, and the owner/operator's long-term maintenance strategy for the site.

Basic wind speed, which, as previously noted, corresponds to a 3-second gust, can be converted to mean hourly wind speed at 32.8 ft above ground, $U(32.8\ ft)$, using a factor of approximately 1.5 for open terrain (Vickery and Skerlj, 2005):

$$U(32.8\,ft) = U_3(32.8\,ft)\ /\ 1.5$$

Using $U(32.8\ ft)$ as the reference wind speed, the mean hourly wind speed at the top of a landfill, $U(H)$, with H being the height of landfill slope, is calculated using the Power-Law equation for atmospheric boundary layers (Peterson and Hennessey, 1978):

$$\frac{U(H)}{U(32.8\,ft)} = \left(\frac{H}{32.8}\right)^{\alpha}$$

where, α is the Power-Law exponent. A value of 0.14 is used herein based on the wind tunnel test results of ClosureTurf. This exponent corresponds to an open terrain boundary condition. Therefore, the equation above can be re-arranged as follows:

$$U(H) = U(32.8\,ft) \cdot \left(\frac{H}{32.8}\right)^{0.14}$$

2.3 Wind-Pressure Coefficient

Profiles of the wind-pressure coefficient, C_p, developed based on the wind tunnel test results of ClosureTurf are presented in Figures 3 and 4 for landfills with 4H:1V and 3H:1V slopes, respectively. The corresponding C_p values are listed in Tables 1 and 2. Two types of engineered turf were tested, specifically, CT with standard density turf and CT HD with higher density turf.

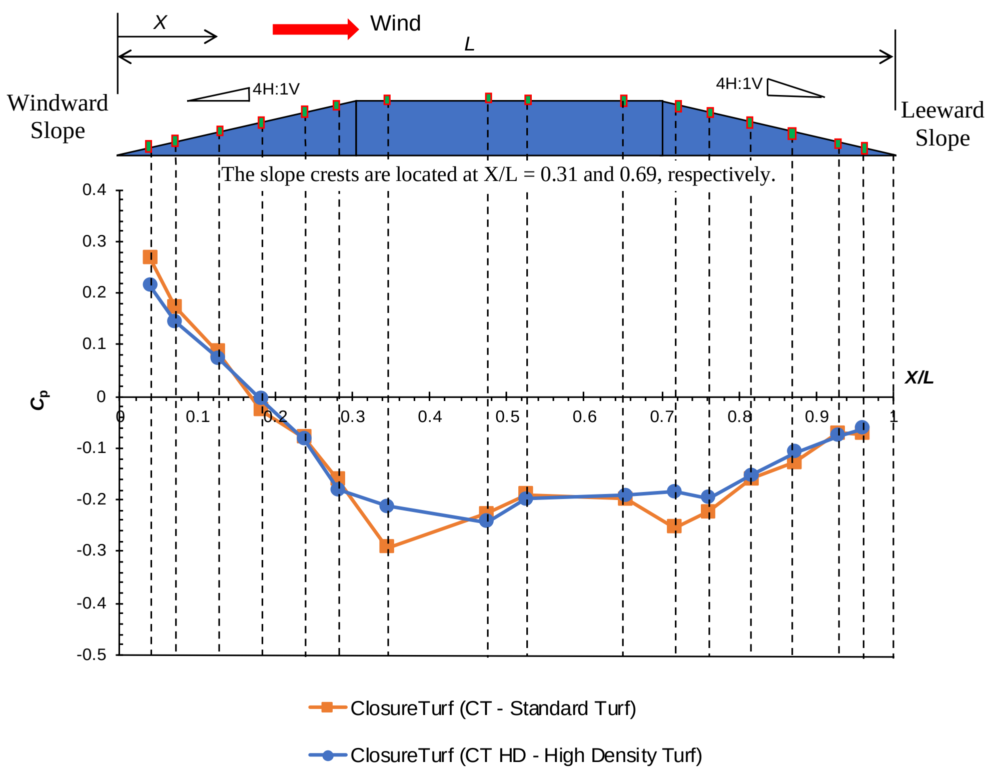


Figure 3. Average Wind-Pressure Coefficient Profiles for ClosureTurf (4H:1V Slopes)

Note: Positive values correspond to wind load acting toward the surface (i.e., downward pressure or compression). Negative values correspond to wind load acting away from the surface (i.e., uplift pressure or suction). This note applies to the other figures and tables of C_p in this Technical Note.

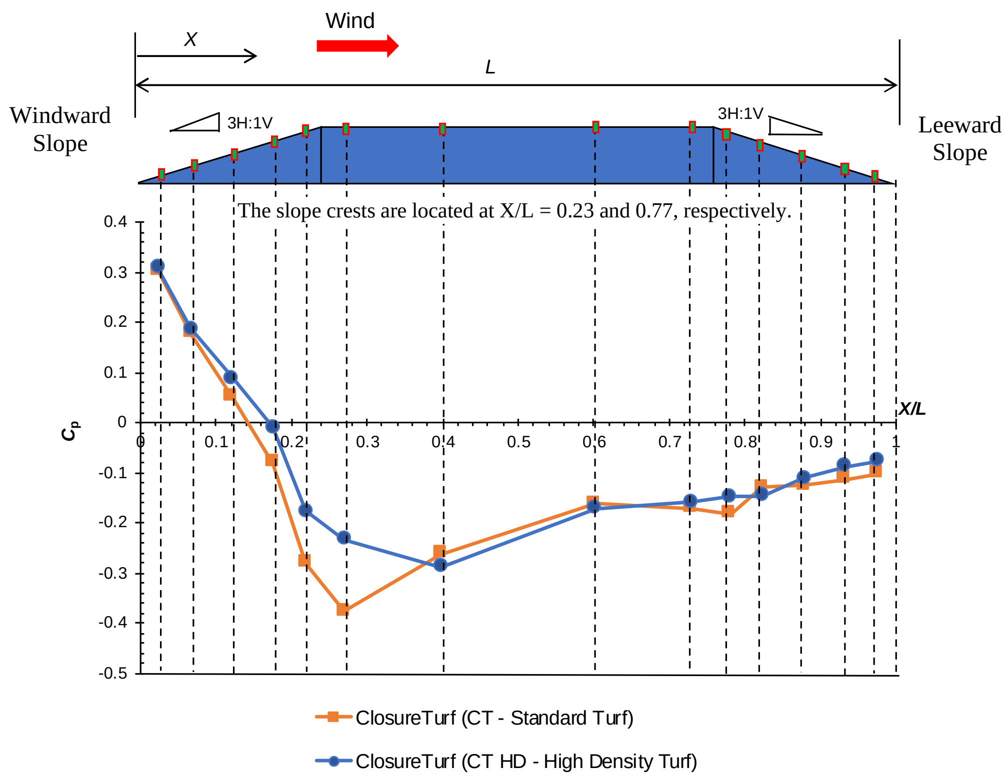


Figure 4. Average Wind-Pressure Coefficient Profiles for ClosureTurf (3H:1V Slopes)

Table 1. Average Wind-Pressure Coefficients for ClosureTurf (4H:1V Slopes)

X/L	Wind Pressure Coefficient, *Cp* (4H:1V Slope)	
	CT (Standard Turf)	CT HD (High Density Turf)
0.04	0.27	0.22
0.07	0.17	0.15
0.13	0.09	0.08
0.18	-0.03	-0.01
0.24	-0.08	-0.08
0.28	-0.16	-0.18
0.35	-0.29	-0.21
0.47	-0.23	-0.24
0.53	-0.19	-0.20
0.65	-0.20	-0.19
0.72	-0.25	-0.18
0.76	-0.22	-0.20
0.82	-0.16	-0.15
0.87	-0.13	-0.11
0.93	-0.07	-0.08
0.96	-0.07	-0.06

Note: The slope crests are located at X/L = 0.31 and 0.69, respectively.

Table 2. Average Wind-Pressure Coefficients for ClosureTurf (3H:1V Slopes)

X/L	Wind Pressure Coefficient, C_p (3H:1V Slope)	
	CT (Standard Turf)	CT HD (High Density Turf)
0.02	0.30	0.31
0.07	0.18	0.19
0.12	0.05	0.09
0.18	-0.08	-0.01
0.22	-0.28	-0.18
0.27	-0.38	-0.23
0.40	-0.26	-0.29
0.60	-0.16	-0.17
0.73	-0.17	-0.16
0.78	-0.18	-0.15
0.82	-0.13	-0.15
0.88	-0.12	-0.11
0.93	-0.11	-0.09
0.98	-0.10	-0.08

Note: The slope crests are located at X/L = 0.23 and 0.77, respectively.

3. ClosureTurf Wind Uplift Analysis Example

This section provides a wind uplift analysis example of ClosureTurf. For convenience, the C_p values are reported in the example as absolute values and the context of the value (i.e., uplift or compression) in each case is made clear.

Example 1: A hypothetical landfill site is located in Atlanta, GA. It has a slope of 3H:1V with a maximum height of 100 ft. The top deck of the landfill is at El. 1,150 ft above mean sea level. The maximum length of top deck is 200 ft with a maximum slope of 5%. ClosureTurf is selected to close the site with the standard-density engineered turf CT and 50-mil Super Gripnet geomembrane. The specified thickness of aggregate infill is 0.5 in. minimum, not to exceed 0.75 in. Perform a wind uplift analysis for the proposed ClosureTurf final cover system.

Solution:

Step 1: Select $U_3(32.8\ ft)$ according to ASCE 7-22

Go to https://asce7hazardtool.online/ and search for Atlanta, GA. The results are:

REPORT SUMMARY

Site Information

Address:	*Atlanta, Georgia, ,*
Elevation:	1009 ft (NAVD 88)
Lat:	33.74831
Long:	-84.39111
Standard:	ASCE/SEI 7-22
Risk Category:	I
Soil Class:	Default

Wind

Wind Speed	99 Vmph
10-year MRI	71 Vmph
25-year MRI	79 Vmph
50-year MRI	84 Vmph
100-year MRI	89 Vmph
300-year MRI	99 Vmph
700-year MRI	105 Vmph
1,700-year MRI	113 Vmph
3,000-year MRI	118 Vmph
10,000-year MRI	128 Vmph
100,000-year MRI	145 Vmph
1,000,000-year MRI	163 Vmph

For the purpose of illustrating the wind uplift design methodology, MRI 25-Year (i.e., a 25-year recurrence interval) is used in the example. The basic wind speed for MRI 25-Year is 79 mph (equal to 115.9 ft/s), which corresponds to the 3-second gust speed at 32.8 ft above ground. Therefore, $U_3(32.8\ ft)$ = 79 mph = 115.9 ft/s.

Step 2: Calculate $U(H)$ with H = 100 ft

The mean hourly wind speed for open terrain is:

$$U(32.8\,ft) = \frac{U_3(32.8\,ft)}{1.5} = \frac{115.9}{1.5} = 77.3\,ft/s$$

The mean hourly wind speed at the top of the landfill is:

$$U(H) = U(32.8\,ft) \cdot \left(\frac{H}{32.8\,ft}\right)^{0.14} = 77.3 \times \left(\frac{100}{32.8}\right)^{0.14} = 90.4\,ft/s$$

Therefore, at the height of H = 100 ft, the mean hourly wind speed $U(H)$ = 90.4 ft/s.

Step 3: Select Wind-Pressure Coefficient (C_p) Values

Because the landfill slope is 3H:1V and the engineering turf is the standard turf CT, the C_p profile in Figure 4 (and Table 2) for CT is used for calculation of wind uplift pressure. According to Table 2, the maximum C_p value, $C_{p,max}$, is 0.38 (uplift).

Step 4: Calculate Ground Elevation Factor

$$K_e = e^{-0.0000362 \cdot Z_e} = e^{-0.0000362 \times 1150} = 0.959$$

Step 5: Calculate Maximum Wind Uplift Pressure

$$\begin{aligned} P_{max} &= \frac{1}{2} \cdot C_{p,max} \cdot \rho \cdot U(H)^2 \cdot K_e \cdot K_d \\ &= 0.5 \times 0.38 \times 0.0024 \times 90.4^2 \times 0.959 \times 1.1 = 3.93\ psf \end{aligned}$$

The maximum wind uplift is expected to occur on the top deck near the crest of slope.

Step 6: Estimate Self-Weight of ClosureTurf

Using the minimum aggregate thickness of 0.5 in. and a unit weight of aggregate of 115 pcf, the calculated self-weight of the aggregate infill layer is: (0.5/12) x 115 = 4.79 psf. (Note: It has been observed that contractors typically provide more than the minimum amount of aggregate infill to assure the minimum 0.5 in. aggregate thickness specification is met. Based on experience, typical final infill thicknesses have been in the range of 0.50 to 0.75 in. Overfill is not considered in the wind load calculation, which provides a degree of conservatism to the analysis.)

According to the ClosureTurf datasheet (see excerpt below), CT turf weighs about 1,000 pounds (lbs) over 4,500 ft^2 and the 50-mil Super Gripnet weighs about 5,000 lbs over 11,500 ft^2. Therefore, the self-weights per unit area of these two materials are, respectively, 1000 lbs/4,500 ft^2 = 0.22 psf (for CT turf) and 5,000 lbs/11,500 ft^2 = 0.43 psf (for 50-mil Super Gripnet).

	Thickness		Width		Length		Area (approx.)		Weight (avg.)	
	mil	mm	ft.	m	ft.	m	ft^2	m^2	lbs	kg
Super Gripnet®	50	1.25	23	7	500	152	11,500	1,068	~5,000	~2,268
Turf Component	N/A	N/A	15	4.6	300	91.44	4,500	418	~1,000	~454

The total self-weight of the ClosureTurf is therefore: 4.79 + 0.22 + 0.43 = 5.44 psf > 3.93 psf.

Step 7: Calculate Factor of Safety against Wind Uplift

The factor of safety (FS) against the initiation of uplift, FS (uplift) is calculated to be 1.38 (i.e., 5.44 psf/3.93 psf).

Due to the combination of small uncertainty in the design parameters, limited consequences of failure, and conservatism in the analysis, a minimum FS in the range of 1.1 to 1.2 is considered adequate for purposes of design. Therefore, the ClosureTurf cover is anticipated to have sufficient resistance against potential initiation of wind uplift for the considered conditions.

4. Remarks

It is suggested that if the design engineer wishes to increase the level of conservatism, it can be achieved by selecting a larger FS or starting the analysis using a more conservative basic wind speed. The final decision on selecting these parameters is the responsibility of the design engineer.

If the calculated maximum wind uplift pressure becomes greater than the self-weight of ClosureTurf, the following design measures can be considered:

1. Tension-strain analysis – A tension-strain analysis can be performed to evaluate whether the wind-induced tension in the ClosureTurf is acceptable. The methodology presented in the technical paper by Giroud et al. (1995) for evaluation of tension and strain in exposed geomembranes due to wind uplift can be used to evaluate ClosureTurf. The design methodology and an analysis example are presented in Attachment C-1 of this Technical Note.
2. Thicker aggregate infill – The C_p profiles in Figure 3 or Figure 4, depending on the slope, can be used to identify any area (which is likely to be limited to the vicinity of the slope crest) where thicker aggregate infill is required to provide the necessary ballast. It is suggested, however, that the maximum aggregate thickness not exceed 1.0 in., since turf fiber height is about 1.25 in. and aggregate infill close to or above the turf surface is subject to movement by wind.
3. Rock ballast – In some cases a stormwater diversion berm or conveyance ditch on the landfill top deck may be considered for the effect that it has on ballasting the ClosureTurf. The ballasting effect of rock- or gravel-lined swales near the slope crest can also be accounted for in the wind load calculation.
4. Anchor trench – An anchor trench may be considered on the top deck near the slope crest to provide additional resistance to wind load, if necessary. In some cases, the anchor trench may be required for other reasons, for example, phased construction of the final cover system.
5. A combination of the above-mentioned design measures can be considered.

Attachment C-1
ClosureTurf Wind-Induced Tension-Strain Analysis

A.1. Design Methodology

A published and widely accepted methodology from the technical literature for evaluating wind uplift of exposed geomembranes is adopted herein to evaluate the wind-induced tension of ClosureTurf when uplifted, with modifications made to include the engineered turf component.

The wind-induced "uplift tension-strain relationship" of a geomembrane has been developed by Giroud et al. (1995), which is expressed as:

$$\varepsilon_w = \frac{2T_w}{S_e L} sin^{-1}\left[\frac{S_e L}{2T_w}\right] - 1 \quad \ldots\ldots (1)$$

Where, ε_w is the strain in the geomembrane induced by wind uplift; T_w, lb/ft, is the tension in the geomembrane induced by wind uplift; L, ft, is the length of geomembrane exposed to wind between two anchors (measured along the slope); and S_e is the effective suction, lb/ft^2.

A schematic representation of an uplifted geomembrane used by Giroud et al. (1995) to develop the above governing equation is shown in Figure A-1. Note that the notation T in the figure is changed to T_w in Eq. (1) to indicate the tension induced by wind uplift. The wind-induced uplift is assumed to be 2-dimensional (i.e., plane strain conditions) in order to develop the equation.

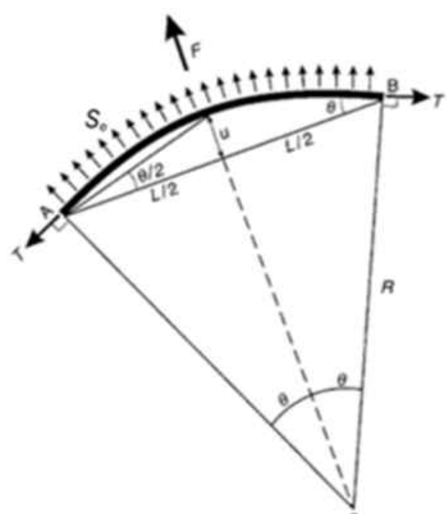


Figure A-1. Schematic Representation of Uplifted Geomembrane (after Giroud et al., 1995)

The effective suction, S_e, is the difference between the wind uplift pressure P, lb/ft^2, and the normal component of the unit weight of geomembrane per unit area W, lb/ft^2 (see Figure A-2):

$$S_e = P - W cos\beta \quad \ldots\ldots (2)$$

where β is the slope angle.

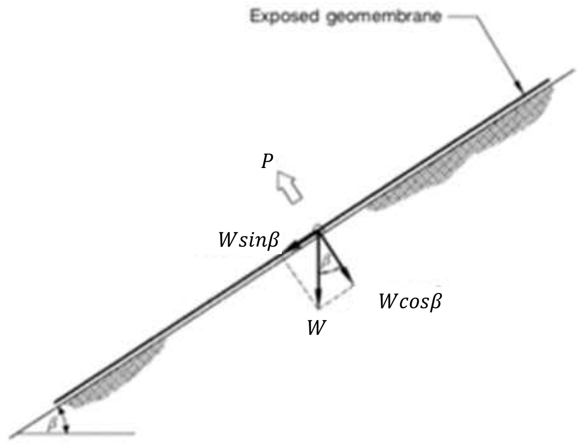


Figure A-2. Geomembrane on a Slope and Subject to Wind-Induced Uplift
(after Zornberg and Giroud, 1997)

Assuming the geomembrane has a linear elastic tension-strain relationship (i.e., the strain is within the range of elastic deformations):

$$T_w = J\varepsilon_w \quad \dots \dots (3)$$

where J, lb/ft, is the tensile stiffness of geomembrane (i.e., the product of the tensile modulus and thickness).

The “uplift tension-strain relationship” expressed in Eq. (1) can be re-written as:

$$\frac{S_e L}{2J\varepsilon_w} = sin\left[\frac{S_e L}{2J}(1 + \frac{1}{\varepsilon_w})\right] \quad \dots \dots (4)$$

This equation has no explicit solution and therefore, the calculated wind-induced tensile strain must be determined by iteration. However, Giroud (2009) provided a quasi-exact, explicit solution to the above equation to facilitate calculations:

$$\varepsilon_w = \frac{0.3467\left(\frac{S_e L}{J}\right)^{2/3}}{1 - 0.3103\left(\frac{S_e L}{J}\right)^{2/3}} \quad \dots \dots (5)$$

The difference between the value of strain obtained from the quasi-exact solution and the exact solution is less than 0.01% for strains between 0 and 20% and less than 0.2% for a strain of 40% (Giroud, 2009). Note that the maximum allowable tensile strain for design is in the range of 5 to 15% depending on the type of geomembrane being considered (Peggs, et al., 2005). Typical design tensile strains will be less than these maximum allowable values. Hence the range of tensile strains considered herein is within the range of high accuracy for the quasi-exact solution.

After the tensile strain is obtained using Eq. (5), the tension in the uplifted geomembrane can be calculated using Eq. (3). The factor of safety (FS) against yield of the geomembrane, FS_y, is calculated using the tension at yield divided by the tension in the uplifted geomembrane:

$$FS_y = \frac{T_y}{T_w} \dots \dots (6)$$

where T_y, lb/ft, is the tension at yield, which can be found in the geomembrane product data sheet provided by the manufacturer. Note that the tension at yield approximately defines the limit of elastic behavior of the geomembrane.

During wind tunnel testing conducted on ClosureTurf, it was observed that the engineered turf and underlying geomembrane were lifted together due to wind loads (in other words, they did not separate). For purposes of the tension analysis, it is assumed that the engineered turf has the same elongation and hence, the same tensile strain as the geomembrane. Tension in the engineered turf can be calculated using Eq. (3) with the tensile stiffness for the engineered turf. Similar to the geomembrane, the FS against yield of the engineered turf can be calculated using Eq. (6) with the tension at yield for the engineered turf.

An example calculation is presented in the section below to illustrate the analysis procedure and use of the above equations.

A.2. Wind Uplift and Tension-Strain Analysis Example:

Problem: A hypothetical landfill site is located in Pensacola, FL. It has a side slope of 3H:1V with a maximum vertical height of 100 ft. The top deck of the landfill is at El. 200 ft above mean sea level. The maximum length of top deck is 200 ft with a maximum slope of 5%. ClosureTurf is selected as the final cover to close the site that consists of the standard-density engineered turf CT and 50-mil LLDPE Super Gripnet geomembrane. The specified thickness of aggregate infill is 0.5 in. minimum, not to exceed 0.75 in. Perform a wind uplift analysis for the proposed ClosureTurf final cover system.

Solution:

<u>Part 1 – Calculate Maximum Wind Uplift Pressure</u>

<u>Step 1</u>: Select basic wind speed according to ASCE 7-22

The basic wind speed, $U_3(32.8\ ft)$, corresponds to the 3-second gust speed at 32.8 ft above ground. It can be obtained from the online database: https://asce7hazardtool.online/. Using this database and searching for Pensacola, FL, the results are shown in the figure below. For the purposes of illustrating the tension-strain analysis presented in the second part of the example, the basic wind speed for Mean Return Interval (MRI) 50-Year is selected, which is 110 mph. Therefore, $U_3(32.8\ ft)$ = 110 mph = 161.3 ft/s.

REPORT SUMMARY

Site Information

Address:	Pensacola, Florida, ,
Elevation:	63 ft (NAVD 88)
Lat:	30.42099
Long:	-87.21726
Standard:	ASCE/SEI 7-22
Risk Category:	I
Soil Class:	Default

Wind

Wind Speed	142 Vmph
10-year MRI	80 Vmph
25-year MRI	98 Vmph
50-year MRI	110 Vmph
100-year MRI	129 Vmph
300-year MRI	142 Vmph
700-year MRI	157 Vmph
1,700-year MRI	171 Vmph
3,000-year MRI	180 Vmph
10,000-year MRI	190 Vmph
100,000-year MRI	217 Vmph
1,000,000-year MRI	241 Vmph

Figure A-3. Selection of Basic Wind Speed According to ASCE 7-22

Step 2: Calculate mean hourly wind speed at top of landfill

The mean hourly wind speed that corresponds to the selected basic wind speed is:

$$U(32.8\,ft) = \frac{U_3(32.8\,ft)}{1.5} = \frac{161.3}{1.5} = 107.5\,ft/s$$

The mean hourly wind speed at the top of the landfill (i.e., H = 100 ft) is:

$$U(H) = U(32.8\,ft) \cdot \left(\frac{H}{32.8\,ft}\right)^{0.14} = 107.5 \times \left(\frac{100}{32.8}\right)^{0.14} = 125.7\,ft/s$$

Therefore, at a height of H = 100 ft, the mean hourly wind speed $U(H)$ = 125.7 ft/s.

Step 3: Select maximum wind pressure coefficient value

Because the landfill slope is 3H:1V and the engineering turf is the standard turf CT, the C_p profile in Figure 4 (and Table 2) for CT, as presented in Section 2.3 of this Technical Note, is used for calculation of wind uplift pressure. According to Table 2, the maximum C_p value, $C_{p,max}$, is 0.38 (uplift). Note that for convenience, the C_p value is reported as an absolute value and the context of the value (i.e., uplift) is made clear.

Step 4: Calculate maximum wind uplift pressure

The maximum wind uplift is expected to occur on the top deck near the crest of slope.

$$P_{max} = \frac{1}{2} \cdot C_{p,max} \cdot \rho \cdot U(H)^2 \cdot K_e \cdot K_d$$

The ground elevation factor corresponding to El. 200 ft is calculated as:

$$K_e = e^{-0.0000362 \cdot Z_e} = e^{-0.0000362 \times 200} = 0.993$$

The wind directionality factor, K_d, is selected as 1.1.

The maximum wind uplift pressure is calculated as:

$$P_{max} = 0.5 \times 0.38 \times 0.0024 \times 125.7^2 \times 0.993 \times 1.1 = 7.87\ psf$$

<u>Step 5</u>: Estimate self-weight of ClosureTurf

Using the minimum aggregate thickness of 0.5 in. and a unit weight of aggregate of 115 pcf, the calculated self-weight of the aggregate infill layer is: (0.5/12) x 115 = 4.79 psf. (Note: It has been observed that contractors typically provide more than the minimum amount of aggregate infill to assure the minimum 0.5 in. aggregate thickness specification is met. Based on experience, typical final infill thicknesses have been in the range of 0.50 to 0.75 in. Overfill is not considered in the wind load calculation, which provides a degree of conservatism to the analysis.)

According to the ClosureTurf datasheet (see Table A-1), CT turf weighs about 1,000 lbs over 4,500 ft^2 and the 50-mil Super Gripnet weighs about 5,000 lbs over 11,500 ft^2. Therefore, the selfweights per unit area of these two materials are, respectively, 1000 lbs/4,500 ft^2 = 0.22 psf (for CT turf) and 5,000 lbs/11,500 ft^2 = 0.43 psf (for 50mil Super Gripnet).

Table A-1. Dimensions and Weights of ClosureTurf Components

	Thickness		Width		Length		Area (approx.)		Weight (avg.)	
	mil	mm	ft.	m	ft.	m	ft²	m²	lbs	kg
Super Gripnet®	50	1.25	23	7	500	152	11,500	1,068	~5,000	~2,268
Turf Component	N/A	N/A	15	4.6	300	91.44	4,500	418	~1,000	~454

The total self-weight of the ClosureTurf is therefore: *W* = 4.79 + 0.22 + 0.43 = 5.44 psf .

<u>Step 6</u>: Calculate factor of safety against wind uplift

The factor of safety (FS) against the initiation of uplift, *FS (uplift)* is calculated to be:

$$FS\ (uplift) = W/P_{max} = 5.44/7.87 = 0.69$$

The calculated FS is less than 1.0; therefore, the ClosureTurf cover is anticipated to experience wind uplift under the selected basic wind speed. A tension-strain analysis is performed next.

Part 2 – Tension-Strain Analysis

Step 7: Back-calculate critical wind pressure coefficient

The critical wind pressure coefficient (i.e., the wind pressure coefficient required to just initiate uplift at the design wind speed), C_p', is back-calculated for the condition where the maximum wind uplift pressure, P'_{max}, equals the self-weight of ClosureTurf:

$$W = P'_{max} = \frac{1}{2} \cdot C_p' \cdot \rho \cdot U(H)^2 \cdot K_d \cdot K_e$$

$$C_p' = \frac{2W}{\rho \cdot U(H)^2 \cdot K_d \cdot K_e} = \frac{2 \times 5.44}{0.0024 \times 125.7^2 \times 0.993 \times 1.1} = 0.26 \text{ (uplift)}$$

Step 8: Identify area subject to wind uplift (i.e., "uplifted zone")

The line representing the critical wind pressure coefficient intercepts the wind pressure coefficient profile for the standard-density turf at X/L of approximately 0.21 and 0.42, respectively, as shown in the figure below.

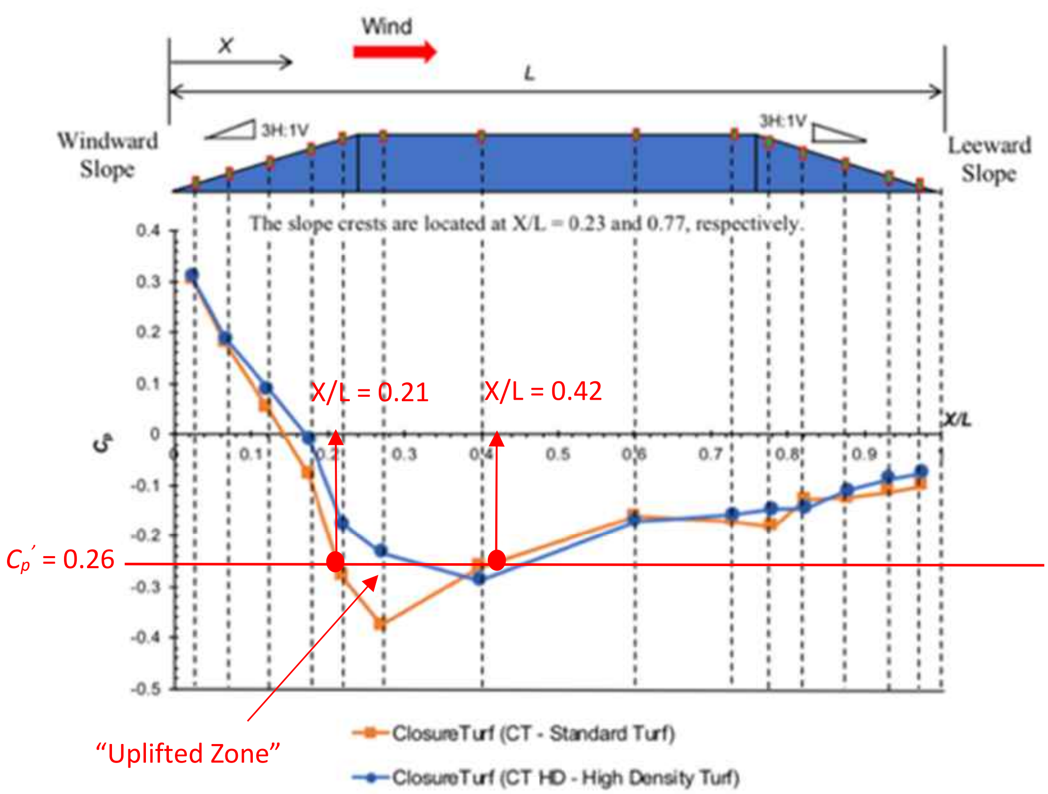


Figure A-4. Wind Pressure Coefficient Profile for 3H:1V Slopes

The area below the critical coefficient line (i.e., X/L between 0.21 and 0.42) is considered to be the “uplifted zone”, where the wind-induced uplift pressure exceeds the selfweight of ClosureTurf and therefore, ClosureTurf is expected to be lifted. The remaining area is not expected to experience uplift because the uplift pressure induced by wind is less than the selfweight of ClosureTurf.

<u>Step 9</u>: Calculate average wind pressure coefficient in the “uplifted zone”

By simplifying the wind pressure profile of the “uplifted zone” as a triangle, the average wind coefficient in this zone can be estimated as:

$$\overline{C_p} = C_p' + \frac{1}{2}\left(C_{p,max} - C_p'\right) = 0.26 + \frac{1}{2}(0.38 - 0.26) = 0.32 \text{ (uplift)}$$

<u>Step 10</u>: Calculate average wind uplift pressure in “uplifted zone”

It is noted that the maximum C_p is used in Step 4 to evaluate the initiation of wind uplift. In contrast, the average C_p is used in this step to estimate the average wind uplift pressure in the “uplifted zone” and the average tensile strains in ClosureTurf in the subsequent steps.

The average wind uplift pressure in the “uplifted zone” is calculated as:

$$\bar{P} = \frac{1}{2} \cdot \overline{C_p} \cdot \rho \cdot U(H)^2 \cdot K_e \cdot K_d = 0.5 \times 0.32 \times 0.0024 \times 125.7^2 \times 0.993 \times 1.10 = 6.63\ psf$$

<u>Step 11</u>: Calculate normal component of average wind uplift pressure in “uplifted zone”

A majority of the “uplifted zone” is located on the top deck (i.e., X/L between 0.42 and 0.23 [crest]) and a small portion is located on the windward slope (i.e., X/L between 0.21 and 0.23[crest]). The slope of top deck is 5% (or β_{top} = 2.9 degrees) and the slope of the sideslope is 3H:1V (or β_{side} = 18.4 degrees). The weighted average of the normal component of the unit weight of ClosureTurf (see Figure A-2) in the “uplifted zone” is calculated as:

$$\overline{Wcos\beta} = \frac{Wcos2.9^{\circ} \times (0.42 - 0.23) + Wcos18.4^{\circ} \times (0.23 - 0.21)}{0.42 - 0.21} = 0.994W$$

Because a majority of the “uplifted zone” is on the top deck, the normal component of the unit weight of ClosureTurf is very close to the total unit weight.

<u>Step 12</u>: Calculate effective suction

To account for a target wind resistance FS of 1.1, as discussed at the end of Section 3 of this Technical Note, the reduced unit weight of ClosureTurf (i.e., W/1.1) is used to calculate the effective suction, S_e, in the “uplifted zone”:

$$S_e = \bar{P} - \frac{\overline{W cos\beta}}{1.1} = \bar{P} - \frac{0.994W}{1.1} = 6.63 - \frac{0.994 \times 5.44}{1.1} = 1.71\ psf$$

<u>Step 13</u>: Calculate slope distance of "uplifted zone"

Based on the site geometry, the total horizontal distance at the base of the landfill is:

$$L_{landfill} = 2 \times (3 \times 100) + 200 = 800\ ft$$

The horizontal distance of the "uplifted zone" on the windward slope is: (0.23 – 0.21) x 800 ft = 16 ft. The horizontal distance of the "uplifted zone" on the top deck is: (0.42 – 0.23) x 800 ft = 152 ft.

The slope distance on the windward slope is: 16/cos18.4° = 16.9 ft. The slope distance on the top deck is: 152/cos2.9° = 152.2 ft.

The total slope distance of the "uplifted zone", L, is: 16.9 + 152.2 = 169.1 ft.

<u>Step 14</u>: Calculate ClosureTurf tensile stiffness

Assuming linear elastic deformation, the tension-strain relationship is expressed as:

$$T_w = J\varepsilon_w$$

ClosureTurf consists of the geomembrane and engineered turf components. The wind-induced tension in the ClosureTurf system is the sum of the tension in these two components:

$$T_w = T_{w,GM} + T_{w,ET} = J_{GM}\varepsilon_{w,GM} + J_{ET}\varepsilon_{w,ET}$$

where, GM denotes the geomembrane component and ET denotes the engineered turf component. Based on observations during wind tunnel testing showing that the engineered turf and underlying geomembrane were lifted together, it is assumed that the engineered turf and geomembrane have the same elongation and hence, the same tensile strain:

$$\varepsilon_{w,GM} = \varepsilon_{w,ET} = \varepsilon_w$$

Hence,

$$T_w = J_{GM}\varepsilon_{w,GM} + J_{ET}\varepsilon_{w,ET} = (J_{GM} + J_{ET})\varepsilon_w$$

Therefore, the total stiffness of ClosureTurf is:

$$J = J_{GM} + J_{ET}$$

Given that only 2-dimensional wind uplift is considered herein and the wind-uplift loading is short term, wide width tensile test results are considered appropriate for wind-uplift design. The wide width tensile testing according to ASTM D4885 was conducted on samples of the structured geomembranes of ClosureTurf (i.e., MicroSpike®, MicroDrain®, and Super Gripnet®). The results of this test program are summarized in Table A-2. Examples of the test results are included in Attachment C-2.

Table A-2. Wide Width Tensile Properties of Structured Geomembranes of ClosureTurf

Structured Geomembrane			Stiffness (lb/in)	Yield Strength (lb/in)	Yield Strain (%)	Maximum Strength (lb/in)	Elongation at Break (%)
HDPE	40-mil MicroSpike®	MD	2,681	100.8	15.9	105.7	485.9
		XD	3,059	108.6	10.6	108.6	413.1
	50-mil MicroDrain®	MD	2,739	124.3	29.8	147.4	393.6
		XD	4,053	146.3	10.9	146.3	458.2
	50-mil Super Gripnet®	MD	3,189	152.6	41.4	191.1	414.8
		XD	4,002	161.9	10.3	161.9	404.5
LLDPE	40-mil MicroSpike®	MD	1,193	69.7	22.5	80.2	476.9
		XD	1,391	69.9	17.8	74.2	487.6
	50-mil MicroDrain®	MD	1,972	106.4	24.8	130.2	466.4
		XD	2,192	110.1	14.3	119.2	483.2
	50-mil Super Gripnet®	MD	1,576	89.3	36.5	119.6	446.7
		XD	2,096	98.1	15.2	113.4	487.4

Notes: (1) MD = Machine Direction; XD = Cross-Machine Direction; (2) The stiffness values are the mean values of "Initial Tangent Modulus (lbs/in)" in the test reports.

Based on the wide width tensile test results, the stiffness values for the 50-mil HDPE and LLDPE Super Gripnet geomembranes are:

- For 50-mil HDPE Super Gripnet:
  - Machine Direction: $J_{GM,\ 50\text{-}mil\ HDPE\ SG,\ MD}$ = 3198 lb/in = 3.8×10^4 lb/ft
  - Cross-Machine Direction: $J_{GM,\ 50\text{-}mil\ HDPE\ SG,\ XD}$ = 4002 lb/in = 4.8×10^4 lb/ft

- For 50-mil LLDPE Super Gripnet:
  - Machine Direction: $J_{GM,\ 50\text{-}mil\ LLDPE\ SG,\ MD}$ = 1576 lb/in = 1.9×10^4 lb/ft
  - Cross-Machine Direction: $J_{GM,\ 50\text{-}mil\ LLDPE\ SG,\ XD}$ = 2096 lb/in = 2.5×10^4 lb/ft

The wide width tensile testing was also conducted on the standard-density engineered turf (see Attachment C-3). The average peak tensile strength was reported as 3,633 lb/ft at 28.2% strain on MD and 2,300 lb/ft at 9.8% strain on XD. The tension-strain curve before the peak is approximately linear. Therefore, the stiffness of the standard engineered turf is calculated as:

$$J_{ET,\ MD} = 3633 \text{ lb/ft} / 0.282 = 1.3 \times 10^4 \text{ lb/ft}$$

$J_{ET,\,XD}$ = 2300 lb/ft / 0.098 = 2.3x10^4 lb/ft

For the hypothetical project in this example, the 50-mil LLDPE geomembrane and standarddensity engineered turf are considered. Since during panel layout the machine direction of the engineered turf usually aligns with the machine direction of the engineered turf, the total stiffness of ClosureTurf is calculated as follows:

- $J = J_{GM,50-mil\ LLDPE\ SG,MD} + J_{ET,MD} = 1.9 \times 10^4 + 1.3 \times 10^4 = 3.2 \times 10^4$, along MD of engineered turf and structured geomembrane
- $J = J_{GM,50-mil\ LLDPE\ SG,XD} + J_{ET,XD} = 2.5 \times 10^4 + 2.3 \times 10^4 = 4.8 \times 10^4$, along XD of engineered turf and structured geomembrane

Step 15: Calculate tensile strain in ClosureTurf

The tensile strain in ClosureTurf is calculated along both the MD and XD of the engineered turf and structured geomembrane, as tension may be induced in either direction depending on the panel layout and wind direction.

The strain in ClosureTurf along the MD of the engineered turf and structured geomembrane is calculated as:

$$\varepsilon_{w,MD} = \frac{0.3467\left(\frac{S_e L}{J}\right)^{2/3}}{1 - 0.3103\left(\frac{S_e L}{J}\right)^{2/3}} = \frac{0.3467\left(\frac{1.71 \times 169.1}{3.2 \times 10^4}\right)^{2/3}}{1 - 0.3103\left(\frac{1.71 \times 169.1}{3.2 \times 10^4}\right)^{2/3}} = 0.015 = 1.5\%$$

The strain in ClosureTurf along the XD of the engineered turf and structured geomembrane is calculated as:

$$\varepsilon_{w,XD} = \frac{0.3467\left(\frac{S_e L}{J}\right)^{2/3}}{1 - 0.3103\left(\frac{S_e L}{J}\right)^{2/3}} = \frac{0.3467\left(\frac{1.71 \times 169.1}{4.8 \times 10^4}\right)^{2/3}}{1 - 0.3103\left(\frac{1.71 \times 169.1}{4.8 \times 10^4}\right)^{2/3}} = 0.012 = 1.2\%$$

The calculated tensile strain values are significantly less than the tensile strain at yield of the 50mil LLDPE Super Gripnet in either MD (i.e., 36.5%) or XD (i.e., 15.2%) (see Table A-2). These values are also significantly less than the tensile strain at yield in either MD (i.e., 28.2%) or XD (i.e., 9.8%) of the engineered turf. The calculated tensile strain values indicate that both the geomembrane and engineered turf are within the range of elastic deformations.

Step 16: Calculate tension in ClosureTurf

The tension in ClosureTurf along the MD of the engineered turf and structured geomembrane is calculated as:

$$T_{w,GM,MD} = 1.9 \times 10^4 \times 0.015 = 285\ lb/ft \text{ (Geomembrane)}$$

$$T_{w,ET,MD} = 1.3 \times 10^4 \times 0.015 = 195\ lb/ft \text{ (Engineered Turf)}$$

The total tension along MD is: $T_{w,MD} = 285 + 195 = 480\ lb/ft$

The tension in ClosureTurf along the XD of the engineered turf is calculated as:

$$T_{w,GM,XD} = 2.5 \times 10^4 \times 0.012 = 300\ lb/ft \text{ (Geomembrane)}$$

$$T_{w,ET,XD} = 2.3 \times 10^4 \times 0.012 = 276\ lb/ft \text{ (Engineered Turf)}$$

The total tension along XD is: $T_{w,XD} = 300 + 276 = 576\ lb/ft$

Step 17: Calculate factor of safety (FS) against yield

For the 50-mil LLDPE Super Gripnet geomembrane, the wide width tensile strength at yield is 89.3 lb/in (or 1,072 lb/ft) in the MD and 98.1 lb/in (or 1,177 lb/ft) in the XD, as presented in Table A-2. The FS against yield is calculated as:

$$FS_{y,GM} = \frac{T_y}{T_w} = \frac{1072}{285} = 3.8 \text{ (MD)}$$

$$FS_{y,GM} = \frac{T_y}{T_w} = \frac{1177}{300} = 3.9 \text{ (XD)}$$

For the standard-density engineered turf, the wide width tensile strength at yield is 3,633 lb/ft (MD) and 2,300 lb/ft (XD). The FS against yield is calculated as:

$$FS_{y,ET} = \frac{T_y}{T_w} = \frac{3633}{195} = 18.6\ (MD)$$

$$FS_{y,ET} = \frac{T_y}{T_w} = \frac{2300}{276} = 8.3\ (XD)$$

A minimum acceptable FS of 2.0 is selected in this example to incorporate both a global FS of 1.5 and possible minor reductions in ClosureTurf stiffness due to construction-related and long-term exposure-related effects. The above calculated FSs against yield of the geomembrane and engineered turf are greater than the minimum acceptable FS. Therefore, tensile yield of the geomembrane and engineered turf components of ClosureTurf in the "uplifted zone" due to wind-induced loads should not occur. The ClosureTurf located outside the "uplifted zone" is not expected to experience uplift based on the analysis results. In addition, the ClosureTurf final cover system is required to be terminated in an anchor trench along the perimeter of the landfill, providing additional wind uplift resistance in areas proximal to the anchor trench.

Based on the analysis results for the hypothetical example landfill, wind uplift in a local area near the landfill slope crest is expected under the selected design wind speed; however, no damage to the engineered turf or underlying structured geomembrane is anticipated due to the wind-induced loads. The ClosureTurf final cover system at this hypothetical landfill site is judged to have an adequate FS against tensile yield due to wind uplift.

Attachment C-2

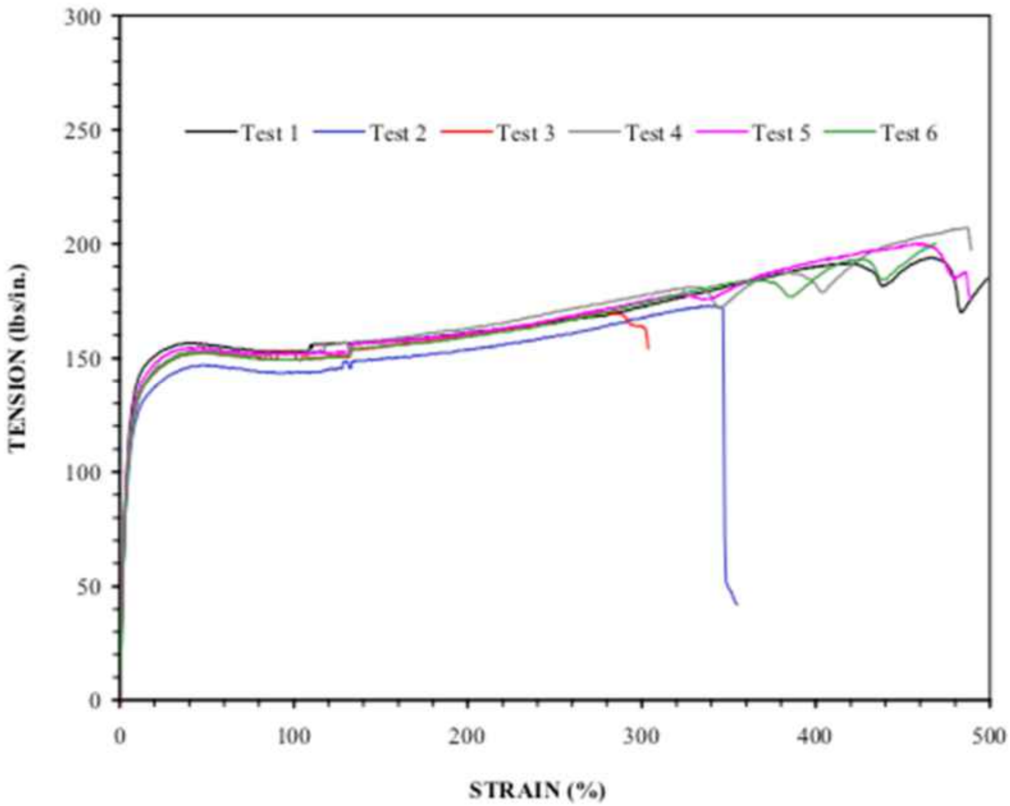
Examples of Wide Width Tensile Test Results of Structured Geomembranes of ClosureTurf

WATERSHED GEOSYNTHETICS LLC

WIDE-WIDTH TENSILE TESTING OF GEOMEMBRANE (ASTM D 4885)

Agru 50-mil HDPE Super Gripnet Geomembarne # GTA 0068830036 in MD

SGI Lab Sample ID: S23273



Test No.	Initial Tangent Modulus (lbs/in)	Tension at 5% (lbs/in)	Tension at 10% (lbs/in)	Yield Strength (lbs/in)	Yield Strain (%)	Max Strength (lbs/in)	Elongation at Breaking (%)
1	3004	112.1	139.1	156.7	37.2	194.1	464.2
2	3125	100.2	124.7	146.9	46.4	173.0	334.4
3	3251	106.0	130.7	151.8	43.0	170.0	271.3
4	3045	103.8	129.7	153.2	39.5	206.9	483.0
5	3501	109.5	134.2	154.7	38.8	200.0	456.1
6	3207	106.2	131.2	152.3	43.5	202.6	479.9
Mean	3189	106.3	131.6	152.6	41.4	191.1	414.8
STD	179	4.2	4.8	3.3	3.5	15.8	89.5

NOTES:

Clamp:	Curtis Sure Grip with cushion
Specimen Width (in.):	8.0
Specimen Length (in.):	8.0
Gage Length (in.)	4.0
Strain Rate (% per minute):	10

SGI TESTING SERVICES, LLC

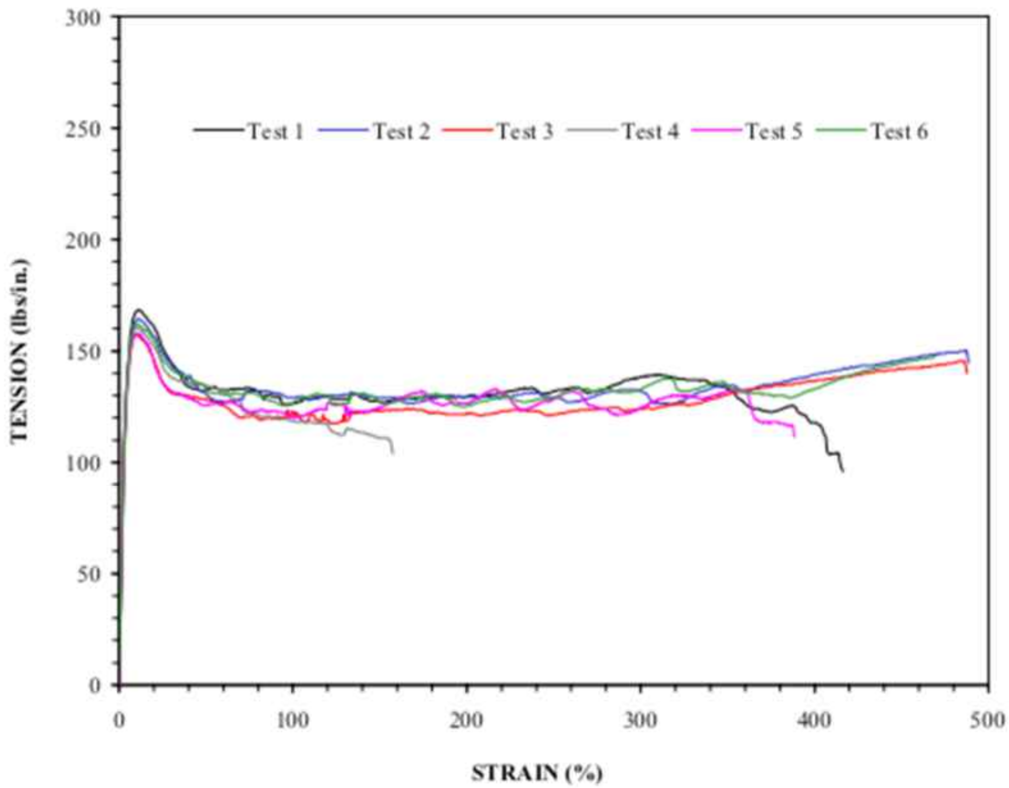
DATE OF REPORT:	11/3/2021
FIGURE NO.	9
PROJECT NO.	SGI21014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC

WIDE-WIDTH TENSILE TESTING OF GEOMEMBRANE (ASTM D 4885)

Agru 50-mil HDPE Super Gripnet Geomembarne # GTA 0068830036 in XD

SGI Lab Sample ID: S23273



Test No.	Initial Tangent Modulus (lbs/in)	Tension at 5% (lbs/in)	Tension at 10% (lbs/in)	Yield Strength (lbs/in)	Yield Strain (%)	Max Strength (lbs/in)	Elongation at Breaking (%)
1	3855	140.5	167.8	168.6	11.3	168.6	416.2
2	3779	139.3	163.8	164.6	10.9	164.6	488.5
3	4218	138.6	157.2	157.2	9.4	157.2	487.7
4	4195	140.6	160.6	160.6	9.7	160.6	157.3
5	3981	135.7	157.7	158.2	10.4	158.2	388.5
6	3983	138.5	161.9	162.1	10.2	162.1	489.0
Mean	4002	138.9	161.5	161.9	10.3	161.9	404.5
STD	177	1.8	4.0	4.2	0.7	4.2	128.5

NOTES:

Clamp:	Curtis Sure Grip with cushion
Specimen Width (in.):	8.0
Specimen Length (in.):	8.0
Gage Length (in.)	4.0
Strain Rate (% per minute):	10

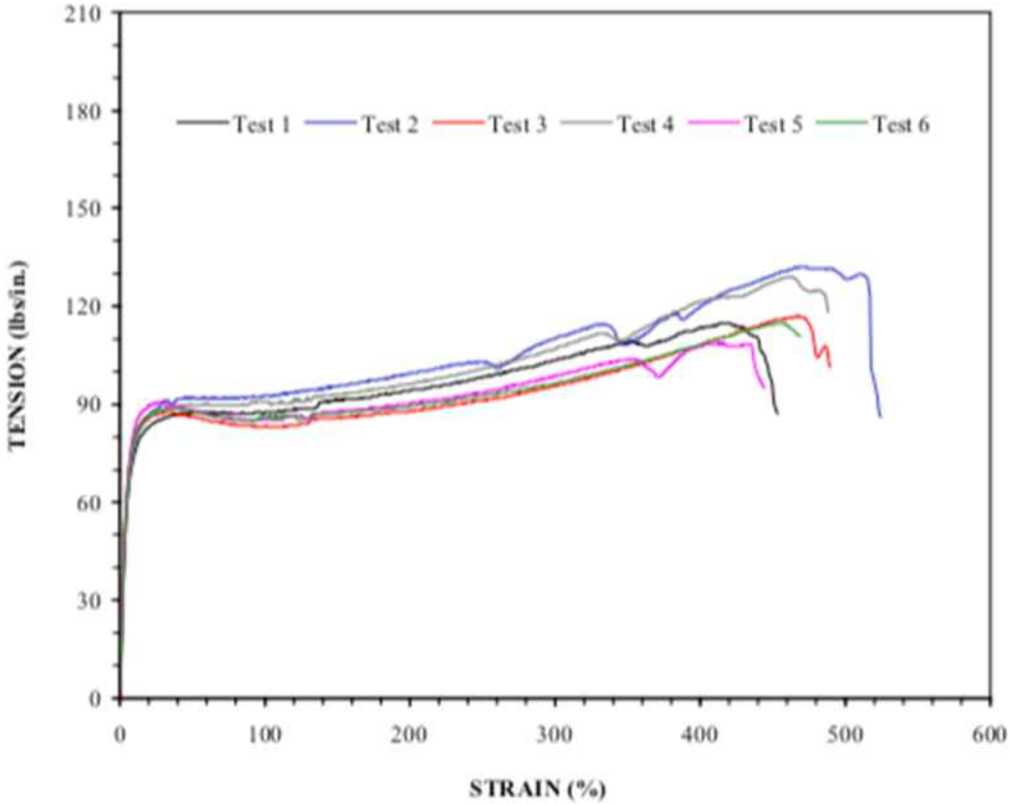
SGI TESTING SERVICES, LLC

DATE OF REPORT:	11/4/2021
FIGURE NO.	10
PROJECT NO.	SGI21014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC
WIDE-WIDTH TENSILE TESTING OF GEOMEMBRANE (ASTM D 4885)

Agru 50-mil LLDPE Super Gripnet Geomembarne #FNA0039890078 in MD

SGI Lab Sample ID: S23269



Test No.	Initial Tangent Modulus (lbs/in)	Tension at 5% (lbs/in)	Tension at 10% (lbs/in)	Yield Strength (lbs/in)	Yield Strain (%)	Max Strength (lbs/in)	Elongation at Breaking (%)
1	1593	57.9	74.8	87.2	41.3	115.3	417.7
2	1815	62.8	78.6	91.8	39.0	132.5	470.0
3	1694	63.7	80.0	87.6	33.5	117.3	467.4
4	1514	60.6	77.1	89.8	40.8	129.1	460.4
5	1383	64.2	82.5	90.7	27.8	108.9	412.7
6	1460	60.9	79.4	88.6	36.8	114.8	451.7
Mean	1576	61.7	78.7	89.3	36.5	119.6	446.7
STD	159	2.3	2.6	1.8	5.1	9.1	25.3

NOTES:

Clamp:	Curtis Sure Grip with cushion
Specimen Width (in.):	8.0
Specimen Length (in.):	8.0
Gage Length (in.)	4.0
Strain Rate (% per minute):	10

SGI TESTING SERVICES, LLC

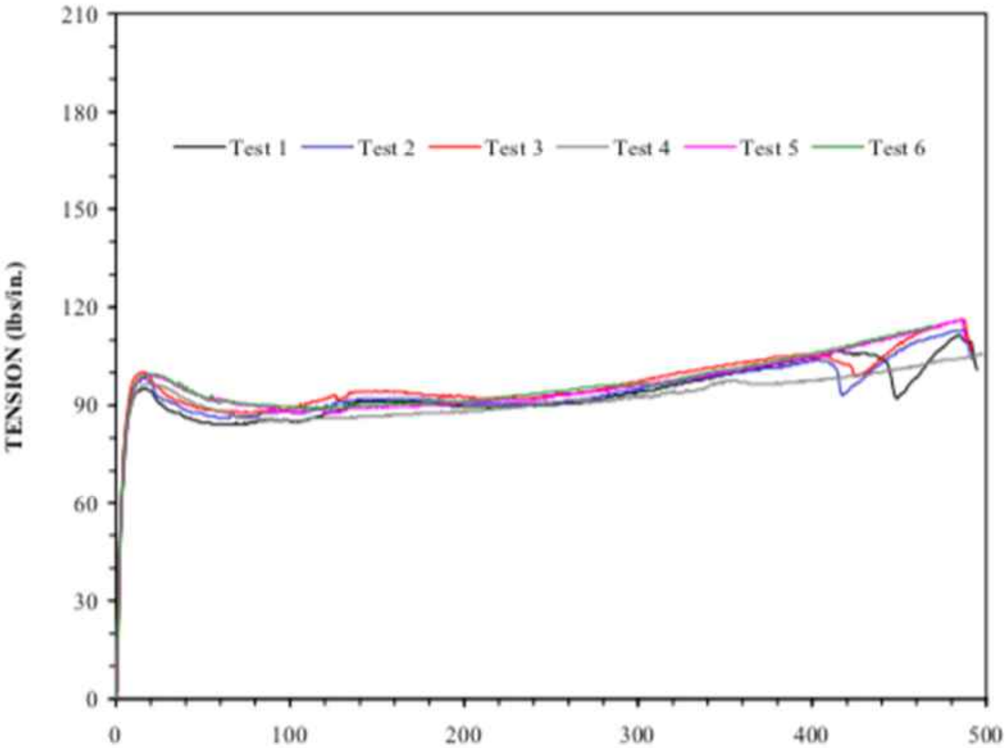
DATE OF REPORT:	10/24/2021
FIGURE NO.	1
PROJECT NO.	SGI21014
DOCUMENT NO.	
FILE NO.	

WATERSHED GEOSYNTHETICS LLC

WIDE-WIDTH TENSILE TESTING OF GEOMEMBRANE (ASTM D 4885)

Agru 50-mil LLDPE Super Gripnet Geomembarne #FNA0039890078 in XD

SGI Lab Sample ID: S23269



Test No.	Initial Tangent Modulus (lbs/in)	Tension at 5% (lbs/in)	Tension at 10% (lbs/in)	Yield Strength (lbs/in)	Yield Strain (%)	Max Strength (lbs/in)	Elongation at Breaking (%)
1	2034	75.3	92.6	95.1	14.4	111.3	482.8
2	2180	79.3	95.2	98.5	15.9	113.3	486.7
3	2064	80.5	97.7	100.0	13.5	116.8	487.4
4	2149	74.5	92.2	96.6	16.0	105.9	497.1
5	2048	75.4	94.0	99.0	17.0	116.3	485.4
6	2102	77.3	95.2	99.5	14.3	116.8	485.0
Mean	2096	77.1	94.5	98.1	15.2	113.4	487.4
STD	58	2.4	2.0	1.9	1.3	4.3	5.0

NOTES:

Clamp:	Curtis Sure Grip with cushion
Specimen Width (in.):	8.0
Specimen Length (in.):	8.0
Gage Length (in.)	4.0
Strain Rate (% per minute):	10

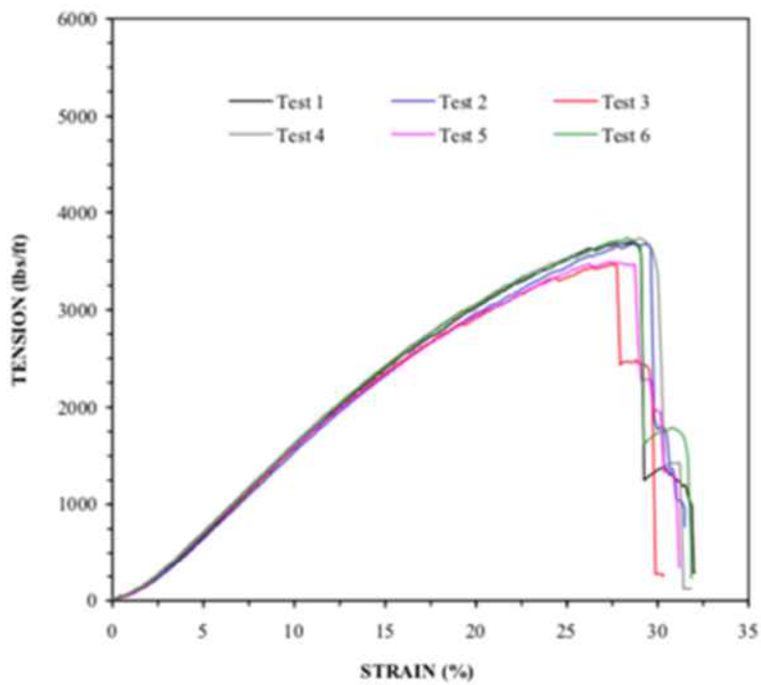
SGI TESTING SERVICES, LLC

DATE OF REPORT:	11/3/2021
FIGURE NO.	2
PROJECT NO.	SGI21014
DOCUMENT NO.	
FILE NO.	

Attachment C-3

Wide Width Tensile Test Results of Standard-Density Engineered Turf

WATERSHED GEOSYNTHETICS LLC
WIDE-WIDTH TENSILE TESTING (ASTM D 4595)
CT32 Synthetic Turf Sample in MD
SGI Sample ID No. S22008



Test No.	Tension at 2% (lb/ft)	Tension at 5% (lb/ft)	Tension at 10% (lb/ft)	Ultimate Strength (lb/ft)	Strain at Ultimate (%)
1	177	670	1580	3689	28.4
2	166	650	1541	3675	28.6
3	185	683	1571	3464	27.4
4	205	725	1636	3734	29.0
5	191	701	1583	3494	27.3
6	193	699	1605	3741	28.3
Mean	186	688	1586	3633	28.2
STD	13	26	32	122	0.7

NOTES:

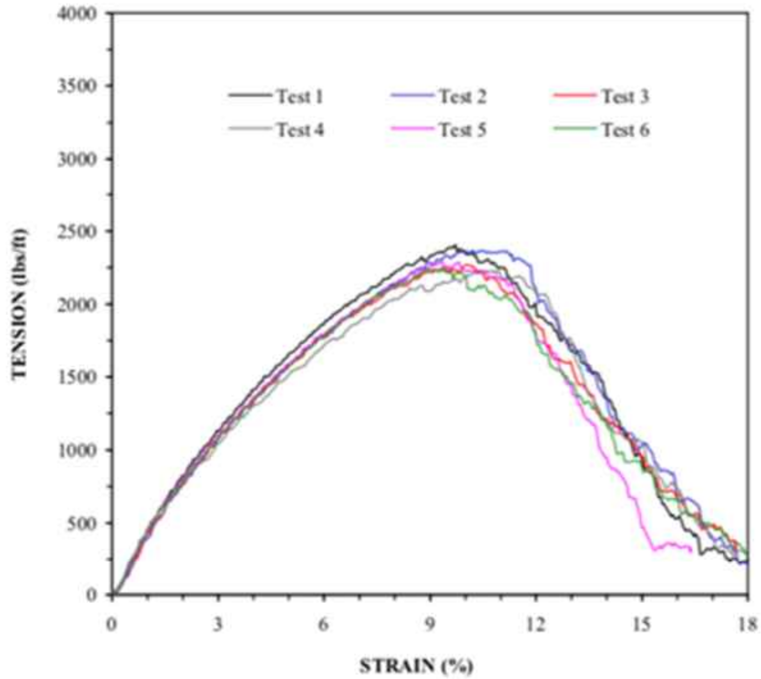
Clamp:	Curtis
Specimen Width (in.):	8.0
Yarn Count (yarns/in.):	Not Measured
Specimen Length (in.):	8
Preload (lbs):	1% of breaking load
Strain Rate (% per minute):	10

SGI TESTING SERVICES, LLC

DATE TESTED:	4/10/2019
FIGURE NO.	2
PROJECT NO.	SGI19014
DOCUMENT NO.	
FILE NO.	

Note: “CT32 Synthetic Turf” denoted in the test report is the standard-density engineered turf, CT.

WATERSHED GEOSYNTHETICS LLC
WIDE-WIDTH TENSILE TESTING (ASTM D 4595)
CT32 Synthetic Turf Sample in XD
SGI Sample ID No. S22008



Test No.	Tension at 2% (lb/ft)	Tension at 5% (lb/ft)	Tension at 10% (lb/ft)	Ultimate Strength (lb/ft)	Strain at Ultimate (%)
1	825	1662	NA	2405	9.7
2	772	1584	2359	2368	10.2
3	769	1577	NA	2265	10.0
4	786	1514	2182	2228	10.6
5	809	1582	NA	2284	9.3
6	792	1570	NA	2247	9.3
Mean	792	1582	NC	2300	9.8
STD	22	47	NC	71	0.5

NOTES:

Clamp:	Curtis
Specimen Width (in.):	8.0
Yarn Count (yarns/in.):	Not Measured
Specimen Length (in.):	8
Preload (lbs):	1% of breaking load
Strain Rate (% per minute):	10

SGI TESTING SERVICES, LLC

DATE TESTED:	4/10/2019
FIGURE NO.	3
PROJECT NO.	SGI19014
DOCUMENT NO.	
FILE NO.	

Note: "CT32 Synthetic Turf" denoted in the test report is the standard-density engineered turf, CT.

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LIMITATIONS

Appendix D
ClosureTurf Hydrostatic Puncture Test Report

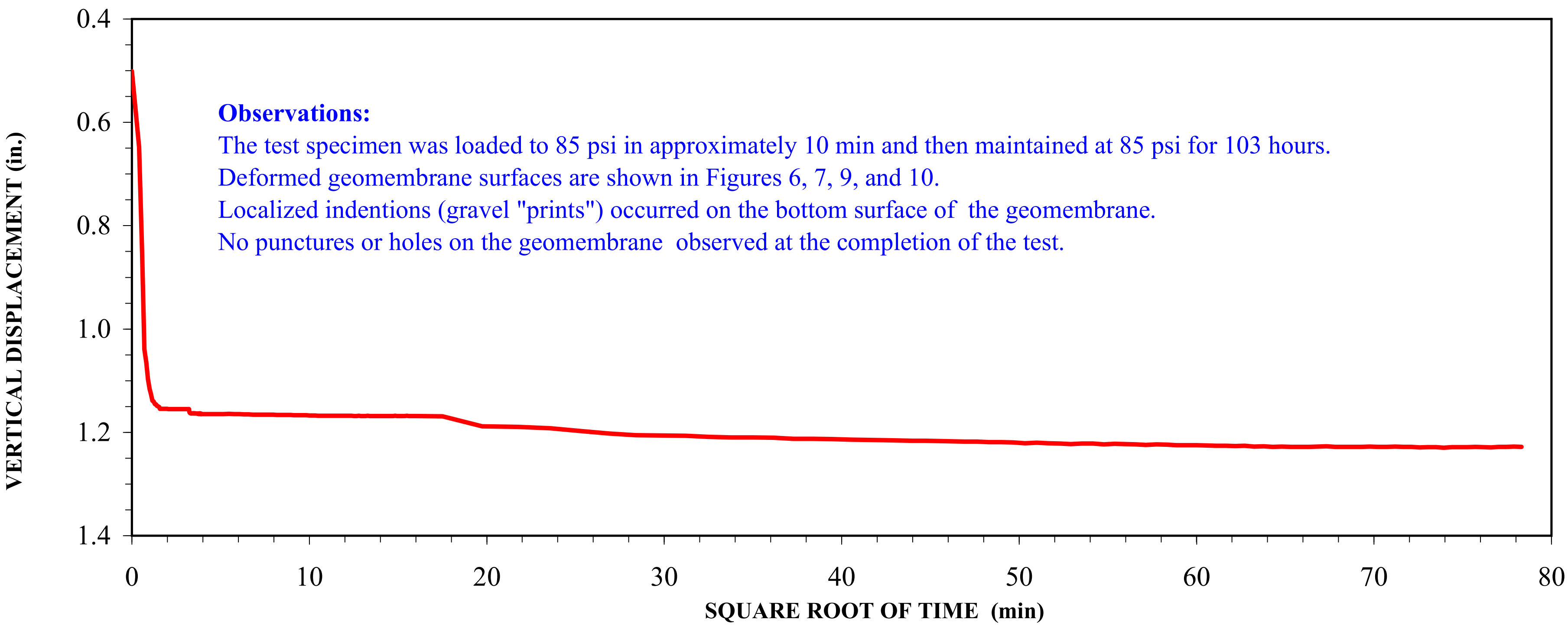
Hydrostatic Puncture Test Report

Notes:

1. The testing was performed on the HydroTurf sample; however, the test results are applicable to ClosureTurf because they both consist of structured geomembrane and engineered turf.
2. The testing was performed on a 40-mil MicroSpike geomembrane. If a thicker (i.e., 50-mil) MicroDrain or Super Gripnet geomembrane is used in ClosureTurf, th epuncture performance is expected to be improved.
3. The testing was performed at a maximum loading of 85 psi. Since no punctures or holes were observed, the ultimate static puncture strength of the system was not reached and therefore, should be greater than 85 psi.

WATERSHED GEOSYNTHETICS LLC- VIRGINIA PROJECT
HYDROSTATIC PUNCTURE TESTING (ASTM D 5514[1])

Concrete sand
HydroeTurf (2.25" long monofilament) #ZH37391 with geotextile (straight stitching pattern) down
Agru 40-mil Microspike HDPE geomembrane #G18C000439 with dull side up and shiny side down
VDOT #57 stone nominally compacted



Test No.	Test Specimen Size: Length (in.)	Width (in.)	Upper Soil Thickness (in.)	Lower Soil Thickness (in.)	Normal Stress (psi)	Total Duration (hours)	Concrete sand: γ_d (pcf)	ω_i (%)	ω_f (%)	#57 Stone: γ_d (pcf)	ω_i (%)	ω_f (%)
1	12.0	12.0	3.0	6.0	85	102						

***NOTE: (1)** Localized strains of the deformed geomembrane not calculated.*

SGI TESTING SERVICES, LLC

DATE OF REPORT:	3/2/2018
FIGURE NO.	A-2
PROJECT NO.	SGI18014
DOCUMENT NO.	
FILE NO.	

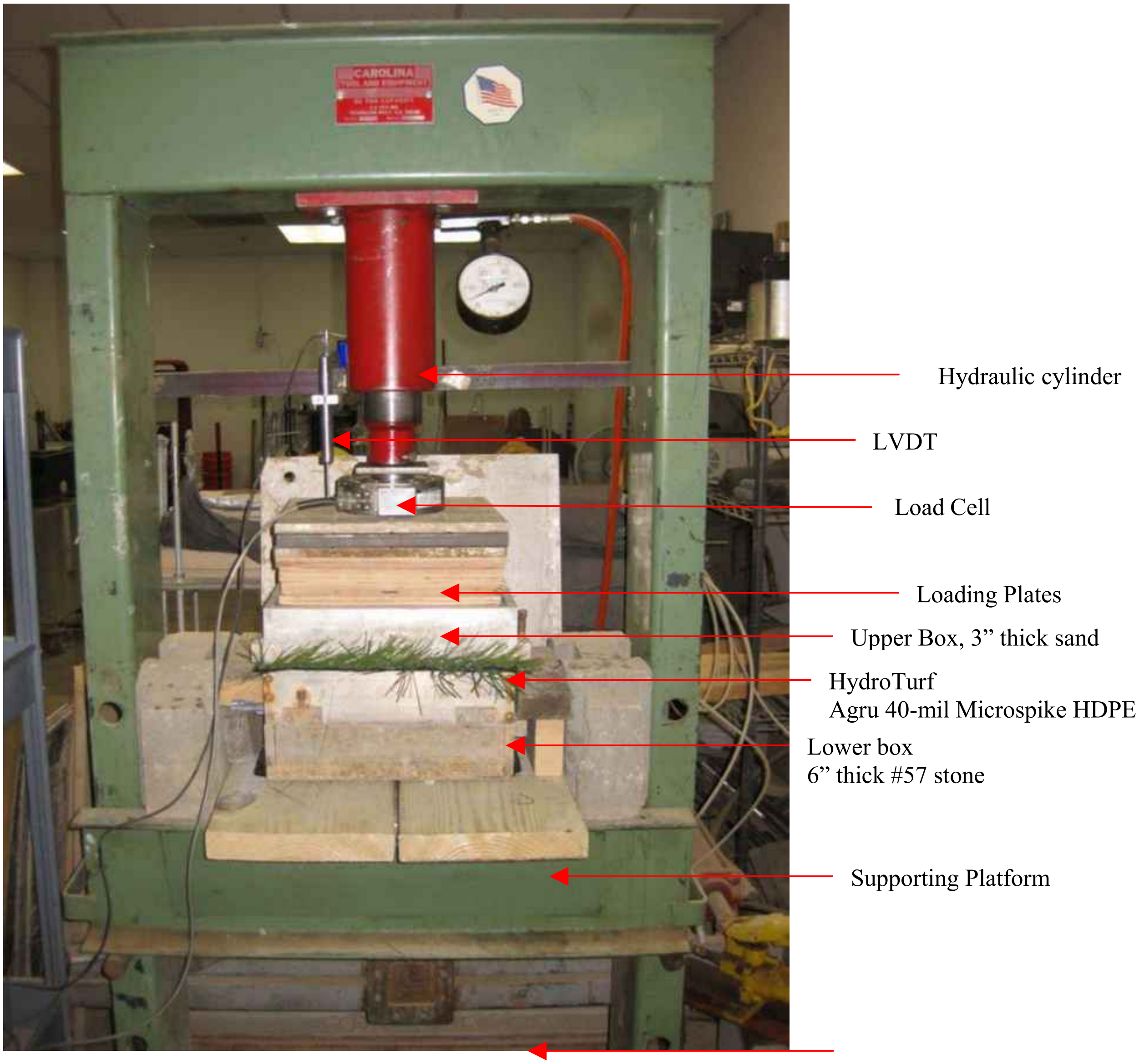


Figure 1. View of hydrostatic puncture test setup.

Figure 2. Compacted VDOT #57 stone in the lower box.

Figure 3. HydroTurf and geomembrane placed on top of compacted #57 stone.


Figure 4.   Concrete sand placed in the upper box on top of HydroTurf.

Figure 5. Bottom surface of HydroTurf after the completion of test.

Figure 6. Deformed top surface of the geomembrane after the completion of test. No punctures or holes observed.

Figure 7. Deformed bottom surface of the geomembrane in contact with #57 stone after the completion of test. No punctures or holes observed.

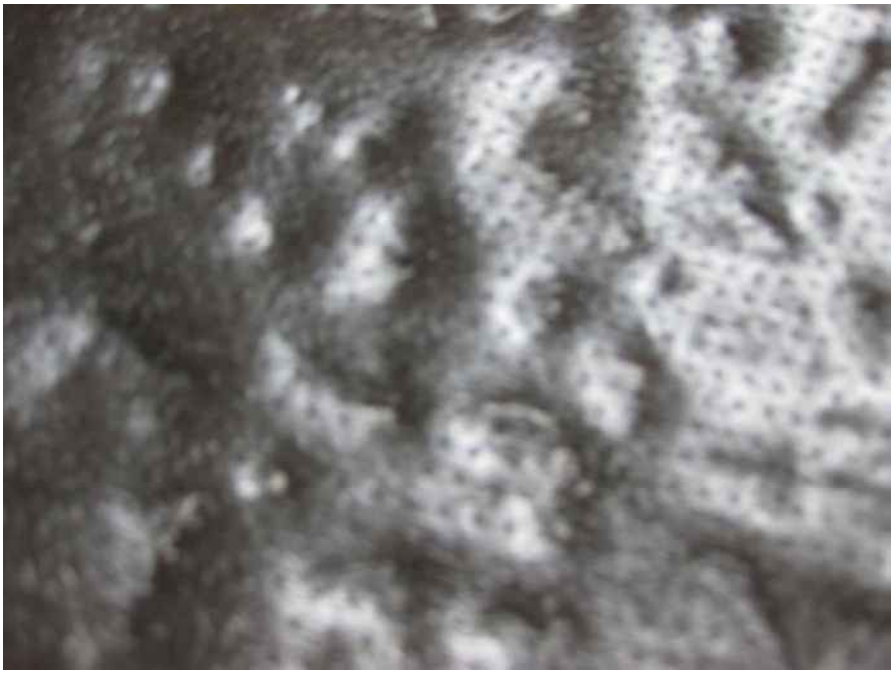


Figure 8. Deformed bottom surface of the geomembrane in contact with #57 stone after the completion of test. No punctures or holes observed.

Figure 9. Deformed top surface of the geomembrane after the completion of test. No punctures or holes observed.

Appendix E
Parametric Study Results for Pond Design

Comparing Stormwater Pond Design for Traditional Soil Cover versus Engineered Synthetic Turf Cover

Antonio Sanchez[1] and Ming Zhu[2]

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[2]Watershed Geosynthetics, 11400 Atlantis Place, Suite 200, Alpharetta, GA 30022

CONFERENCE: 2019 World of Coal Ash – (www.worldofcoalash.org)

KEYWORDS: Landfill Final Cover, Stormwater Pond Design, Engineered Synthetic Turf Cover

ABSTRACT: A parametric study is performed to compare the stormwater pond design of a conceptual waste disposal site with two final cover systems: a traditional soil cover system and an engineered synthetic turf cover system, ClosureTurf®. The geometry of the conceptual site and the design storm events are varied in the study. Two representative runoff curve numbers (CN) are considered for the traditional soil cover system. The stormwater pond is designed with the capacity to attenuate the stormwater runoff flows, as well as to promote water quality treatment through settling of suspended solids. Because the runoff from the ClosureTurf cover system carries little to no solids, the analysis is also performed without the requirement of sediment storage volume for ClosureTurf.

The stormwater analysis results of the traditional soil cover system and the ClosureTurf cover system are compared, including the time of concentration, the perimeter channel peak flow depth, and the stormwater pond peak depth, peak discharge, and peak storage. The analysis results of the conceptual site indicate that the ClosureTurf cover system generates higher peak runoff flow rates than the traditional soil cover system. Under the 25-year (yr), 24-hour (hr) design storm event, the calculated peak storage of the stormwater pond for the ClosureTurf cover system increases by approximately 5% and 10%, respectively, compared to the traditional soil cover system with a CN of 84 and 74; while under the 100-yr, 24-hr design storm event, it increases by approximately 10% and 20%, respectively.

INTRODUCTION

The final cover system is critical to environmental closures of waste disposal facilities, e.g., landfills and coal combustion residual (CCR) impoundments. A traditional soil cover system is typically comprised of (from top to bottom): (i) a topsoil layer; (ii) a vegetative soil layer; (iii) a geocomposite drainage layer; and (iv) a geomembrane barrier layer. The traditional soil cover system design necessitates a construction process with a steady supply of final cover soils. Furthermore, on-going maintenance of the traditional soil cover system is required to establish vegetative cover, which often includes repairing erosion and addressing sedimentation issues during construction and operation of the final cover system.

ClosureTurf is a relatively new alternative to traditional soil cover systems that has been used in the past 10 years. It is comprised of (from bottom to top): (i) a structured geomembrane, (ii) an engineered turf, and (iii) a specialized sand infill (bonded or unbonded). This system replaces the topsoil and vegetative soil layers thereby mitigating the need for a supply of final cover soils. It has also demonstrated other benefits, including faster construction speed, improved runoff quality, reduced post-closure maintenance cost, and less environmental and community impact (e.g., no land disturbance for borrow soils and less truck trips through neighboring communities).

This study presents a comparative analysis of the stormwater pond design between the traditional soil cover system and the ClosureTurf cover system. The sections below discuss the design criteria, design methodology, input parameters, and analysis results.

DESIGN CRITERIA

The following criteria are used in designing the stormwater pond.

Peak Flow Management

A fundamental aspect of landfill engineering is the design of stormwater pond to satisfy local and state regulatory requirements for pre-development versus post-development hydrology. The stormwater pond is designed such that the pre-development peak discharge flow rate is less than the post-development for the 2-, 5-, 10-, 25-, and 100-yr, 24-hr storm events.

Wet Detention Pond

The stormwater pond is designed as a wet detention pond to achieve water quality and quantity performance. A wet detention pond is an impounded area with the capacity to attenuate the stormwater runoff flows and promote water quality treatment through settling of suspended solids. The wet detention pond for the traditional soil cover system is required to include the sediment storage volume within the permanent pool volume. For ClosureTurf, the sediment storage volume is not needed because the runoff carries little to no solids.

The wet detention pond is designed with a primary spillway to manage flows up to the 25-yr, 24-hr storm event and an emergency spillway to support managing flows up to the 100-yr, 24-hr storm event without overtopping. Under the 25-yr, 24-hr storm event, the pond is designed without overtopping into the emergency spillway. Under the 100-yr, 24-hr storm event, the pond is designed to have at least 1.0 feet (ft) (0.3 meters, m) of freeboard. A pre-treatment forebay is not considered in the study.

Water Quality Volume (WQV)

WQV is the storage needed to capture and treat the runoff from 90% of the average annual rainfall. For the purposes of this study, the WQV for the site is assumed to be runoff for the 1.0-inch (2.5 centimeters, or cm) rainfall event and the design treatment is the release of the WQV over 24 to 72 hr after the storm event.

Sediment Storage Volume

For a traditional soil cover system, the permanent pool within the stormwater pond is typically required to include the sediment storage volume for erosion and sedimentation management. The sediment storage volume used in this study is equivalent to 67 cubic yards per acre of drainage area (or 127 cubic meters per hectare). As discussed previously, this volume is not needed for ClosureTurf. For the purposes of this study, ClosureTurf is analyzed with and without the sediment storage volume to evaluate its effect on the overall stormwater pond design.

Channel Geometry

Stormwater runoff and concentrated discharges from the final cover are conveyed to the wet detention pond via perimeter channels. In this study, the perimeter channels are designed to convey the flow for the 25-yr, 24-hr storm event with at least 0.5 ft (0.15 m) of freeboard.

DESIGN METHODOLOGY

Modeling Software

The design calculations for the drainage areas, channels, and ponds are performed using the hydrology and hydraulic procedures in the Soil Conservation Service (SCS) Technical Release (TR-55) [SCS, 1986] and other recognized engineering procedures and equations, such as the Manning's kinematic equation, that are encoded in the HydroCAD™ software [HydroCAD, 2018].

Runoff Curve Number

SCS TR-55 includes the Runoff Curve Number Method for estimating runoff flow depth.

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \tag{1}$$

$$S = \frac{1000}{CN} - 10 \tag{2}$$

Where, Q = runoff (inches, in.); P = rainfall (in.); S = potential maximum retention after runoff begins (in.); and CN = curve number. S expresses the soil and cover conditions of the drainage area through the variable CN, which has a range of 0 to 100.

Travel Time

SCS TR-55 includes the travel time methods for sheet flow, shallow concentrated flow, and open channel flow. For the purposes of this study, it is assumed that sheet flow and shallow concentrated flow characterize the stormwater runoff over the cover systems. Travel time for sheet flow is calculated as follows [SCS, 1986]:

$$T_s = \frac{0.007\ (nL)^{0.8}}{(P_2{}^{0.5})s^{0.4}} \tag{3}$$

Where, T_s = sheet flow travel time (hr); n = Manning's roughness coefficient; L = sheet flow length (ft); P_2 = 2-yr, 24-hr rainfall (in.); and s = slope of hydraulic grade line (land slope, ft/ft).

After a maximum of 100 ft, sheet flow is assumed to become shallow concentrated flow. Travel time for shallow concentrated flow is calculated [SCS, 1986] as follows:

$$T_{sc} = \frac{L}{3600V} \tag{4}$$

$$V = Ks^{0.5} \tag{5}$$

Where, T_{sc} = shallow concentrated flow travel time (hr); L = shallow concentrated flow length (ft); V = unpaved surface flow velocity (ft per second, or fps); K is the velocity factor (fps); and s = slope of hydraulic grade line (land slope, ft/ft).

Time of Concentration

The sum of T_s and T_{sc} for a drainage area is the time of concentration, which is the total duration time for runoff to travel from the hydraulically most distant point in the drainage to a point of interest, such as an outfall or confluence.

INPUT PARAMETERS

ClosureTurf exhibits a reduced potential for evapotranspiration and stormwater infiltration due to absence of soil layers in the final cover system. Therefore, it is important to summarize the difference in input parameters used for the traditional soil cover system and ClosureTurf cover system to calculate the stormwater runoff.

Rainfall

For the purposes of the study, Effingham, South Carolina is selected as the site location. The vicinity of the site is classified as either a Type II or III rainfall distribution [SCS, 1986]. Table 1 [NOAA, 2019] lists the rainfall depths associated with the 24-hr design storm events.

Table 1. Rainfall Depths for 24-hr Storm Events

24-hr Storm Event	Rainfall Depth (in.; cm in parentheses)
2-yr	3.54 (9.0)
5-yr	4.52 (11.5)
10-yr	5.38 (13.7)
25-yr	6.71 (17.0)
100-yr	9.20 (23.4)

Existing Conditions and Site Design

The site is assumed to be a 40-acre (16-hectare) area with a combined woods and grass land cover under the existing conditions. The site soils are assumed to be of the hydrologic soil group (HSG) 'B' classification, which is designated for moderately deep and well-draining soils with fine to course texture. The drainage within the site is characterized by a 1% land slope from the headwaters of the site down to the outfall.

The conceptual site design for both the final cover systems is assumed to be a simple landfill design comprised of a singular peak elevation with a shallow top deck that drains onto steeper side slopes. The side slopes do not include benches because their length is less than 100 ft (30.5 m), which is the maximum sheet flow length. The stormwater runoff from the side slopes is collected and conveyed by channels that discharge into the stormwater pond. For the purposes of this study, the top deck slopes and side slopes vary to assess the effect on the stormwater pond design. Table 2 lists the top deck and side slope variations for each scenario. A schematic of the site stormwater management system is presented in Figure 1.

Table 2. Site Geometry Scenarios

Scenario	Side Slopes	Top Deck Slopes
1	5H:1V	1%
2	5H:1V	2%
3	5H:1V	5%
4	5H:1V	8%
5	3H:1V	1%
6	3H:1V	2%
7	3H:1V	5%
8	3H:1V	8%

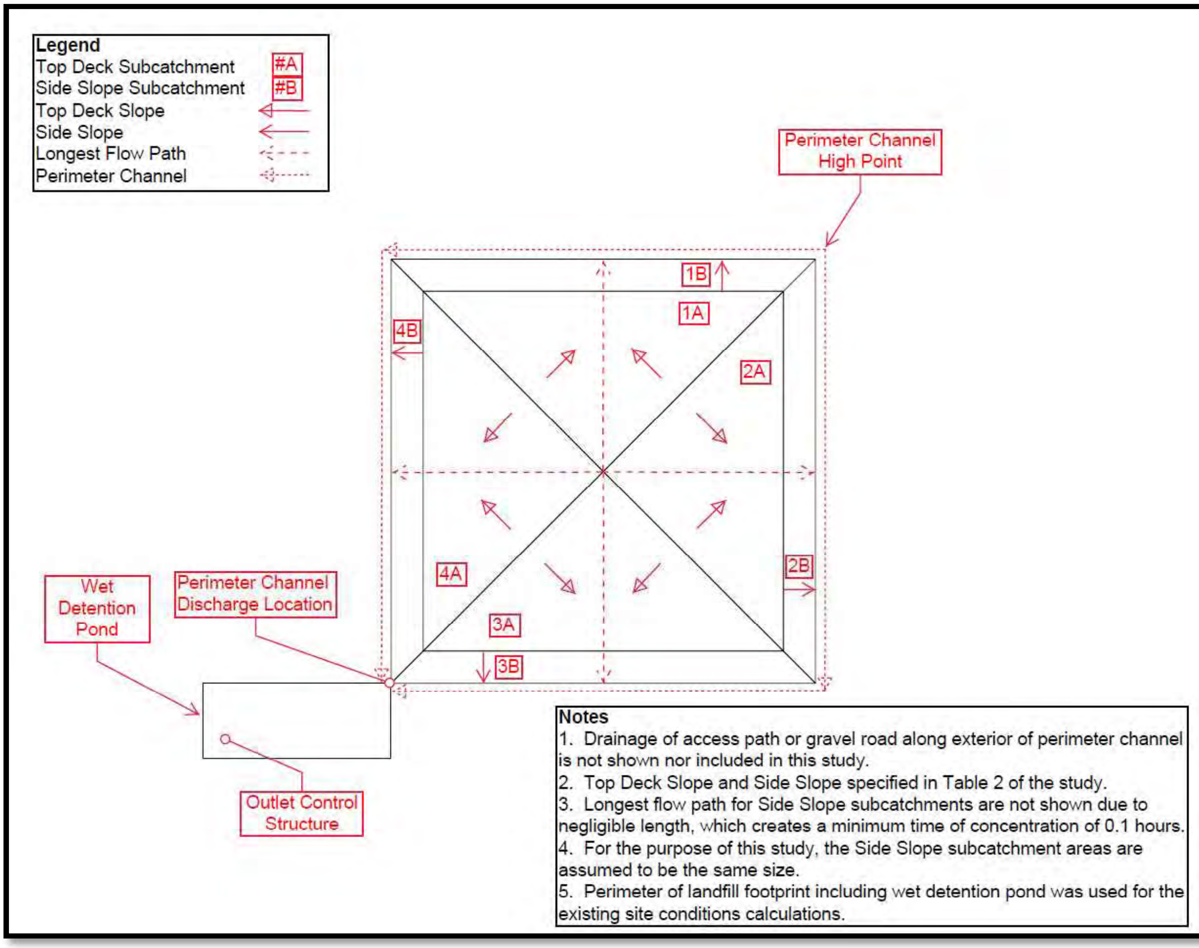

Figure 1. Final Cover Stormwater Management System Schematic

Runoff Curve Number

The CN is determined by the hydrologic soil group (HSG), cover type, treatment, and hydrologic condition, and antecedent runoff condition (ARC). For the existing site conditions, a CN value of 58 corresponds to a “woods and grass in good conditions” land use for HSG B. For the traditional soil cover, two CN values are considered in the study to represent a typical range used in the landfill design: (1) A CN value of 74 corresponds to “open space in good condition” land use for HSG C. HSG C is comprised of moderately fine to fine texture soils with low infiltration rates and they consist chiefly of soils with a layer that mitigate infiltration; and (2) A CN value of 84 corresponds to “open space in fair condition” land use for HSG D, which have clay soils and lower infiltration rates. For ClosureTurf, a CN value ranges from 92 to 95 for high intensity and normal intensity rainfall events [Watershed Geosynthetics, 2018]. A CN value of 95 is a conservative assumption for runoff calculations and thus considered in the study.

The CN values for the drainage areas under each site condition are summarized in Table 3 [Watershed Geosynthetics, 2018; HydroCAD™, 2018].

Table 3. Curve Numbers Used in Analyses

Condition	Curve Number (CN)
Existing Conditions	58
Traditional Soil Cover System (HSG C, good condition)	74
Traditional Soil Cover System (HSG D, fair condition)	84
ClosureTurf Cover System	95
Stormwater Pond	98

Manning's Roughness Coefficient for Sheet Flow

The Manning's roughness coefficients are selected for the existing conditions, the traditional soil cover system, and ClosureTurf cover system, as presented in Table 4. The existing conditions are characterized as woods with light underbrush. The traditional soil cover system is characterized as dense grass. The ClosureTurf cover system parameters are selected from the ClosureTurf Design Manual [Watershed Geosynthetics, 2018].

Table 4. Manning's Roughness Coefficient for Sheet Flow

Condition	Manning's Roughness Coefficient, n
Existing Conditions	0.40
Traditional Soil Cover System	0.15
ClosureTurf Cover System	0.12 (for slopes > 10%) 0.22 (for slopes < 10%)

Velocity Factors for Shallow Concentrated Flow

The conditions associated with selecting the velocity factors for the existing conditions, traditional soil cover, and ClosureTurf are characterized as woodland, short grass pasture, and unpaved [Watershed Geosynthetics, 2018], respectively. The selected velocity factors are summarized in Table 5.

Table 5. Velocity Factors for Shallow Concentrated Flow

Shallow Concentrated Flow Land Use	Velocity Factor, K, (fps; mps in parentheses)
Existing Conditions	5 (1.5)
Traditional Soil Cover System	7 (2.1)
ClosureTurf Cover System	16.1 (4.9)

The relationship between the shallow concentrated flow velocity, the velocity factor, and slope is shown in Equation (5) in the previous section.

Wet Detention Pond

In this study, the wet detention pond is designed as a rectangular prismatoid with a length to width ratio (at bottom) of 3 to 1 to avoid short circuiting of inflows that can reduce the potential for settling of suspended solids. The side slopes of bottom dimensions are fixed at 175-ft (53.3 m) wide and 525-ft (160 m) long, and the side slopes are fixed at 3 Horizontal to 1 Vertical (3H:1V).

Outlet Control Structures

The outlet control structure is selected to be a perforated vertical riser structure with circular vertical orifice perforations and a singular horizontal orifice. In addition, an emergency spillway is included to manage the high intensity storm (i.e., the 100-yr, 24-hr storm event).

Channel Geometry and Lining

Typical landfill design includes perimeter channels that capture runoff or concentrated discharges from the final cover system. These flows are then conveyed to the stormwater pond. The perimeter channels were designed using a cross-sectional geometry with a 4-ft (1.2-m) bottom width, a 4-ft (1.2-m) depth, 3H:1V side slopes, and a 0.5% longitudinal slope. The perimeter channel design includes the selection of a channel lining design of either vegetation or riprap lining, which depends on the degree of erosional forces within the channels. Riprap channel lining is selected for both the traditional soil cover and ClosureTurf. A 15-in. thick channel lining comprised of a 6-in. (15.2-cm) d_{50} riprap is considered for both design scenarios, which corresponds to a Manning's roughness coefficient of 0.069 [HydroCAD™, 2018].

ANALYSIS RESULTS

The following results are presented for a 10-ft (3-m) deep wet detention pond design that includes a primary spillway comprised of a 4-in. (10.2-cm) diameter vertical low-flow orifice and a 36-in. (91-cm) diameter horizontal orifice as well as a 20-ft (16-m) wide weir as an emergency spillway. The 4-in. (10.2-cm) diameter vertical low-flow orifice satisfies the 24- to 72-hr drawdown requirement. They are located at depths of 0.8 ft (0.2 m), 5.5 ft (1.7 m), and 7.5 ft (2.3 m), respectively, from the bottom of the pond to satisfy the design criteria for the wet detention ponds that include a sediment storage volume. When the sediment storage volume is not included, the low-flow orifice depth is lowered to the bottom of the pond at 0.0 ft.

Time of Concentration

Table 6 presents the calculated times of concentration of the top deck subcatchments by varying the slope from 1% to 8%.

Table 6. Time of Concentration for Varying Top Deck Subcatchments

Top Deck Slope	Time of Concentration (minutes)	
	Traditional Soil Cover System	ClosureTurf Cover System
1%	26.1	20.7
2%	17.6	14.1
5%	11.4	9.2
8%	9.2	7.5

The side slope subcatchments have a travel time set as the minimum value of 0.1 hr (or 6 minutes) given the short flow lengths. The differences in calculated travel times of the side slope subcatchments are negligible (i.e., less than 0.1 minutes) by varying the slope from 5H:1V to 3H:1V. Furthermore, the analysis results indicate that, generally, the variations in the top deck slopes and side slopes have a negligible impact on the design of the wet detention pond. These results are expected given that the side slope lengths are short and steep for the assumed conceptual site. Although the calculated total time of concentration of flow from the top deck and side slopes varies, the discharges are concentrated into the large and long perimeter channels that provide additional flow rate attenuation prior to discharging to the wet detention pond.

The site geometry with the 8% top deck and 3H:1V side slopes is used to evaluate the stormwater pond design presented in the sections below.

Peak Flow Depth in Perimeter Channels

The calculated peak flow depth within the perimeter channels are presented in Table 7.

Table 7. Perimeter Channel Peak Flow Depth

24-hr Storm Event	Peak Flow Depth (ft; m in parentheses)		
	Traditional Soil Cover System		ClosureTurf Cover System
	CN = 74	CN = 84	
2-yr	1.3 (0.4)	2.0 (0.6)	2.2 (0.7)
5-yr	1.7 (0.5)	2.3 (0.7)	2.5 (0.8)
10-yr	2.0 (0.6)	2.6 (0.8)	2.7 (0.8)
25-yr	2.4 (0.7)	2.9 (0.9)	3.1 (0.9)
100-yr	3.1 (0.9)	3.4 (1.0)	3.6 (1.1)

The results indicate that ClosureTurf cover system requires slightly deeper perimeter channels than the traditional soil cover system.

Peak Discharge (Pre- versus Post-Development)

Table 8 presents the calculated peak discharge flow rates from the site under the pre-development condition (i.e., the existing conditions) and the post-development condition (i.e., after the site is closed with either the traditional soil cover or ClosureTurf).

Table 8. Comparison of Peak Discharge

24-hr Storm Event	Peak Discharge (cfs; cms in parentheses)				
	Existing Conditions	Traditional Soil Cover System		ClosureTurf Cover System	
		CN = 74	CN = 84	With Sediment Storage[1]	No Sediment Storage
2-yr	5 (0.14)	1 (0.03)	1 (0.03)	1 (0.03)	1 (0.03)
5-yr	13 (0.4)	1 (0.03)	1 (0.03)	3 (0.09)	1 (0.03)
10-yr	22 (0.6)	1 (0.03)	3 (0.09)	10 (0.28)	6 (0.17)
25-yr	37 (1.0)	4 (0.11)	11 (0.3)	31 (0.88)	20 (0.6)
100-yr	70 (2.0)	26 (0.7)	43 (1.2)	65 (1.8)	50 (1.4)

Note: [1]. The case with sediment storage is analyzed to show its effect on the stormwater pond design of the ClosureTurf cover system. Sediment storage volume is not needed for the ClosureTurf cover system because the runoff carries little to no suspended solids.

The results indicate that the ClosureTurf cover system generally generates more peak discharges than the traditional soil cover system. However, both final cover systems generate lower peak discharges than the existing conditions and thus satisfy the pre- and post-development design criteria.

Peak Flow Depth in Pond

Table 9 presents the calculated peak depth within the wet detention pond.

Table 9. Wet Detention Pond Peak Depth

24-hr Storm Event	Peak Depth (ft; m in parentheses)			
	Traditional Soil Cover System		ClosureTurf Cover System	
	CN = 74	CN = 84	With Sediment Storage[1]	No Sediment Storage
2-yr	2.8 (0.9)	3.7 (1.1)	4.9 (1.5)	4.2 (1.3)
5-yr	3.8 (1.2)	4.8 (1.5)	5.7 (1.7)	5.5 (1.7)
10-yr	4.7 (1.4)	5.6 (1.7)	5.9 (1.8)	5.8 (1.8)
25-yr	5.7 (1.7)	6.0 (1.8)	6.5 (2.0)	6.2 (1.9)
100-yr	6.4 (2.0)	7.0 (2.1)	7.9 (2.4)	7.5 (2.3)

See Note 1 under Table 8.

Peak Storage in Pond

The peak storage in the wet detention pond is calculated based on the peak flow depth presented in Table 9 using the stage-storage relationship of the wet detention pond and the results are presented in Table 10.

Table 10. Wet Detention Pond Peak Storage

24-hr Storm Event	Peak Storage, (acre-ft; 1,000 cubic meters in parentheses)			
	Traditional Soil Cover System		ClosureTurf Cover System	
	CN = 74	CN = 84	With Sediment Storage[1]	No Sediment Storage
2-yr	6.3 (7.8)	8.4 (10.4)	11.5 (14.2)	9.8 (12.1)
5-yr	8.7 (10.7)	11.4 (14.1)	13.6 (16.8)	13.1 (16.2)
10-yr	11.0 (13.6)	13.5 (16.7)	14.2 (17.5)	13.9 (17.1)
25-yr	13.6 (16.8)	14.3 (17.6)	15.8 (19.5)	15.1 (18.6)
100-yr	15.5 (19.1)	17.2 (21.2)	19.8 (24.4)	18.8 (23.2)

See Note 1 under Table 8.

The calculated peak storage volumes for the ClosureTurf cover system are greater than those for the traditional soil cover system. With no sediment storage volume required for the ClosureTurf cover system, the calculated peak storage of the pond increases by approximately 5% and 10%, respectively, compared to the traditional soil cover system with a CN of 84 and 74 under the 25-yr, 24-hr design storm event; while under the 100-yr, 24-hr design storm event, it increases by approximately 10% and 20%, respectively.

SUMMARY

This paper presents a parametric study to compare the stormwater pond design of a conceptual waste disposal site with two final cover systems: the traditional soil cover system and the ClosureTurf cover system. As expected, the study indicates that the stormwater pond design is largely affected by the selected runoff curve number (CN) for the final cover system. The ClosureTurf cover system, which usually has a higher CN than the traditional soil cover system, generates higher peak runoff rates and volumes, which results in the need for a slightly deeper perimeter drainage channel and a moderately larger stormwater pond. Because the ClosureTurf cover system has no soil layers and the runoff carries little to no suspended solids, the sediment storage volume is not needed, which offsets a portion of the increase in the stormwater pond size due to the higher CN of ClosureTurf.

The analysis results presented in this paper indicate that, under the assumed 25- or 100-yr, 24-hr design storm event, the stormwater pond size for the ClosureTurf cover system may increase by approximately 5% to 20% depending on the selected CN for the traditional soil cover system, which is assumed to vary from 74 to 84 in the analyses. When a higher CN is used in the stormwater pond design for the traditional soil cover system, the increase in the pond size is smaller when the ClosureTurf cover system is considered.

It should be noted that the study presented in the paper is based on the assumed conceptual site plan and hydrologic and hydraulic conditions. A site-specific analysis should be performed to evaluate difference in the stormwater pond design for these two final cover systems, especially for a site where the stormwater pond has already been constructed according to the original closure design of the traditional soil cover system. Furthermore, when selecting the final cover system for waste disposal facilities, other factors should be evaluated too, including regulatory requirements, technical performance, construction and post-closure maintenance costs, environmental and community impact, etc., to achieve safe, economical, and sustainable closures.

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Appendix F
Evaluation of Aggregate Infill Criteria for ClosureTurf

WatershedGeo®
Unearthing Solutions

Technical Note

EVALUATION OF AGGREGATE INFILL CRITERIA FOR CLOSURETURF®

Aggregate infill is one component of the ClosureTurf® three-component system. An extensive testing program was implemented to evaluate the criteria and performance properties for the aggregate infill in the ClosureTurf system. The program included large scale hydraulic performance testing by independent third-party laboratories including TRI Environmental (TRI) at the Denver Downs Research facility in Greeneville, South Carolina and the Civil Infrastructure Testing and Evaluation Lab (CITEL) at Pennsylvania State University in University Park, Pennsylvania. A description of the hydraulic testing procedures and results are provided in this document.

AGGREGATE INFILL FUNCTION

The aggregate infill component of ClosureTurf is utilized as a protective layer for the geotextile backing of the engineered turf component. The polypropylene geotextile backing material contains ultraviolet (UV) radiation degradation inhibitors protecting it against UV damage. Aggregate infill functions as an additional protective layer against UV degradation of the geotextile backing. Optimal aggregate infill performance occurs with minimal aggregate movement.

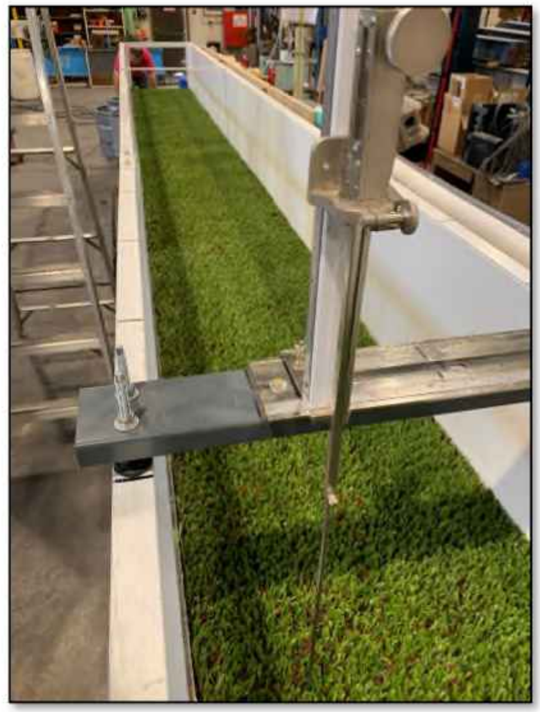
Laboratories tested aggregate infill mobilization in ClosureTurf in general accordance with ASTM D 6460, *Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion* and ASTM D 6459 *Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Hillslopes from Rainfall-Induced Erosion*. The results of the testing were also analyzed in accordance with each Standard to quantify infill mobilization during tested conditions. Photographs of tested aggregate samples are provided as Attachment A.

AGGREGATE INFILL LARGE SCALE HYDRAULIC TESTING

The TRI large-scale hydraulic testing (ASTM D 6460) was conducted in a rectangular flume having a 0.10 ft/ft slope. CITEL testing was conducted in a variable slope flume with slope settings of 0.10, 0.20 and 0.30 ft/ft. Installed subgrade was a loamy soil over which ClosureTurf with a ½-inch aggregate infill was installed following installation guidelines. Water is supplied to the facility by gravity flow or pumps and controlled and measured through upstream sluice gates or magnetic flow meters as presented in Figure 1.

A test consists of measuring infill thickness, initiating overtopping flow on the ClosureTurf® for a period of 30 minutes, discontinuing overtopping flow and measuring infill depth to evaluate aggregate loss. The test procedure is repeated a minimum of four times with increasing overtopping flow amounts or until enough aggregate infill has been removed to expose the majority of the geotextile backing.

TRI Facility



CITEL Facility

Figure 1. ClosureTurf® Flume Installation

Reported test results include aggregate infill loss during each 30-minute overtopping period and the corresponding hydraulic shear stress during the 30-minute test period. The testing was conducted on six different aggregate infills having a range of grain size distributions, fine aggregate angularities and specific gravities. Aggregate infill angularity and specific gravity are presented in Table 1. Tested aggregate infill grain size distributions are presented in Figure 2. Hydraulic shear stress results are presented in Figure 3. Testing also included three engineered turf profiles: ClosureTurf (CT), high friction ClosureTurf (CT HF) and high density ClosureTurf (CT HD). CT is the standard engineered turf. CT HF has similar turf blade count to ClosureTurf with an alternating turf stitch orientation. CT HD has a higher turf blade count density with approximately double the turf blade count of CT. Figure 4 presents aggregate mobilization results based on turf density.

Table 1. Tested Aggregate Infill Angularity and Specific Gravity

Test Aggregate No.	Fine Aggregate Angularity (FAA) (%) (ASTM C 1252 / AASHTO T 304) (Method A)	Bulk Specific Gravity, Dry (SG) (ASTM C 128 / AASHTO T 84)
1	47.2	2.64
2	40.5	2.60
3	43.1	2.59
4	45.7	2.64
5	47.1	2.85
6	43.7	1.96

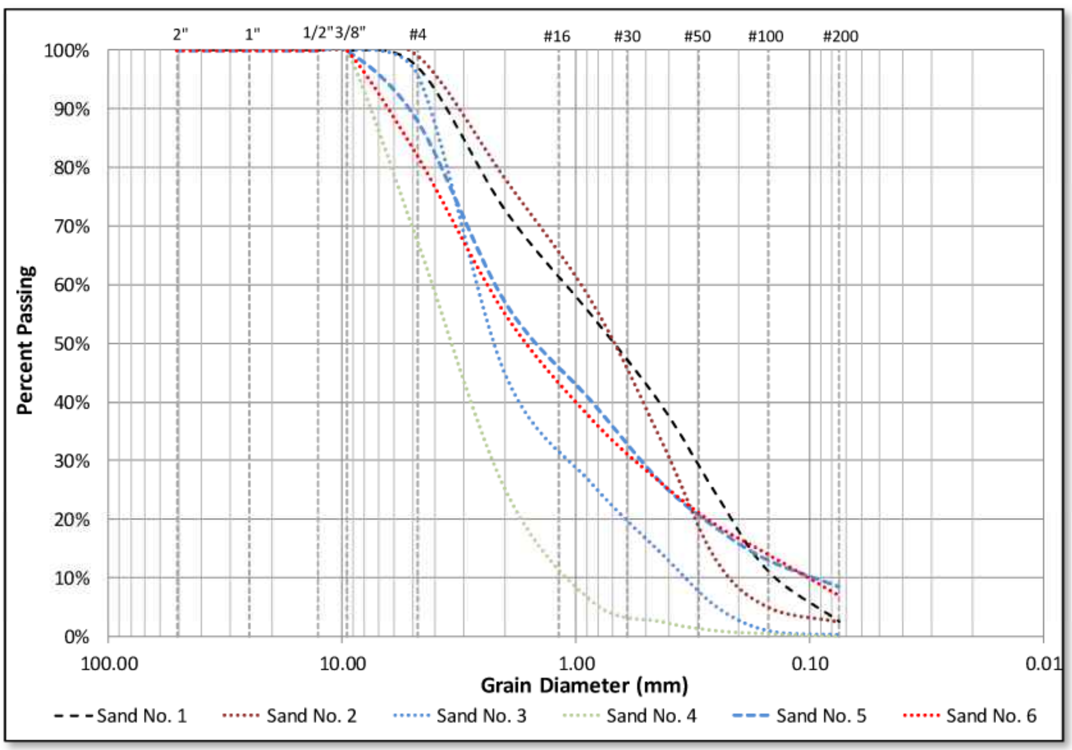


Figure 2. Tested Aggregate Infill Grain Size Distributions (ASTM C 136 / AASHTO T 27)

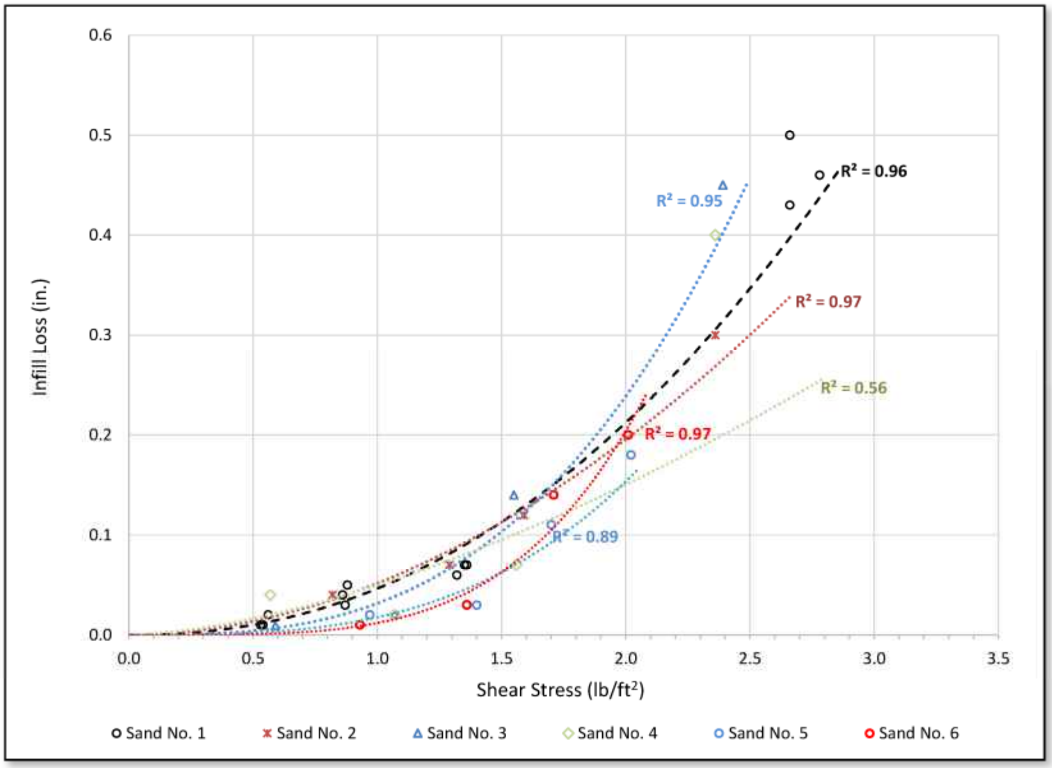


Figure 3. Measured Infill Loss as a Function of Hydraulic Shear Stress

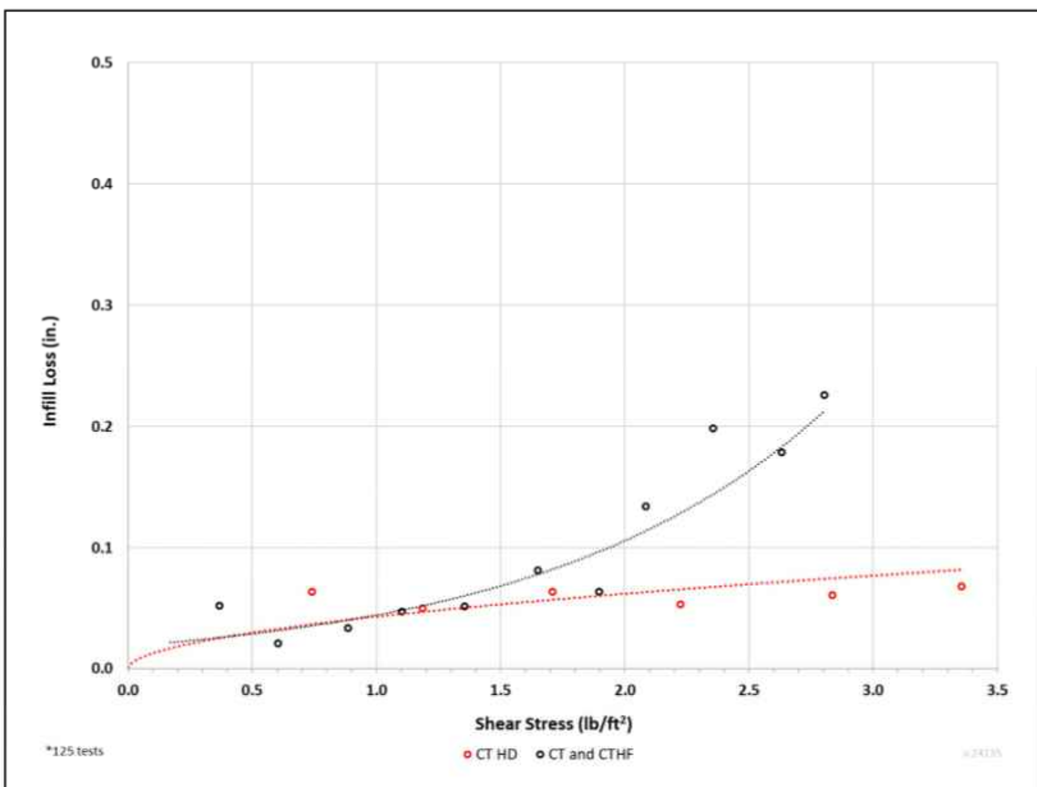


Figure 4. Aggregate Mobilization Comparison by Turf Density

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AGGREGATE INFILL LARGE SCALE RAINFALL EROSION TESTING

The TRI large-scale rainfall erosion testing (ASTM D 6459) was conducted on a rectangular plot measuring 40 feet by 8 feet (length x width) and having a 0.33 ft/ft slope. The subgrade was a loamy soil over which ClosureTurf with a ½-inch aggregate infill was installed following installation guidelines as presented in Figure 5a. Artificial rainfall is produced by ten “rain trees” arranged around the perimeter of the test slope. Each rain tree has four sprinkler heads atop a 15 ft. riser pipe. The rainfall system produces target rainfall intensities of 2, 4 and 6 inches per hour at pre-calibrated rain drop size distributions for a period of 20 minutes per intensity resulting in a one-hour test. Incremental infill losses are presented in Table 2. All runoff was collected during testing to quantify sediment mobilization. Testing in progress is presented in Figure 5b.

Table 2. Aggregate Infill Rainfall Erosion Results

Test Aggregate No.	Nominal Rainfall Intensity (in./hr.)	Incremental Infill Loss (%)	
		Standard Density Turf	High Density Turf
1	2.0	0.01	0.01
1	4.0	0.03	0.01
1	6.0	0.04	0.05
3	2.0	0.00	-
3	4.0	0.00	-
3	6.0	0.00	-
4	2.0	0.00	-
4	4.0	0.00	-
4	6.0	0.00	-

(a) Infill Installation **(b) Testing in Progress**

Figure 5. ClosureTurf® TRI Rainfall Erosion Testing

Based on the large scale rainfall erosion and hydraulic shear test results and aggregate infill material properties, an aggregate infill specification was developed as summarized in Figure 6 and as appears in the Watershed Geo® CSI specification, SECTION 31 05 16, *ClosureTurf® AGGREGATE INFILL COMPONENT*.

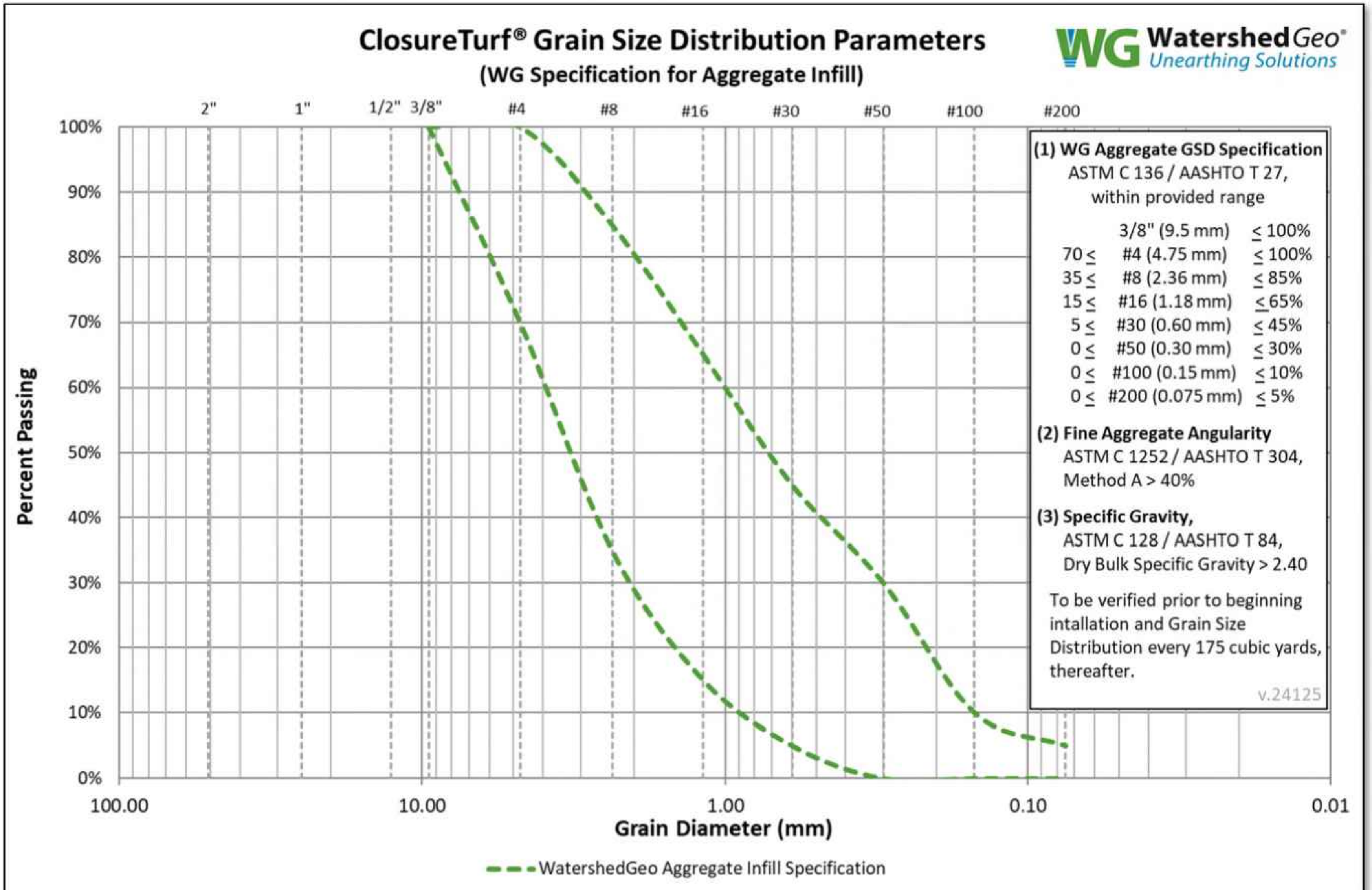


Figure 6. ClosureTurf® Aggregate Infill Specification

Attachment A

Figure A1. Tested Aggregate No. 1

Figure A2. Tested Aggregate No. 2

Figure A3. Tested Aggregate No. 3

Figure A4. Tested Aggregate No. 4

Figure A5. Tested Aggregate No. 5

Figure A6. Tested Aggregate No. 6

LIMITATIONS

ClosureTurf® is a U.S. registered trademark which designates a product from Watershed Geosynthetics LLC. This product is the subject of issued U.S. and foreign patents and/or pending U.S. and foreign patent applications. All information, recommendations and suggestions appearing in this literature concerning the use of our products are based upon tests and data believed to be reliable; however, this information should not be used or relied upon for any specific application without independent professional examination and verification of its accuracy, suitability and applicability. Since the actual use by others is beyond our control, no guarantee or warranty of any kind, expressed or implied, is made by Watershed Geosynthetics LLC as to the effects of such use or the results to be obtained, nor does Watershed Geosynthetics LLC assume any liability in connection herewith. Any statement made herein may not be absolutely complete since additional information may be necessary or desirable when particular or exceptional conditions or circumstances exist or because of applicable laws or government regulations. Nothing herein is to be construed as permission or as a recommendation to infringe any patent.

Appendix G
Example Aggregate Infill Hydraulic Shear Calculations

Technical Note

EXAMPLE AGGREGATE INFILL HYDRAULIC SHEAR CALCULATIONS

INTRODUCTION

Aggregate infill hydraulic stability in ClosureTurf® has been independently tested by the third-party laboratories, TRI Environmental and the Civil Infrastructure Testing and Evaluation Lab (CITEL). Test results demonstrate minimal aggregate infill mobilization at hydraulic shear values exceeding 1.5 lb/ft^2. The suggested design value for evaluating the potential for infill mobilization is 0.8 lb/ft^2 for standard density turf (i.e., CT, CT X and CT HF) or 1.5 lb/ft^2 for high density turf (CT HD).

An example set of calculations utilizing site specific parameters to estimate hydraulic shear from rainfall runoff are provided. The purpose of the calculations is to evaluate whether the calculated maximum hydraulic shear stress in the aggregate infill of ClosureTurf exceeds the suggested critical hydraulic shear stress. The calculations that follow are meant to serve as a suggested method to estimate the maximum hydraulic shear stress possible at potential ClosureTurf installations.

Two different hydraulic shear calculations are evaluated, differentiated by location and the choice of geomembrane liner used in the ClosureTurf system. The drainage length details are as follows, and the calculation results are summarized in Table 1.

1. Top deck with CT and MicroSpike® + side slope with CT and Super Gripnet® or MicroDrain®.
2. Side slope with CT and Super Gripnet® or MicroDrain®.

Table 1. Summary of Hydraulic Shear Calculation Results

Drainage Path No.	Segment No.	Slope (%)	Length (ft)	Geomembrane Liner	Calculated Maximum Hydraulic Shear Stress (psf)	Suggested Critical Hydraulic Shear Stress (psf)	Hydraulic Shear Stress (Meets or Does Not Meet)
1	1	3	208	MicroSpike	0.15	0.8	meets suggested criteria
	2	32	111	Super Gripnet/ MicroDrain	0.48	0.8	meets suggested criteria
2	1	27	383	Super Gripnet	0.53	0.8	meets suggested criteria

Drainage Path 1 – MicroSpike® on Top Deck & Super Gripnet®/MicroDrain® on the Side Slope – 100-year, 60-minute Design Storm

Drainage Path 1 consists of a top deck with a 3.0% slope and a drainage length of approximately 208 ft which drains to a side slope with a drainage length of approximately 111 ft at a 32% slope (3.1H:1V). The calculation assumes CT and MicroSpike geomembrane for the top deck and CT and Super Gripnet or MicroDrain geomembrane for the side slope.

Design Parameters:

Top Deck:

- Drainage length: L_1 = 208 ft (See Figure 1)
- Slope: S_1 = 3%
- Slope angle: $\alpha_1 = \tan^{-1}(3/100) = 1.72°$
- Hydraulic gradient: i_1 = 3.0% or 0.03
- Manning's roughness coefficient: n_1 = 0.22 (for slope ≤ 10%; See Watershed Geo ClosureTurf Design Guidance Manual)
- Geomembrane type: MicroSpike (without internal drainage layer)

Side Slope:

- Drainage length: L_2 = 111 ft (see Figure 1)
- Slope: S_2 = 3.1H:1V (32.3%)
- Slope angle: $\alpha_2 = \tan^{-1}(1/3.1) = 17.9°$
- Hydraulic gradient: i_2 = 32.3% or 0.323
- Manning's roughness coefficient: n_2 = 0.12 (for slope > 10%; See Watershed Geo ClosureTurf Design Guidance Manual)
- Geomembrane type: Super Gripnet or MicroDrain (with internal drainage layer)
- Transmissivity of ClosureTurf with Super Gripnet or MicroDrain (use the data in Figure 4, the ClosureTurf transmissivity test report by SGI to calculate the transmissivity at the slope of 32.3% or i = 0.323):
  - Flow Rate: $q = 12.28 \times i^{0.624} = 12.28 \times 0.323^{0.624} = 6.07\ gpm/ft$
  - Transmissivity: $\theta_{i=0.323} = 0.00020697 \times \frac{q}{i} = 0.00020697 \times \frac{6.07}{0.323} = 3.89 \times 10^{-3}\ m^2/sec$

Other Design Parameters:

- Design rainfall intensity (see Figures 2 and 3, the 100-yr, 1-hr rainfall intensity map):

$$R = 3.78\frac{in}{hr} = 0.315\frac{ft}{hr}$$

- Critical hydraulic shear stress of ClosureTurf with aggregate infill:

$$\tau_C = 0.8\ psf$$

Step 1: Calculate the maximum hydraulic shear stress of flow on the top deck:

Flow rate on the top deck under the design rainfall intensity (assuming unit width of 1 ft of final cover):

$$q_1 = L_1 \cdot R \cdot \cos\alpha_1 = 208\,ft \times 0.315\frac{ft}{hr} \times \cos 1.72° = 65.49\frac{ft^2}{hr} = 0.0182\frac{ft^2}{s}$$

The flow rate:

$$q_1 = v_1 \cdot A_1 = v_1 \cdot (H_1 \times 1\,ft) = v_1 \cdot H_1$$

Where, H_1 is flow depth on the top deck (ft). Using the Manning's Equation and assuming the hydraulic radius equals to the flow depth (in ft):

$$v_1 = \frac{1.49}{n_1} H_1^{\frac{2}{3}} \sqrt{S_1}$$

Therefore,

$$q_1 = v_1 \cdot H_1 = \frac{1.49}{n_1} H_1^{\frac{2}{3}} \sqrt{S_1} \cdot H_1 = \frac{1.49}{n_1} H_1^{\frac{5}{3}} \sqrt{S_1}$$

Solve the above equation for H_1,

$$H_1 = \left(\frac{q_1 \cdot n_1}{1.49 \cdot \sqrt{S_1}}\right)^{\frac{3}{5}} = \left(\frac{0.0182 \times 0.22}{1.49 \cdot \sqrt{0.03}}\right)^{\frac{3}{5}} = 0.0821 ft$$

The maximum hydraulic shear stress by the water flow on slope:

$$\tau_1 = \gamma_w \cdot H_1 \cdot S_1 = 62.4\frac{lb}{ft^3} \times 0.0821 ft \times 0.03 = 0.15\,psf < \tau_c (= 0.8\,psf) \quad \checkmark$$

The calculated maximum hydraulic shear stress on the aggregate infill is less than the suggested critical hydraulic shear stress, indicating minimal aggregate infill mobilization is expected to occur.

Step 2: Calculate the maximum hydraulic shear stress of flow on the side slope

Water from the top deck will flow onto the side slope. The total flow at the end of the side slope is:

$$q_{total} = q_1 + q_2 = q_1 + L_2 \cdot R \cdot \cos\alpha_2 = 65.49\frac{ft^2}{hr} + \left(111ft \times 0.315\frac{ft}{hr} \times \cos 17.9°\right)$$
$$= 98.76\frac{ft^2}{hr} = 0.0274\frac{ft^2}{s}$$

Part of the flow is expected to be through the internal drainage channel of the Super Gripnet or MicroDrain (i.e., the space within the drainage studs of Super Gripnet or MicroDrain). The internal flow capacity of ClosureTurf with Super Gripnet or MicroDrain is:

$$q_{int} = \theta_{i=0.323} \cdot i_2 = 3.89 \times 10^{-3}\frac{m^2}{sec} \times 0.323$$
$$= 3.89 \times 10^{-3} \times \frac{(3.28ft)^2}{\left(\frac{1}{3600}\right)hr} \times 0.323 = 48.66\frac{ft^2}{hr}$$

The remaining flow will be through the turf and aggregate infill:

$$q'_{total} = q_{total} - q_{int} = 98.76\frac{ft^2}{hr} - 48.66\frac{ft^2}{hr} = 50.10\frac{ft^2}{hr} = 0.0139\frac{ft^2}{s}$$

The flow rate:

$$q'_{total} = v_2 \cdot A_2 = v_2 \cdot (H_2 \times 1\,ft) = v_2 \cdot H_2$$

Where, H_2 is flow depth on the slope (ft). Using the Manning's Equation and assuming the hydraulic radius equals to the flow depth (in ft):

$$v_2 = \frac{1.49}{n_2}H_2^{\frac{2}{3}}\sqrt{S_2}$$

Therefore,

$$q'_{total} = v_2 \cdot H_2 = \frac{1.49}{n_2}H_2^{\frac{2}{3}}\sqrt{S_2} \cdot H_2 = \frac{1.49}{n_2}H_2^{\frac{5}{3}}\sqrt{S_2}$$

Solve the above equation for H_2,

$$H_2 = \left(\frac{q'_{total} \cdot n_2}{1.49 \cdot \sqrt{S_2}}\right)^{\frac{3}{5}} = \left(\frac{0.0139 \times 0.12}{1.49 \cdot \sqrt{0.323}}\right)^{\frac{3}{5}} = 0.0238ft$$

The maximum hydraulic shear stress by the water flow on the slope:

$$\tau_2 = \gamma_w \cdot H_2 \cdot S_2 = 62.4\frac{lb}{ft^3} \times 0.0238ft \times 0.323 = 0.48\,psf < \tau_c(= 0.8\,psf) \quad ✓$$

The calculated maximum hydraulic shear stress on the aggregate infill is less than the suggested critical hydraulic shear stress, indicating minimal aggregate infill mobilization is expected to occur.

Drainage Path 2 – Side Slope with Super Gripnet® – 100-year, 60-minute Design Storm

Drainage Path 2 consists of a side slope with a drainage length of approximately 383 ft at a 3.7H:1V slope. This calculation assumes CT and Super Gripnet geomembrane for the side slope.

Design Parameters:

Side Slope:

- Drainage length: L_1 = 383 ft (See Figure 1)
- Slope: S_1 = 3.7H:1V (27.0%)
- Slope angle: $\alpha_1 = \tan^{-1}(1/3.7) = 15.12°$
- Hydraulic gradient: i_1 = 27.0% or 0.270
- Manning's roughness coefficient: n_2 = 0.12 (for slope $>$ 10%; See Watershed Geo ClosureTurf Design Guidance Manual)
- Geomembrane type: Super Gripnet (with internal drainage layer)
- Transmissivity of ClosureTurf with Super Gripnet or MicroDrain (use the data in Figure 4, the ClosureTurf transmissivity test report by SGI to calculate the transmissivity at the slope of 27.0% or i = 0.270):
  - Flow Rate: $q = 12.28 \times i^{0.624} = 12.28 \times 0.270^{0.624} = 5.42\ gpm/ft$
  - Transmissivity: $\theta_{i=0.270} = 0.00020697 \times \frac{q}{i} = 0.00020697 \times \frac{5.42}{0.270} = 4.15 \times 10^{-3}\ m^2/sec$

Other Design Parameters:

- Design rainfall intensity (see Figures 2 and 3, the 100-yr, 1-hr rainfall intensity map):

$$R = 3.78\frac{in}{hr} = 0.315\frac{ft}{hr}$$

- Critical hydraulic shear stress of ClosureTurf with aggregate infill:

$$\tau_C = 0.8\,psf$$

Step 1: Calculate the maximum hydraulic shear stress of flow on the side slope:

Flow rate on the side slope under the design rainfall intensity (assuming unit width of 1 ft of final cover):

$$q_1 = L_1 \cdot R \cdot \cos\alpha_1 = 383\,ft \times 0.315\frac{ft}{hr} \times \cos 15.12° = 116.5\frac{ft^2}{hr} = 0.0324\frac{ft^2}{s}$$

Part of the flow is expected to be through the internal drainage channel of the Super Gripnet (i.e., the space within the drainage studs of Super Gripnet). The internal flow capacity of ClosureTurf with Super Gripnet is:

$$q_{int} = \theta_{i=0.270} \cdot i_1 = 4.15 \times 10^{-3}\frac{m^2}{sec} \times 0.270$$
$$= 4.15 \times 10^{-3} \times \frac{(3.28ft)^2}{\left(\frac{1}{3600}\right)hr} \times 0.270 = 43.40\frac{ft^2}{hr}$$

The remaining flow will be through the turf and aggregate infill:

$$q'_{total} = q_{total} - q_{int} = 116.5\frac{ft^2}{hr} - 43.40\frac{ft^2}{hr} = 73.10\frac{ft^2}{hr} = 0.0203\frac{ft^2}{s}$$

The flow rate:

$$q'_{total} = v_1 \cdot A_1 = v_1 \cdot (H_1 \times 1\,ft) = v_1 \cdot H_1$$

Where, H_1 is flow depth on the slope (ft). Using the Manning's Equation and assuming the hydraulic radius equals to the flow depth (in ft):

$$v_1 = \frac{1.49}{n_1} H_1^{\frac{2}{3}} \sqrt{S_1}$$

Therefore,

$$q'_{total} = v_1 \cdot H_1 = \frac{1.49}{n_1} H_2^{\frac{2}{3}} \sqrt{S_1} \cdot H_1 = \frac{1.49}{n_1} H_1^{\frac{5}{3}} \sqrt{S_1}$$

Solve the above equation for H_1,

$$H_1 = (\frac{q'_{total} \cdot n_1}{1.49 \cdot \sqrt{S_1}})^{\frac{3}{5}} = (\frac{0.0203 \times 0.12}{1.49 \cdot \sqrt{0.270}})^{\frac{3}{5}} = 0.0315\,ft$$

The maximum hydraulic shear stress by the water flow on the slope:

$$\tau_1 = \gamma_w \cdot H_1 \cdot S_1 = 62.4\frac{lb}{ft^3} \times 0.0315ft \times 0.270 = 0.53\,psf < \tau_c (= 0.8\,psf) \quad \checkmark$$

The calculated maximum hydraulic shear stress on the aggregate infill is less than the suggested critical hydraulic shear stress, indicating minimal aggregate infill mobilization is expected to occur.

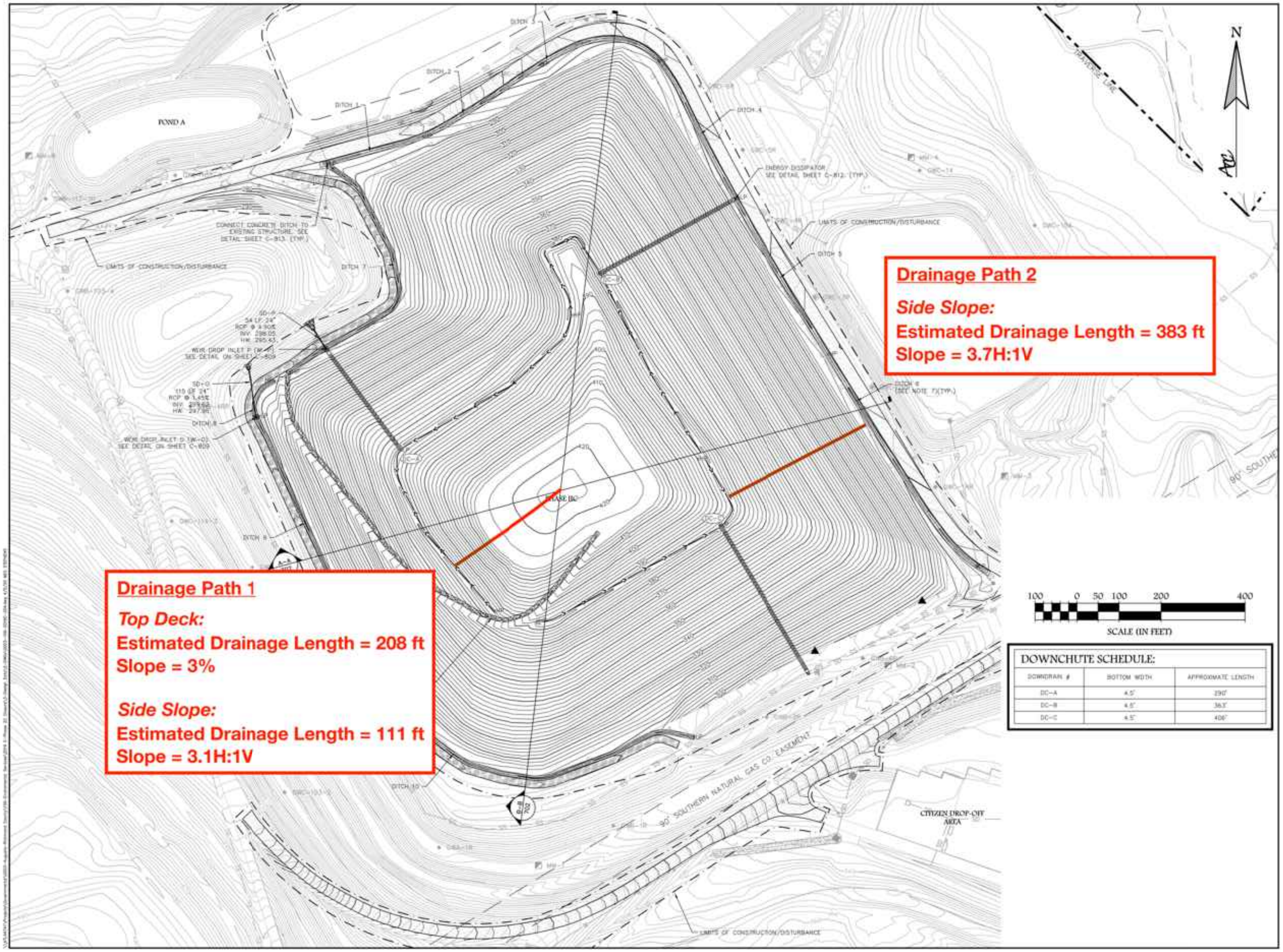


Figure 1. Grading plan with drainage path identified

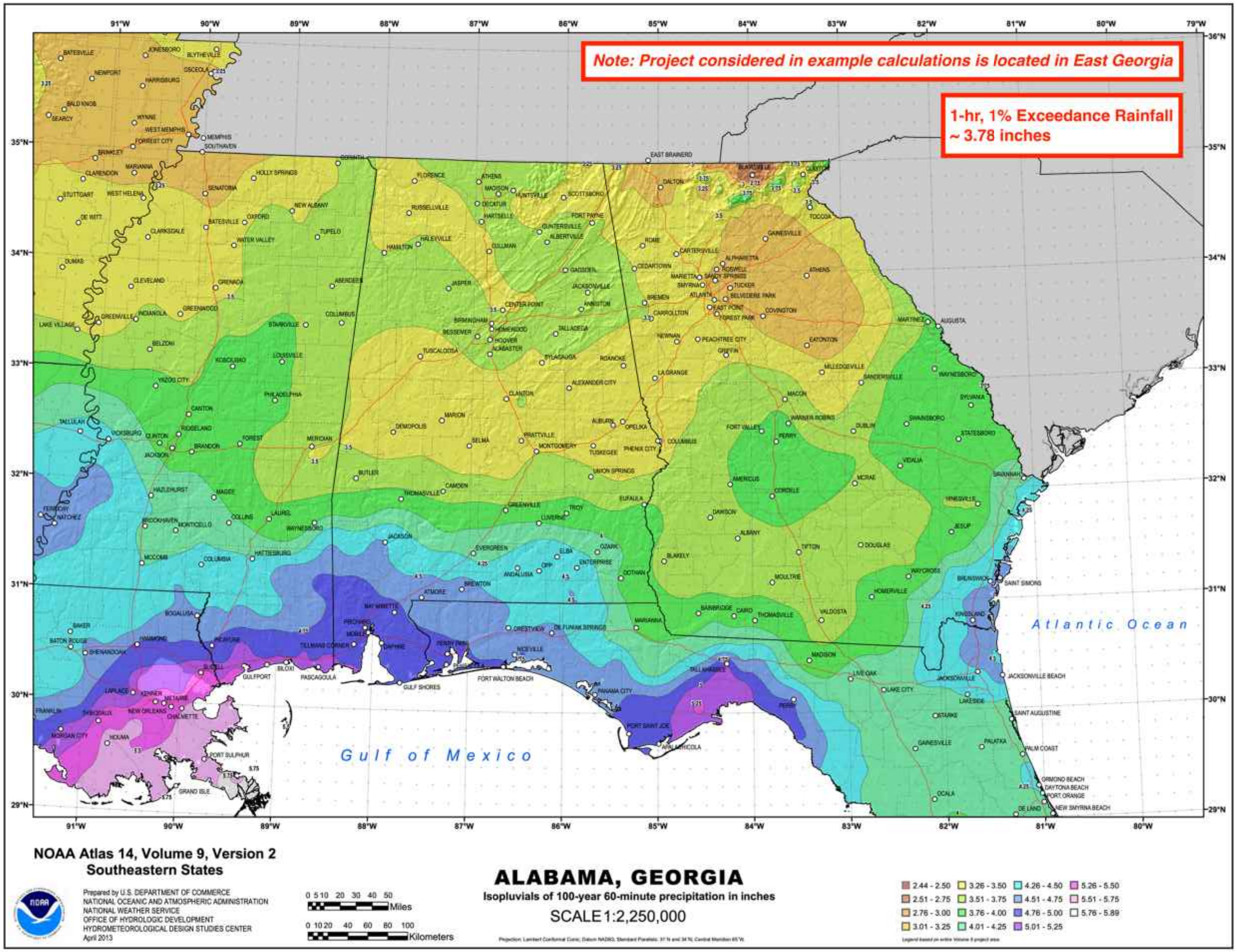


Figure 2. Alabama & Georgia Isopluvials (NOAA Atlas 14)

NOAA Atlas 14, Volume 9, Version 2

POINT PRECIPITATION FREQUENCY ESTIMATES

Sanja Perica, Deborah Martin, Sandra Pavlovic, Ishani Roy, Michael St. Laurent, Carl Trypaluk, Dale Unruh, Michael Yekta, Geoffery Bonnin

NOAA, National Weather Service, Silver Spring, Maryland

PF_tabular | PF_graphical | Maps_&_aerials

PF tabular

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.414 (0.346-0.502)	0.485 (0.405-0.589)	0.604 (0.502-0.736)	0.705 (0.582-0.863)	0.849 (0.674-1.07)	0.963 (0.743-1.23)	1.08 (0.800-1.42)	1.20 (0.846-1.62)	1.36 (0.920-1.89)	1.49 (0.975-2.09)
10-min	0.606 (0.506-0.736)	0.710 (0.593-0.863)	0.885 (0.735-1.08)	1.03 (0.852-1.26)	1.24 (0.987-1.57)	1.41 (1.09-1.81)	1.58 (1.17-2.07)	1.76 (1.24-2.37)	2.00 (1.35-2.76)	2.18 (1.43-3.06)
15-min	0.739 (0.618-0.897)	0.866 (0.723-1.05)	1.08 (0.896-1.31)	1.26 (1.04-1.54)	1.52 (1.20-1.92)	1.72 (1.33-2.20)	1.93 (1.43-2.53)	2.14 (1.51-2.89)	2.44 (1.64-3.37)	2.66 (1.74-3.73)
30-min	1.09 (0.908-1.32)	1.27 (1.06-1.55)	1.58 (1.32-1.93)	1.85 (1.53-2.26)	2.23 (1.77-2.82)	2.53 (1.95-3.24)	2.83 (2.10-3.72)	3.15 (2.22-4.25)	3.59 (2.42-4.96)	3.93 (2.57-5.50)
60-min	1.41 (1.18-1.71)	1.64 (1.37-1.99)	2.03 (1.69-2.47)	2.38 (1.96-2.91)	2.90 (2.31-3.69)	3.32 (2.57-4.28)	3.78 (2.81-4.98)	4.26 (3.01-5.76)	4.93 (3.34-6.85)	5.48 (3.58-7.68)
2-hr	1.74 (1.46-2.09)	2.00 (1.68-2.41)	2.48 (2.08-2.99)	2.91 (2.42-3.52)	3.57 (2.88-4.52)	4.12 (3.23-5.28)	4.72 (3.55-6.18)	5.36 (3.84-7.21)	6.28 (4.29-8.66)	7.03 (4.64-9.77)
3-hr	1.92 (1.63-2.29)	2.19 (1.86-2.62)	2.70 (2.28-3.24)	3.19 (2.67-3.83)	3.94 (3.21-4.99)	4.58 (3.62-5.86)	5.29 (4.00-6.92)	6.07 (4.37-8.14)	7.19 (4.95-9.89)	8.11 (5.39-11.2)
6-hr	2.28 (1.95-2.69)	2.57 (2.19-3.05)	3.14 (2.67-3.73)	3.70 (3.12-4.41)	4.59 (3.78-5.78)	5.37 (4.28-6.82)	6.24 (4.77-8.11)	7.20 (5.25-9.60)	8.62 (6.00-11.8)	9.79 (6.56-13.4)
12-hr	2.71 (2.33-3.17)	3.04 (2.62-3.56)	3.68 (3.16-4.33)	4.30 (3.67-5.08)	5.30 (4.41-6.60)	6.17 (4.97-7.75)	7.13 (5.51-9.18)	8.21 (6.04-10.8)	9.78 (6.87-13.2)	11.1 (7.50-15.0)
24-hr	3.17 (2.76-3.67)	3.56 (3.09-4.13)	4.30 (3.72-5.00)	5.00 (4.30-5.84)	6.09 (5.10-7.48)	7.03 (5.71-8.73)	8.06 (6.28-10.2)	9.20 (6.83-12.0)	10.8 (7.69-14.5)	12.2 (8.35-16.4)
2-day	3.65 (3.20-4.19)	4.11 (3.61-4.72)	4.96 (4.33-5.71)	5.74 (4.98-6.64)	6.95 (5.86-8.42)	7.97 (6.52-9.77)	9.08 (7.13-11.4)	10.3 (7.70-13.3)	12.0 (8.61-15.9)	13.4 (9.29-17.9)
3-day	3.99 (3.52-4.55)	4.48 (3.95-5.12)	5.37 (4.72-6.15)	6.20 (5.41-7.13)	7.46 (6.33-8.99)	8.53 (7.02-10.4)	9.69 (7.66-12.1)	11.0 (8.25-14.0)	12.8 (9.19-16.8)	14.2 (9.91-18.9)
4-day	4.29 (3.80-4.87)	4.80 (4.25-5.45)	5.72 (5.05-6.53)	6.58 (5.77-7.54)	7.90 (6.72-9.47)	9.01 (7.45-10.9)	10.2 (8.11-12.7)	11.5 (8.72-14.7)	13.4 (9.71-17.6)	15.0 (10.4-19.7)
7-day	5.03 (4.50-5.67)	5.61 (5.00-6.33)	6.65 (5.91-7.52)	7.61 (6.72-8.64)	9.06 (7.77-10.8)	10.3 (8.57-12.4)	11.6 (9.29-14.3)	13.1 (9.95-16.5)	15.1 (11.0-19.6)	16.8 (11.8-22.0)
10-day	5.70 (5.12-6.39)	6.33 (5.67-7.10)	7.45 (6.65-8.38)	8.47 (7.51-9.57)	10.0 (8.62-11.8)	11.3 (9.45-13.5)	12.7 (10.2-15.5)	14.2 (10.9-17.8)	16.3 (12.0-21.1)	18.1 (12.8-23.5)
20-day	7.65 (6.94-8.49)	8.39 (7.59-9.31)	9.66 (8.71-10.8)	10.8 (9.66-12.1)	12.4 (10.8-14.4)	13.8 (11.6-16.2)	15.2 (12.3-18.3)	16.7 (12.9-20.7)	18.8 (13.9-24.0)	20.5 (14.7-26.5)
30-day	9.36 (8.53-10.3)	10.2 (9.29-11.3)	11.6 (10.6-12.9)	12.9 (11.6-14.3)	14.6 (12.7-16.7)	16.0 (13.5-18.6)	17.4 (14.1-20.7)	18.8 (14.6-23.1)	20.8 (15.5-26.3)	22.4 (16.1-28.7)
45-day	11.6 (10.6-12.7)	12.6 (11.6-13.9)	14.3 (13.1-15.8)	15.7 (14.3-17.4)	17.6 (15.3-20.0)	19.0 (16.2-21.9)	20.4 (16.7-24.1)	21.8 (17.0-26.5)	23.6 (17.6-29.6)	25.0 (18.1-31.9)
60-day	13.6 (12.5-14.8)	14.8 (13.6-16.2)	16.8 (15.4-18.4)	18.4 (16.7-20.2)	20.4 (17.8-22.9)	21.9 (18.7-25.0)	23.3 (19.1-27.3)	24.6 (19.3-29.7)	26.3 (19.7-32.7)	27.5 (20.0-34.9)

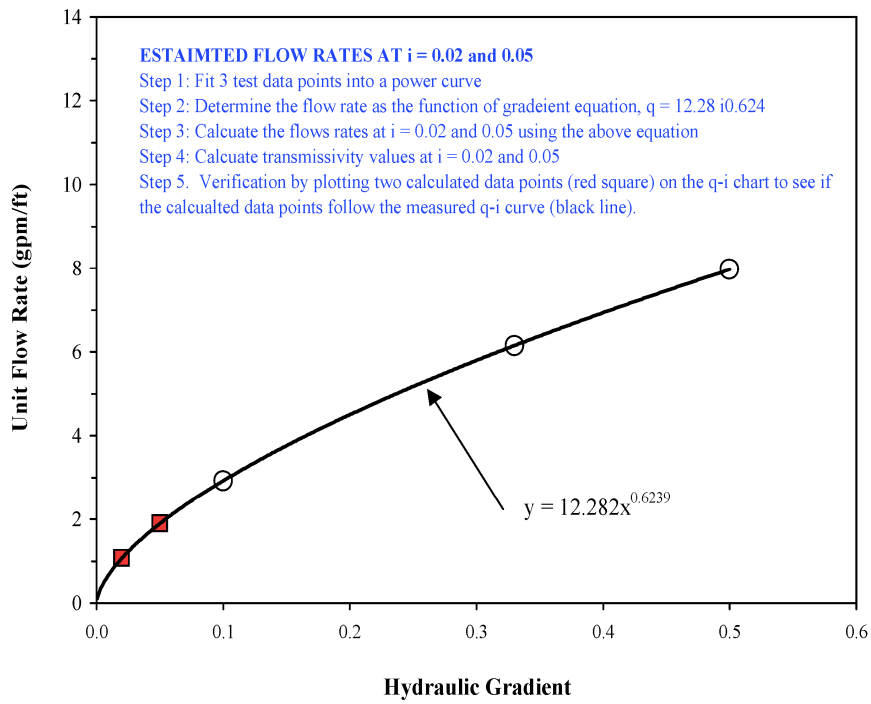
[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

Figure 3. NOAA Precipitation Data

CLOSURETURF LLC -LANDFILL COVER SYSTEM
HYDRAULIC TRANSMISSIVITY TESTING (ASTM D 4716)
Test Configuration (from Top to Bottom): Sand Layer/Polytex Artificial Grass with Geotextile Side Down/
Agru 50-mil Super Gripnet LLDPE Geomembrane with Studs Side Up



Test No.	Flow Direction	Specimen Size Width x Length (in. x in.)	Total Normal Stress[1] σ_n (psf)	Seating Time t (hour)	Hydraulic Gradient i (-)	Transmissivity $\theta = 0.00020697\left(\frac{q}{i}\right)$ (m^2/sec)	Flow Rate $q = 12.28 i^{0.624}$ (gpm/ft)	q' (l/min/m)
					0.02	1.11E-02	1.07	
					0.05	7.84E-03	1.89	
1	MD	12 x12	47	0.25	0.10	6.04E-03	2.92	36.3
2	MD	12 x12	47	0.25	0.33	3.86E-03	6.15	76.4
3	MD	12 x12	47	0.25	0.50	3.30E-03	7.97	99.0

NOTE:
Total normal stress = total weight (sand + steel plate + surcharge) divided by the plan area of test specimen (1 square ft). A normal stress of 47 psf is approximately the minimum total stress required to keep the specimen from uplifting.

DATE TESTED:	1/11/2013
FIGURE NO.	A-1
PROJECT NO.	SGI10007
DOCUMENT NO.	
FILE NO.	

SGI TESTING SERVICES, LLC

Figure 4. Transmissivity test report of ClosureTurf with internal drainage layer

Appendix H
ClosureTurf UV Longevity Evaluation Reports

2022 Evaluation Report

Geosyntec consultants

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Kennesaw, Georgia 30144
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22 November 2022

José Urrutia, P.E.
Vice President of Engineering
Watershed Geosynthetics
11400 Atlantis Place, Suite 200
Alpharetta, GA 30022

Subject: Assessment of ClosureTurf® UV Longevity

Dear Mr. Urrutia:

Watershed Geosynthetics, Inc. (Watershed) has patented an alternative landfill closure system termed ClosureTurf®. ClosureTurf® consists of high-density polyethylene (HDPE) grass blades tufted through a double-layer polypropylene (PP) geotextile backing which overlies an HDPE or linear low-density polyethylene (LLDPE) structured geomembrane (i.e., Super Gripnet®, MicroDrain®, or MicroSpike®) manufactured by AGRU America Inc. The addition of a layer of sand ballast during installation completes the system. The sand ballast provides cover for the lower portion of the HDPE grass blades, the PP geotextile backing, and the structured geomembrane (Figure 1).

A report titled "Literature Review and Assessment of ClosureTurf® UV Longevity" was prepared by Geosyntec Consultants, Inc. (Geosyntec) and dated 15 May 2015 (Geosyntec, 2015). Watershed has requested that Geosyntec provide an updated assessment of the longevity of the ClosureTurf® system with regard to ultraviolet (UV) exposure and degradation. This report (Report) supersedes the Geosyntec (2015) report. Since ClosureTurf® has elements (i.e., the HDPE grass blades) that are permanently exposed to UV radiation, this Report will be focused on the exposed portion of the system.

Geosyntec's approach to this Report incorporates updated laboratory and field data from samples at multiple sites throughout the Southeastern United States (U.S.) and Arizona into the assessment of HDPE grass blade longevity. This Report concludes with a summary of the analysis along with brief discussion for recommendations.

EXECUTIVE SUMMARY

This Report incorporates updated laboratory and field data regarding the retained tensile strength of HDPE geomembrane and synthetic grass blade materials as a function of exposure to ultraviolet (UV) radiation to estimate the longevity of the exposed grass blades of the ClosureTurf® product.

The laboratory update includes a release of additional data from a Geosynthetics Research Institute (GRI) testing program measuring the effects of UV radiation on HDPE geomembrane strips. The test program incubates HDPE geomembrane strip samples under a UV lamp at elevated temperatures (60°C, 70°C, and 80°C) to accelerate the degradation. The tensile strength and elongation of each strip are then measured after a given period of exposure. Data from this test program for HDPE geomembrane can be converted to field exposure for a given site following the method presented in Richgels (2016). Such a conversion was performed for this Report for five sites, where field test data for the ClosureTurf® HDPE grass blades were also obtained. The five sites are: (i) Atlas Testing Facility, New River, Arizona; (ii) Saufley Field Landfill, Pensacola, Florida; (iii) LaSalle-Grant Landfill in Jena, Louisiana; (iv) Baldwin County Landfill, Georgia; and (v) Berkely County Landfill, South Carolina.

Once the conversion from the GRI laboratory UV exposure to the field UV exposure at each site was completed, extrapolations of retained tensile strength of HDPE geomembrane as a function of UV exposure were made to obtain estimates of half-life (i.e., 50% retained tensile strength) and 12.5% retained tensile strength. The 12.5% value was selected to illustrate extended longevity when performance requirements support the selection of service-life tensile strength values lower than the half-life tensile strength values. The extrapolations included an upper bound (Arrhenius) and a lower bound (linear) of retained tensile strength as a function of UV exposure. Based on the GRI laboratory data for HDPE geomembrane, the resulting upper bound estimate of the half-life of an HDPE grass blade is 93 years in New River, Arizona with a lower bound estimate of 75 years, assuming that the laboratory results of HDPE geomembrane are applicable to HDPE grass blades. For the sites in the Southeastern U.S., the upper bound half-life estimate is 157 years, while the lower bound estimate is 83 years. If the 12.5% retained strength is considered for the HDPE grass blades, rather than the half-life, the upper and lower bound estimates for the New River, Arizona site are 216 years and 181 years, respectively. For the Southeastern U.S., if the 12.5% retained strength is considered, the upper bound and lower bound estimates are 376 and 204 years, respectively.

The field test data from the five sites consisted of measurements of the tensile strength of the ClosureTurf® HDPE grass blades at given durations of field exposure. The New River, Arizona site is a field weathering testing facility where samples of ClosureTurf® HDPE grass blades were exposed to sunlight concentrated by an array of mirrors to accelerate the degradation process by a factor of seven. The remaining four sites in the Southeastern U.S. are waste facilities where ClosureTurf® was installed. The field test data of ClosureTurf® HDPE grass blades from the New River, Arizona site (i.e., the accelerated weathering testing site) as well as the four Southeastern U.S. sites (i.e., the real-world weathering sites) consistently plotted above the upper bound curve developed from the GRI laboratory data for HDPE geomembrane. This suggests that the length of time required to reach half-life (or any other value of the percent retained tensile strength) of the HDPE grass blades in the field is longer than indicated by the estimates from the conversion of GRI laboratory data. The disparity is likely due to ignoring the antioxidant depletion phase in the laboratory data as well as site environmental factors (e.g., moisture, shading, slopes, etc.) that are not included in the method of conversion from laboratory exposure to field exposure.

Given these factors and results it is reasonable to expect that the half-life of the HDPE grass blades of the ClosureTurf® product is on the order of 100 years under the New River, Arizona climatic conditions. Since the New River, Arizona site has the highest levels of UV irradiance and temperature in the United States, sites located elsewhere will have greater half-life estimates in general proportion to the ratio of UV irradiance. Furthermore, performance requirements of the ClosureTurf® HDPE grass blades may permit evaluation of longevity beyond the half-life, thereby extending the expected duration of field performance.

DATA SUMMARY

Data sets currently available when this Report is prepared represent an expansion over what was available during the Geosyntec (2015) study. The current data includes measurements of tensile strength of HDPE grass blades after UV exposure from multiple sites where ClosureTurf® has been installed and tensile strength of HDPE geomembrane and grass blades from additional accelerated weathering tests. The data sets of direct measurement of tensile strength as a function of UV exposure utilized in this Report include:

1. Geosynthetics Research Institute (GRI) laboratory data release on the effects of accelerated weathering of HDPE geomembrane strips presented by Dr. Robert Koerner at GeoAmericas (2016). The effects are measured in terms of changes to tensile strength as a function of UV exposure under a fluorescent lamp at various temperatures. The data contains updates from GRI in addition to what was included in the Geosyntec (2015) Report.

2. Data from the New River, Arizona field testing facility. The data includes measurements of retained tensile strength of HDPE grass blades exposed to full spectrum radiation using sunlight concentrated by mirrors to accelerate the weathering process. The testing setup accelerates the effects of exposure duration by a factor of seven.

3. Tensile strength test results of HDPE grass blade samples retrieved from the following ClosureTurf® sites: (i) Saufley Field Landfill, Pensacola, Florida; (ii) LaSalle-Grant Landfill, Jena, Louisiana; (iii) Baldwin County Landfill, Georgia; and (iv) Berkely County Landfill,

South Carolina. The data include measurements of retained tensile strength as a function of real-world sunlight exposure in years.

DATA DISCUSSION

The GRI data set involves controlled exposure of geosynthetic samples to temperature and UV radiation simulating solar maximum exposure with a UV source at three constant temperatures (60°C, 70°C, and 80°C). The testing program is performed in accordance with ASTM D7238 procedures for *Standard Test Method for Effect of Exposure of Unreinforced Polyolefin Geomembrane Using Fluorescent UV Condensation Apparatus.* Charts were produced with this updated data in Richgels (2016), which presents the retained tensile strength of the HDPE geomembrane test samples incubated at each temperature set as a function of the cumulative UV exposure (Figure 2). Stages A to B (antioxidant depletion and transition periods) and Stage C (polymer oxidation) are distinguished in the charts, and the Stage C data points were selected for the regression.

The application of the GRI laboratory data to individual field sites requires conversion of the exposure conditions of the laboratory to local site conditions. While site specific exposure information for the Atlas Testing Facility in New River, Arizona was included in Richgels (2015a, 2015b), exposure conversion to other sites had to be developed. Richgels (2016) performed such a conversion from the GRI laboratory data to several sites in Florida using solar radiation and temperature data from the National Renewable Energy Laboratory (NREL). The temperature and radiation data for each site is expressed by NREL in a Total Meteorological Year (TMY3), a multiyear dataset from which 12 months are chosen that best represent the median conditions. Geosyntec adopted this same procedure for the sites included in this Report.

The Geosyntec (2015) report presented tensile property testing of the field samples of the HDPE grass blades exposed to the New River, Arizona environment at the Atlas Testing Facility for approximate exposure periods of 1, 5, 7, and 10 years. The average values for tensile strength retained at each corresponding period was determined to be 97.2%, 89.7%, 83.8%, and 82.5%, respectively. Watershed is conducting additional accelerated weathering testing at the same facility using the Equatorial Mount with Mirrors for Acceleration (EMMA) solar concentration device, which provides approximately seven years of UV radiation exposure in one calendar year. Additional tensile property testing was performed on samples of the HDPE grass blades collected from the accelerated weathering testing. The approximate exposure periods for these samples were one, two, and three calendar years, which correspond to accelerated exposure periods of approximately 7, 14, and 21 years, respectively. The average values for tensile strength retained for these exposure periods are 92.2%, 83.3%, and 80.7%, respectively (Figure 3).

Similar data was collected for field samples of the HDPE grass blades weathered under climatic conditions at the landfills in Berkley County, South Carolina, Baldwin County, Georgia, Pensacola, Florida, and Jena, Louisiana. The exposure periods of the samples for these sites were:

- Berkley County, 2 years
- Baldwin County, 3 years
- Pensacola, Florida, 5 years
- Jean, Louisiana, 7 and 8 years

The average values for tensile strength retained for these exposure periods were 100%, 99.1%, 97.3%, 85.4%, and 96.8%, respectively (Figure 4). Because the yearly irradiation is fairly uniform in the Southeastern region of the U.S. (Figure 5), the field data obtained from sites in this region were grouped together on a single plot, as shown in Figure 4. The new EMMA and field test data were added onto the figure of half-life projections presented in the Geosyntec (2015) Report, as shown in Figure 6. The new data, which are plotted at or above the trend lines, support the longevity of ClosureTurf projected in the Geosyntec (2015) Report.

PERFORMANCE REQUIREMENTS

The acceptable level of degradation for a given property of polyolefins due to exposure to UV radiation should be based on the performance requirements of that particular aspect of the product. In the case of HDPE grass blades of the ClosureTurf® system, performance requirements for tensile strength may be as low as 2.5 to 3.5 pounds (lbs.) based on the applied loads of pullout forces from equipment operation and water runoff (Diguilo, 2013). Since the original manufactured strength of an HDPE grass blade is a minimum of approximately 20 lbs., the performance requirement is approximately 12.5%, if no factor of safety is included. Both the original manufactured strength of the product and the performance requirement should be evaluated for each individual application. However, for the purposes of this Report, Geosyntec utilized 12.5% of original strength as the performance requirement to illustrate the difference in duration with the half-life criterion.

HDPE GRASS BLADE LONGEVITY EVALUATION

In order to develop a prediction for the longevity of the HDPE grass blades with respect to UV degradation for each of the sites from which field data was collected, Geosyntec implemented the method found in Richgels (2016) for two levels of retained tensile strength (i.e., 50% and 12.5% of the original property value). The method uses the same calculation procedure used in Richgels (2015a and 2015b) but incorporates the updated data from GRI and UV irradiance and temperature data collected from NREL for each site. In the Geosyntec (2015) Report, Geosyntec performed the calculations in accordance with the Richgels (2015a and 2015b) procedure for Arizona climatic conditions and compared the results with the results presented therein, which were generally in agreement. Once the half-life estimates were calculated, Geosyntec repeated the calculations for 12.5% of retained strength. The same two levels of retained tensile strength (i.e., 50% and 12.5%) were utilized in this Report.

Half-Life Estimation (50% of Retained Strength)

The assessment of half-life is based on the updated data from GRI using retained tensile strength of HDPE geomembrane samples incubated under a UV lamp at elevated temperatures. The elevated temperatures accelerate the UV weathering process in accordance with ASTM D7238.

The GRI data includes samples tested at three elevated temperatures: (i) 80 degrees Celsius (°C); (ii) 70°C; and (iii) 60°C. The 80°C data set reached 50% retained strength, the 70°C data set reached approximately 60% retained strength, and the 60°C data set reached approximately 80% retained strength. Logarithmic extrapolations to 50% retained strength were performed for each temperature data set. The amount of exposure time (on a log scale) corresponding to the 50% retained strength plotted vs. the inverse of the corresponding temperature (80°C, 70°C and 60°C) is shown in Figure 7. Figure 7 allows for extrapolation to find the laboratory exposure time required to achieve 50% retained strength at temperatures lower than the test temperatures (i.e., actual field temperatures).

Once the relationship between temperature and laboratory exposure is defined, a relationship between laboratory exposure and field exposure for a particular site can be constructed. Sites included in this Report are: (i) Atlas Testing Facility, New River, Arizona; (ii) Saufley Field Landfill, Pensacola, Florida; (iii) Lasalle-Grant Landfill, Jena, Louisiana; (iv) Berkley County Landfill, South Carolina; and (v) Baldwin County Landfill, Georgia. These locations correspond to the sites where Watershed has obtained tensile strength measurements on HDPE grass blade samples.

Richgels (2015a and 2015b) presents monthly averages at the Arizona site for: (i) peak turf temperature; and (ii) irradiance as a fraction of the laboratory lamp irradiance. The monthly averages of these parameters for the sites outside of Arizona were obtained from NREL, and the irradiance as a fraction of the laboratory lamp irradiance was determined for each site. The average turf temperature was conservatively estimated by increasing the measured ambient temperature by a factor of two (Richgels, 2016). Using these two parameters for a given month combined with the Arrhenius function, an estimate of half-life loss per month is obtained. Summation of the half-life lost per month over a year yields the annual half-life loss. The inverse of the annual half-life loss is the predicted half-life in years. Using this method to estimate the half-life for the Pensacola region, Richgels obtained a half-life of approximately 200 years, while Geosyntec obtained a half-life of 132 years (Table 1). The difference is attributable to rounding errors in the logarithmic projections and updates to the solar radiation and temperature information used in NREL datasets. The half-life estimates for the sites in New River, Arizona, Jena, Louisiana, Berkley County, South Carolina, and Baldwin County, Georgia were calculated by Geosyntec as 93, 151, 157, and 157 years, respectively.

Following the suggestion of Koerner et al. (2015), Richgels (2016) treated the results of the half-life mentioned above as an upper bound estimate. For the lower bound estimate, Koerner et al. (2015) suggested performing a linear extrapolation of the laboratory data to lower field temperatures, rather than using the Arrhenius function. With the linear extrapolation, the ratio of monthly irradiance to laboratory lamp irradiance is scaled linearly to calculate the number of months required to reach half-life at 80ºC, 70ºC and 60ºC. Linear extrapolations per month are made from the elevated lab temperatures to the corresponding average turf temperature in that month (Table 2 and Figures 8 through 12). The resulting half-life loss per month is summed to obtain half-life loss per year. The inverse of that result is the half-life in years. For the Pensacola region, Richgels (2016) calculates a half-life of 118 years using this linear model. Geosyntec's calculation resulted in a half-life of 83 years. The half-life estimates for the sites located in New River, Arizona, Jena, Louisiana, Berkley County, South Carolina, and Baldwin County, Georgia were calculated as 75, 91, 90, and 90 years, respectively.

Figure 13 shows the upper (Arrhenius - logarithmic) and lower (linear) bound curves calculated by Geosyntec along with the field data on the HDPE grass blades provided by Watershed (2014 and 2022) for the New River, AZ site. Because of the uniformity of the annual irradiance among the southeastern sites (Figure 5), little variation was observed in the calculated upper and lower bound curves for these sites. Therefore, Figure 14 shows the limits of the calculated upper and lower bound curves for the southeastern sites along with the field data from these sites. As shown in these figures, the field data falls above the upper and lower bound curves. Note that the first point from the field data collected from the Atlas Testing Facility in Arizona at approximately 1 year is omitted from the trend line (Figure 13). This is because the first data point is assumed to be within the antioxidant phase of degradation rather than the polymer oxidation stage as suggested by Rowe et al. (2010). Additional discussion regarding the stages of degradation for polyolefin materials can be found in CUR 243 (2012).

Service Life Estimation Based on Performance Requirements (12.5% of Retained Strength)

Geosyntec repeated the calculations discussed above but extrapolated the GSI laboratory data down to 12.5% retained strength rather than 50% at 80ºC, 70ºC and 60ºC for the sites located in New River, Arizona, Pensacola, Florida, Jena, Louisiana, Berkley County, South Carolina, and Baldwin County, Georgia. The upper bound (Arrhenius - logarithmic) estimates were 216, 314, 359, 376, and 376 years, respectively. The lower bound (linear) estimates were 181, 204, 223, 236, and 221 years, respectively.

The estimates of service life at 12.5% retained strength provided in the Geosyntec (2015) Report were too large to be reasonable. A likely explanation is that the samples tested at 80ºC, 70ºC and 60ºC had not degraded enough to produce accurate predictions at 12.5% retained strength. Given that the updated data from GRI included additional exposure at each of the three test temperatures, a better estimate for time of exposure to reach 12.5% strength was obtained for this Report. However, if the retained strength for laboratory samples approaches 12.5% retained strength in future data releases, the estimates for the corresponding time of exposure may be further refined.

SUMMARY AND CONCLUSIONS

Watershed has provided Geosyntec with supplemental ClosureTurf® accelerated weathering test data from the Atlas Testing Facility, New River, AZ and new field test data from four ClosureTurf® sites located in the Southeastern U.S. Following the laboratory to field conversion method presented in Richgels (2016), Geosyntec calculated the expected exposure duration at the 50% and 12.5% retained tensile strengths of HDPE grass blades under the exposure conditions at the five locations, based on the GRI laboratory UV test results for HDPE geomembrane and then compared them with the test results of field samples of HDPE grass blades.

The method included upper bound and lower bound calculations for each site. The results of the upper bound calculations using the GRI laboratory data yielded exposure durations for 50% retained tensile strength of: (i) 132 years for Saufley Field Landfill in Pensacola, Florida; (ii) 151 years for LaSalle-Grant Landfill in Jena, Louisiana; (iii) 157 years for the Berkely County Landfill; (iv) 157 years for the Baldwin County Landfill; and (v) 93 years for the Atlas Testing Facility in New River, Arizona.

The results of the lower bound calculations using the GRI laboratory data yielded exposure durations for 50% retained tensile strength of: (i) 83 years for Saufley Field Landfill in Pensacola, Florida; (ii) 91 years for LaSalle-Grant Landfill in Jena, Louisiana; (iii) 90 years for the Berkely County Landfill; (iv) 90 years for the Baldwin County Landfill; and (v) 75 years for the Atlas Testing Facility in New River, Arizona.

These calculations were repeated using 12.5% retained tensile strength to illustrate the difference in exposure duration if a performance-based criteria is used rather than half-life. The results of the upper bound calculations yielded exposure durations of: (i) 314 years for Saufley Field Landfill in Pensacola, Florida; (ii) 359 years for LaSalle-Grant Landfill in Jena, Louisiana; (iii) 376 years for the Berkely County Landfill; (iv) 376 years for the Baldwin County Landfill; and (v) 216 years for the Atlas Testing Facility in New River, Arizona.

The lower bound calculations yielded exposure durations for 12.5% retained tensile strength of: (i) 204, years for Saufley Field Landfill in Pensacola, Florida; (ii) 223 years for LaSalle-Grant Landfill in Jena, Louisiana; (iii) 236 years for the Berkely County Landfill; (iv) 221 years for the Baldwin County Landfill; and (v) 181 years for the Atlas Testing Facility in New River, Arizona.

The results above for the Saufley Field Landfill site in Pensacola, Florida were compared with the results given in Richgels (2016) where a similar conversion was performed. Richgels (2016) obtained an upper bound duration for 50% retained strength of 200 years and a lower bound result of 118 years, compared with Geosyntec's results of 132 years and 83 years, respectively. The differences between Geosyntec and Richgels calculations were attributed to rounding and updates to solar radiation and temperature information used in NREL datasets. However, the comparison generally demonstrates agreement between Geosyntec and Richgels (2016).

Plots of the field data and the upper and lower bound half-life estimates based on the GRI data for the New River, AZ site and the sites in the Southeastern U.S. are shown in Figures 13 and 14, respectively. As displayed in the figures, the field data consistently plots above the upper bound estimates. This difference may be attributable to environmental factors not accounted for in the laboratory or laboratory to field conversion method. These environmental factors may include orientation of the samples in the field, shading from slopes or adjacent grass blades, moisture conditions, etc. (GRI, 2019). Furthermore, as demonstrated in GRI (2019), it is seen that the laboratory lifetimes are somewhat lower than the field lifetimes, indicating that the laboratory incubation devices are more severe in their exposure and radiation when compared to field conditions. Additionally, field samples in the early stages of weathering may be within the antioxidant phase of degradation rather than the polymer oxidation stage as suggested by Rowe *et. al.* (2010). As indicated in Koerner (2011), the duration of the antioxidant depletion phase is dependent upon the type and amount of the various antioxidants present in the formulation. Furthermore, the physical loss of antioxidants involves the distribution of antioxidants in the material and their volatility and extractability to the site-specific environment (Koerner, 2011). Therefore, variations between the field data and the half-life estimates using the GRI laboratory data may be attributable to differences in the rate at which the proprietary antioxidant formulation present in the HDPE grass blades degrades due to site-specific environmental conditions. Finally, because the extrapolation performed to estimate laboratory exposure time required to reach 50% degradation was based upon the regression of the polymer oxidation data points (Stage C) from the GRI data, the half-life projections herein represent a conservative estimate which do not account for the antioxidant depletion phase.

Therefore, a 100-year half-life estimate for the HDPE grass blades of ClosureTurf® is supported for sites in the Southeastern U.S., given that the upper and lower bound estimates bracket a 100-year half-life and the field data regressions plot above the upper bound (Figure 14). While the estimated upper-bound half-life for New River, AZ falls slightly below 100 years due to the higher solar irradiance, the trends observed in the field data also support a half-life estimate that is also on the order of 100 years (Figure 13). The slight disparity between the upper bound estimate and field data is consistent with the discussion provided above. Furthermore, performance requirements of the ClosureTurf® HDPE grass blades may permit evaluation of longevity beyond the half-life, thereby extending the expected duration of field performance with a longer service life.

CLOSING

Geosyntec appreciates the opportunity to assist Watershed in the development of its ClosureTurf® products. Questions and comments may be directed to either of the undersigned at 678-202-9500.

Sincerely,

Will Tanner, P.E.
Principal Engineer (GA, NC, SC, AL, FL)

Chris Abdeen, E.I.T.
Senior Staff Engineer

Attachments: References
Tables
Figures

Copies to: Bryan Scholl (Watershed)
Mike Ayers (Watershed)

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TABLES

Table 1. HDPE Grass Blade Upper Bound Half-Life Calculations- Saufley Landfill, Pensacola, FL

Month	UV Lamp On[1] (hrs/day)	Average Peak Turf Temp [2] (C)	Average Peak Turf Temp (K)	Average Peak Turf Temp (1/K)	Reaction Rate[3]	Lab Half-Life[4] (lamp hrs)	Field Equivalent[5] (days)	Field Equivalent[6] (months)	Half Life Loss per Month[7]
January	5.19	24.99	298.14	0.0034	-13.72	909876	175241	5653	0.000176899
February	5.42	25.13	298.28	0.0034	-13.71	902464	166396	5943	0.000168273
March	6.80	29.60	302.75	0.0033	-13.45	692347	101754	3282	0.000304656
April	7.09	38.19	311.34	0.0032	-12.96	425411	60016	2001	0.000499866
May	8.83	46.69	319.84	0.0031	-12.50	269585	30519	984	0.001015757
June	7.43	51.58	324.73	0.0031	-12.25	209627	28210	940	0.001063454
July	6.41	54.56	327.71	0.0031	-12.10	180417	28147	908	0.001101362
August	6.15	53.40	326.55	0.0031	-12.16	191246	31118	1037	0.000964064
September	7.15	52.63	325.78	0.0031	-12.20	198737	27785	896	0.001115708
October	7.14	42.52	315.67	0.0032	-12.73	336152	47112	1520	0.000658012
November	6.75	31.70	304.85	0.0033	-13.33	613209	90913	3030	0.000329987
December	5.06	26.43	299.58	0.0033	-13.63	834692	164850	5318	0.000188049
Lab	20							**Yearly Half-life Loss[8]**	0.007586087
								Half-life[9] (years)	131.82

Notes:

(1) UV lamp on (hours per day) is determined as the ratio of UV irradiance determined in accordance with Richgels (2016) to the lamp irradiance used in the laboratory study conducted by GRI (3.05 $MJ/m^2/day$).
(2) Monthly average ambient temps for Pensacola, FL from NREL database multiplied by a factor of 2 to estimate monthly average peak turf temp (Richgels, 2016).
(3) Reaction rate is calculated from the regression curve shown in Figure 7 for the upper bound (logarithmic) case.
(4) Lab half-life in hours is equal to 1/e^(Reaction Rate).
(5) Field equivalent (days) is calculated by dividing the lab half-life in hours by the UV lamp on hours per day.
(6) Field equivalent in days is converted to months using the given days in that particular month.
(7) Half-life loss per month is the inverse of the corresponding field equivalent in months.
(8) The yearly half-life loss is the sum of each individual months half-life loss.
(9) The half-life in years is the inverse of the yearly half-life loss.

Table 2. HDPE Grass Blade Lower Bound Half-Life Calculations- Saufley Landfill, Pensacola, FL

Month	UV Lamp On[1] (hours/day)	Months @ 80 C[2]	Months @ 70 C[2]	Months @ 60 C[2]	Average Peak Turf Temp[3] (C.)	Half-life Months (from Regression)	Half-life Loss per month
January	5.19	316	644	787	24.99	1700	0.000588355
February	5.42	334	682	834	25.13	1794	0.000557343
March	6.80	241	491	601	29.60	1208	0.000828074
April	7.09	239	487	596	38.19	1037	0.000963898
May	8.83	185	378	463	46.69	682	0.001465817
June	7.43	228	465	568	51.58	750	0.001333715
July	6.41	256	521	638	54.56	782	0.001279345
August	6.15	267	544	665	53.40	839	0.001192233
September	7.15	237	483	590	52.63	759	0.001316773
October	7.14	230	468	573	42.52	920	0.001086971
November	6.75	251	512	626	31.70	1219	0.000820551
December	5.06	324	660	807	26.43	1706	0.000586084
Lab	20					**Yearly Half-life Loss**	0.01106492
						Half-life (years)	83.20

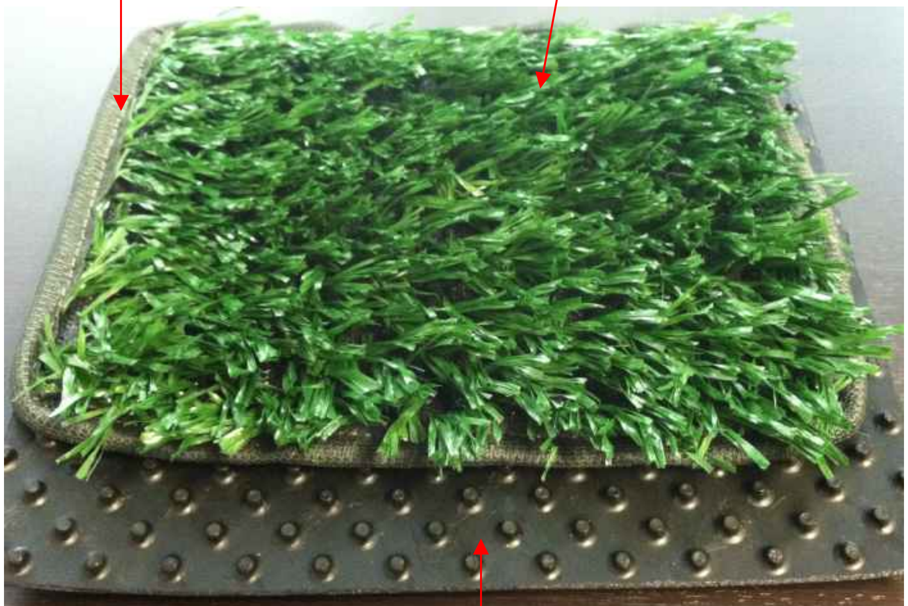
Notes:

(1) UV lamp on (hours per day) is determined as the ratio of UV irradiance determined in accordance with Richgels (2016) to the lamp irradiance used in the laboratory study conducted by GRI (3.05 $MJ/m^2/day$).

(2) The months required at each temperature is calculated using the regressions from Figure 8 for each temperature, projected down to half-life, then dividing the lamp-hours at half-life by the UV lamp on hours per day for a given month. Once this calculation is done for 80, 70 and 60 C, a linear regression (as shown in Figure 8) is used to obtain the half-life months at the corresponding average peak turf temp.

(3) Monthly average ambient temps for Pensacola, FL from NREL database multiplied by a factor of 2 to estimate monthly average peak turf temp (Richgels, 2016).

FIGURES



Note: The sand ballast infill is not shown in the sample photo on the left, but is shown in a field application photo on the right.

ClosureTurf® Components

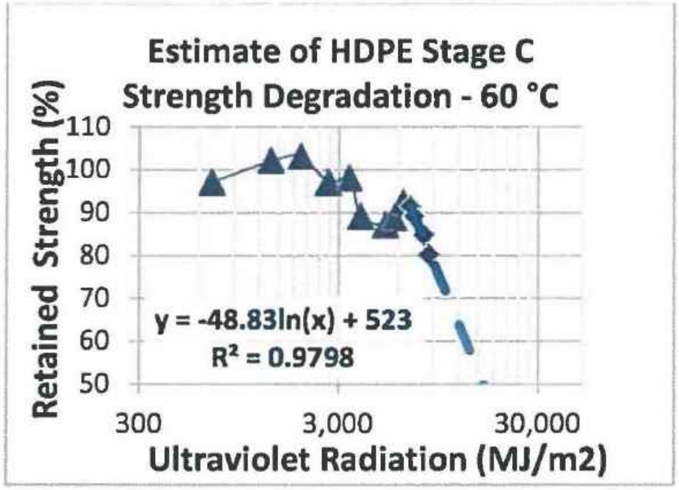
Watershed Geosynthetics – ClosureTurf® UV Assessment

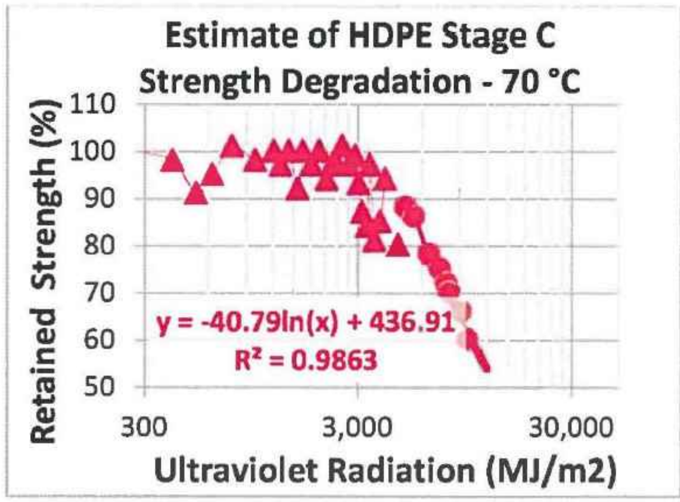
Geosyntec consultants

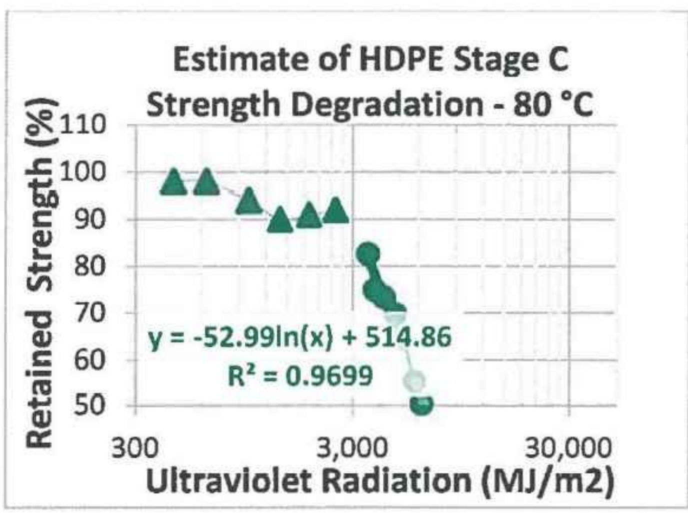
Figure 1

Kennesaw, GA

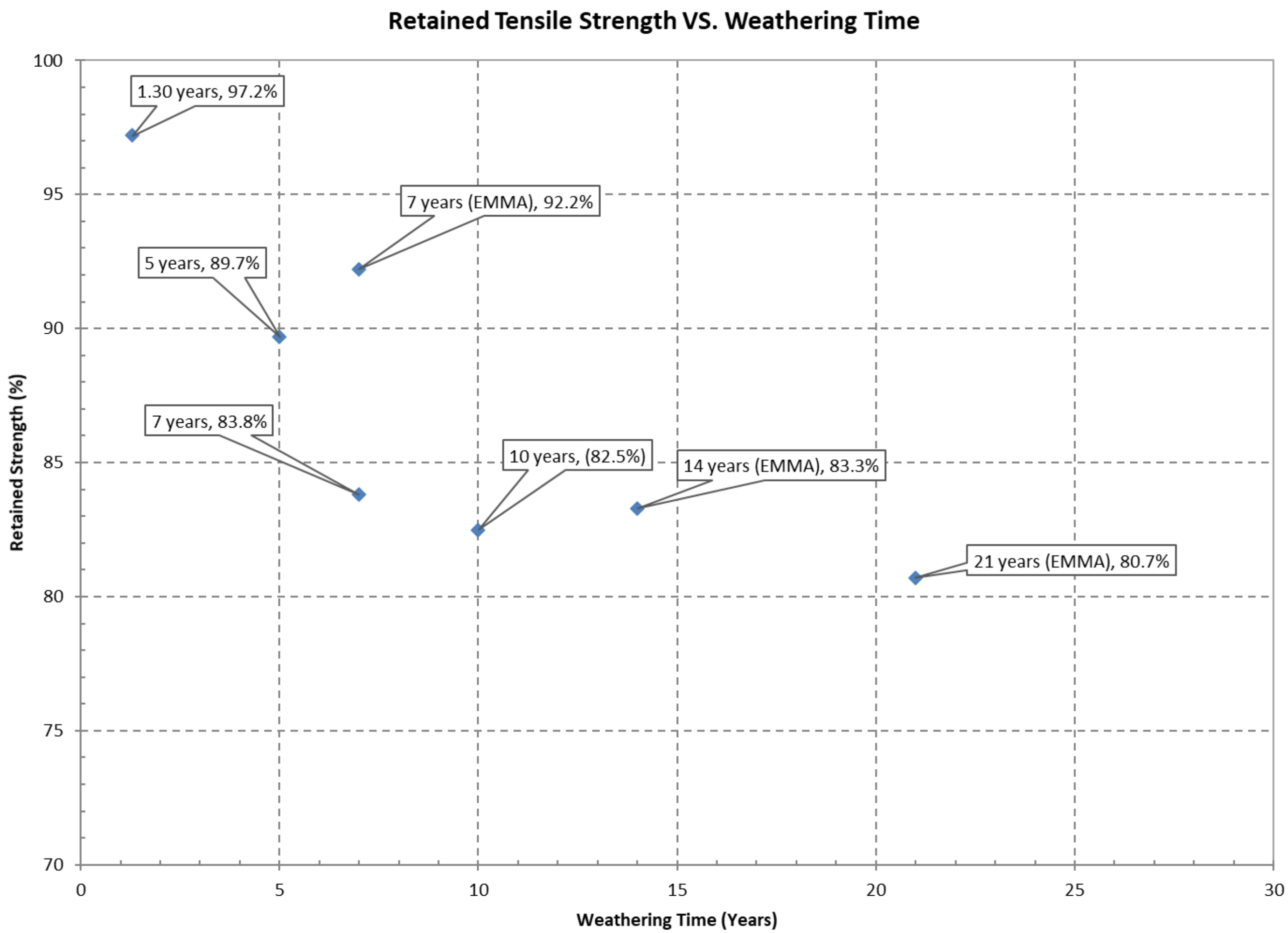
August 2022







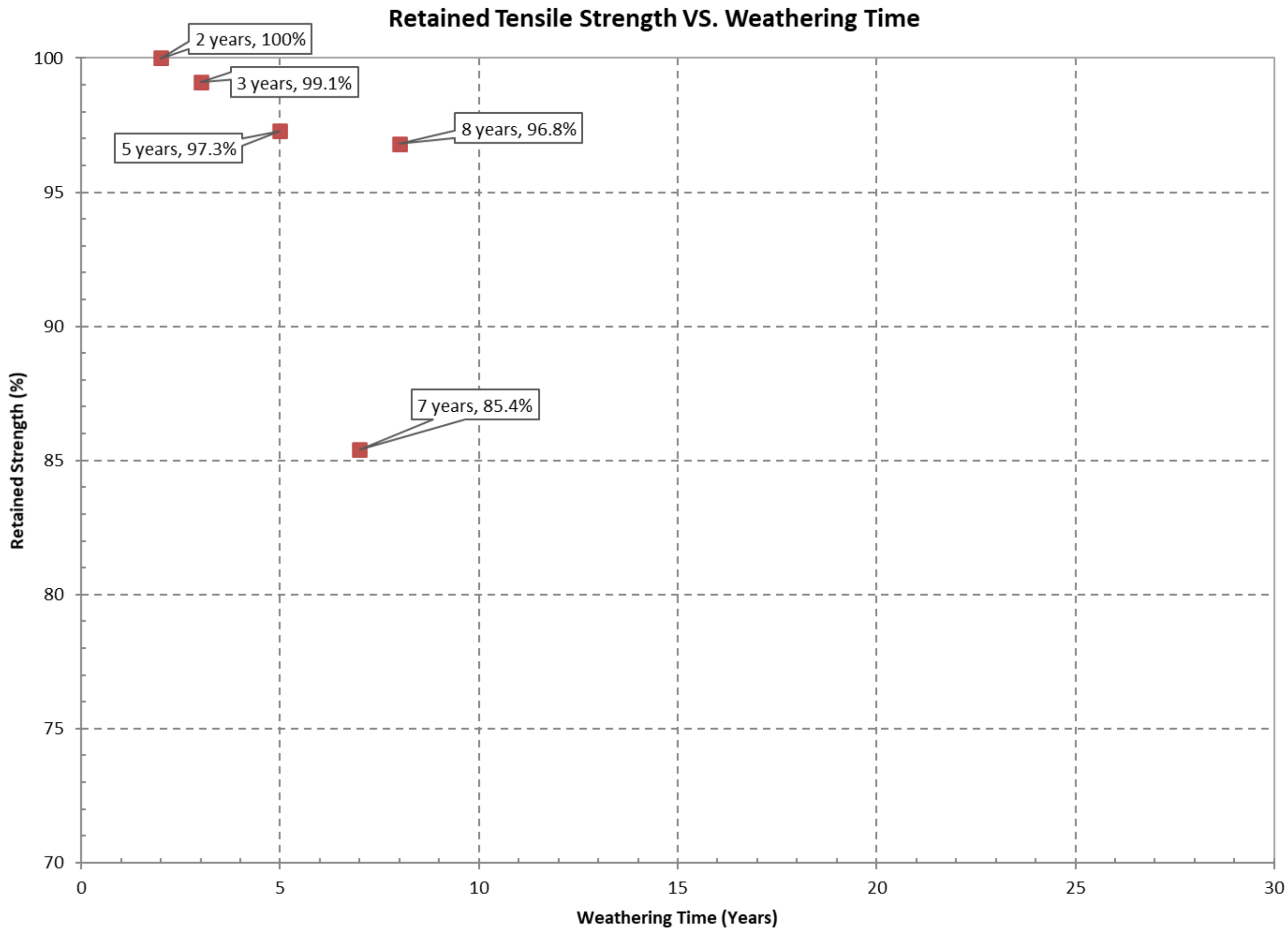
GRI Data Release - Three Stage Oxidation of HDPE for Different Temperatures Watershed Geosynthetics – ClosureTurf® UV Assessment		
Geosyntec consultants		Figure 2
Kennesaw, GA	August 2022	



Notes:

1. The first data point at Weathering Time of 1.3 years is considered to be within the initial stage of UV degradation (i.e., anti-oxidant depletion), rather than polymer oxidation which is represented by the final six data points.
2. Each data point represents the average result of 10 tensile strength tests.
3. The accelerated weathering testing is conducted using the Equatorial Mount with Mirrors for Acceleration (EMMA) solar concentration device, which provides approximately seven years of UV radiation exposure in one calendar year.

Field Test Data (Watershed 2014, 2022) **New River, AZ Atlas Testing Facility** Watershed Geosynthetics – ClosureTurf® UV Assessment			
Geosyntec consultants		Figure **3**	
Kennesaw, GA	November 2022		



Notes:

1. Each data point represents the average result of 10 tensile strength tests.

Field Test Data (Watershed, 2022)
Southeastern United States Locations
Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **4**

Kennesaw, GA | November 2022

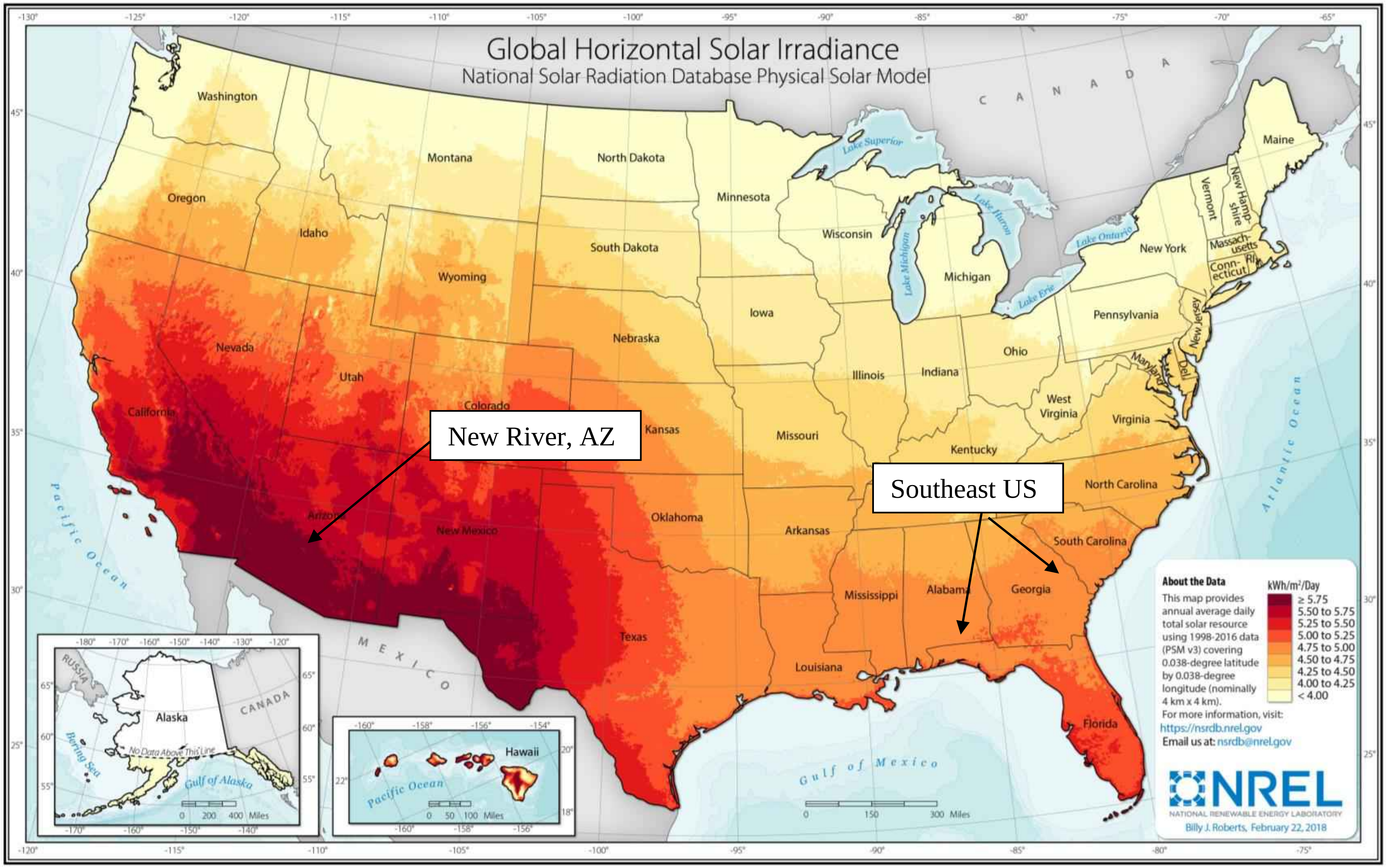
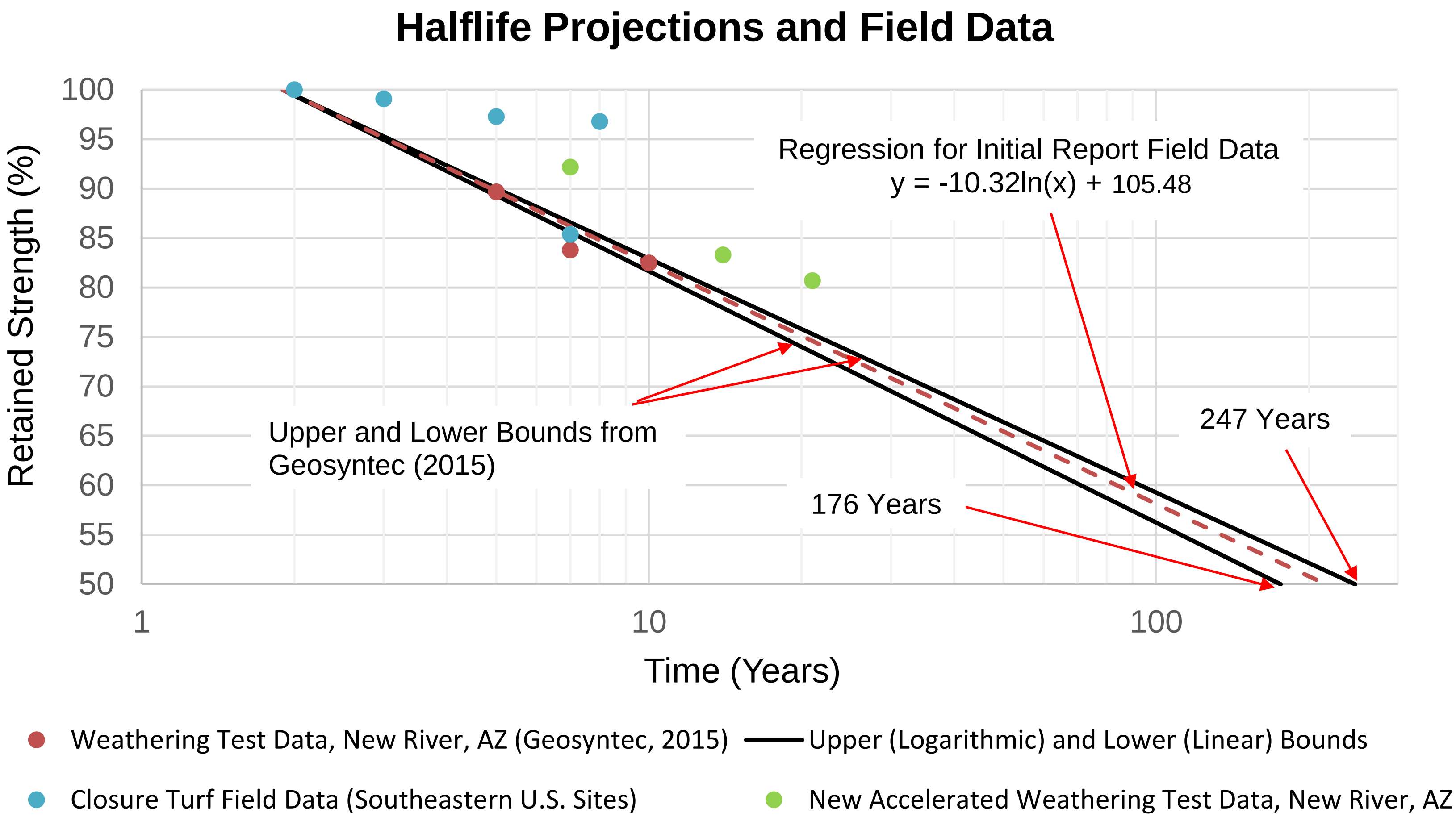


Image available at: https://www.nrel.gov/gis/solar-resource-maps.html

Horizontal Solar Irradiance Watershed Geosynthetics – ClosureTurf® UV Assessment		
Geosyntec consultants		Figure 5
Kennesaw, GA	November 2022	

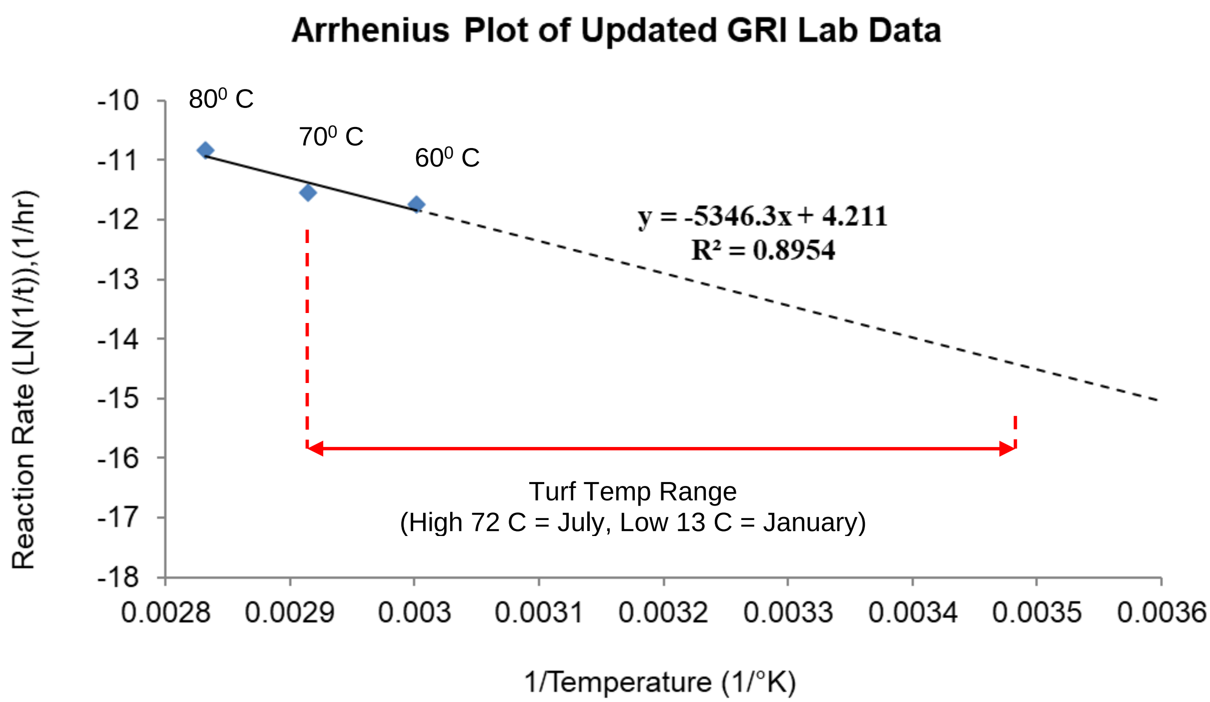


Geosyntec (2015) Halflife Projections
Vs. New Field and Accelerated Weathering Data
Watershed Geosvthetics – ClosureTurf® UV Assessment

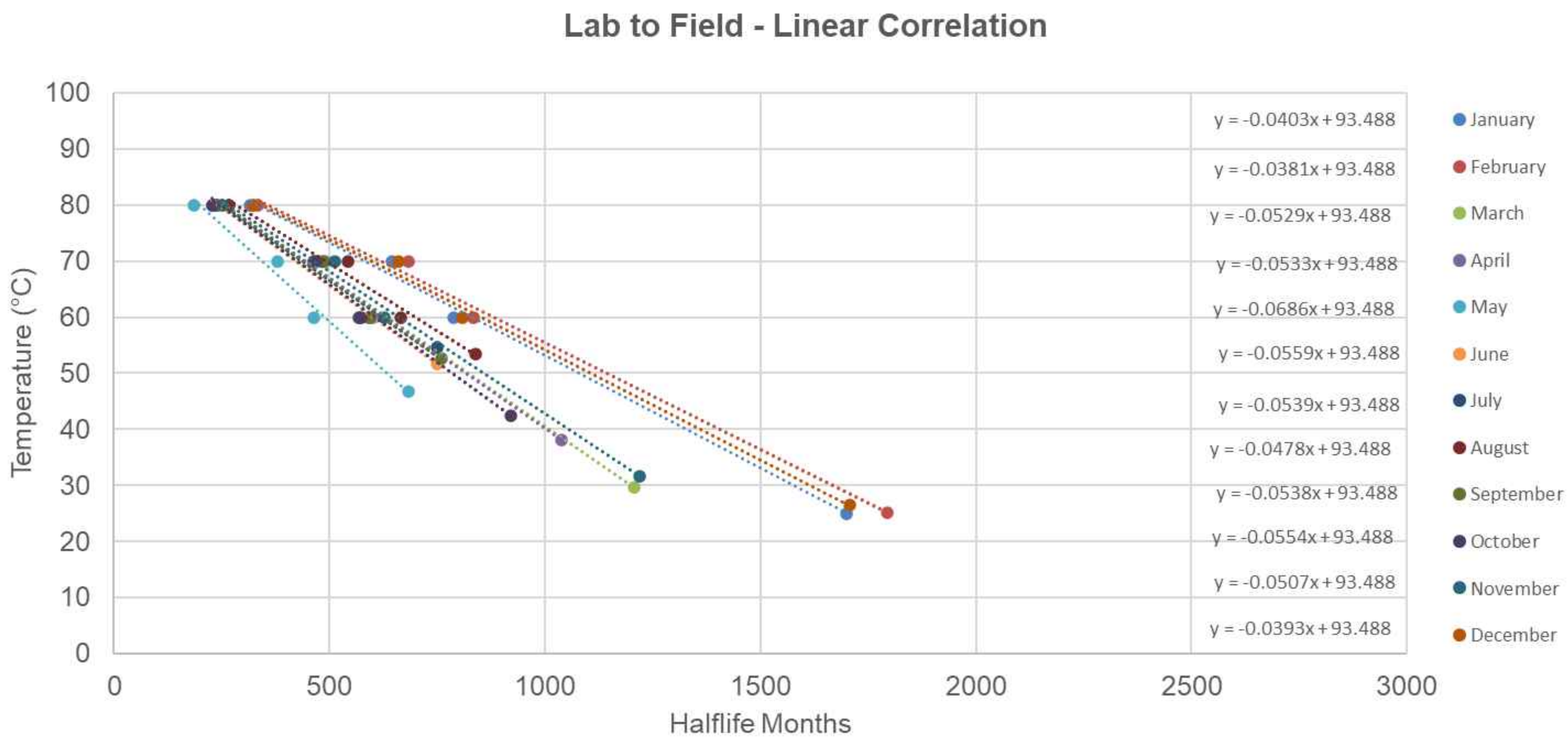
Geosyntec consultants

Figure
6

Kennesaw, GA | November 2022



Arrhenius Plot of Lab Data Watershed Geosynthetics – ClosureTurf® UV Assessment		
Geosyntec consultants		Figure 7
Kennesaw, GA	November 2022	



Notes:

1. Each month was projected down to the turf temperature to get the half-life months. The inverse of half-life months is half-life loss per month. The sum of all the half-life losses for each month in a year is the yearly half-life loss, the inverse of which is the half-life. An example calculation for the Saufley Landfill site is provided in Table 2.
2. Trendline equations are listed in order chronologically from January to December.

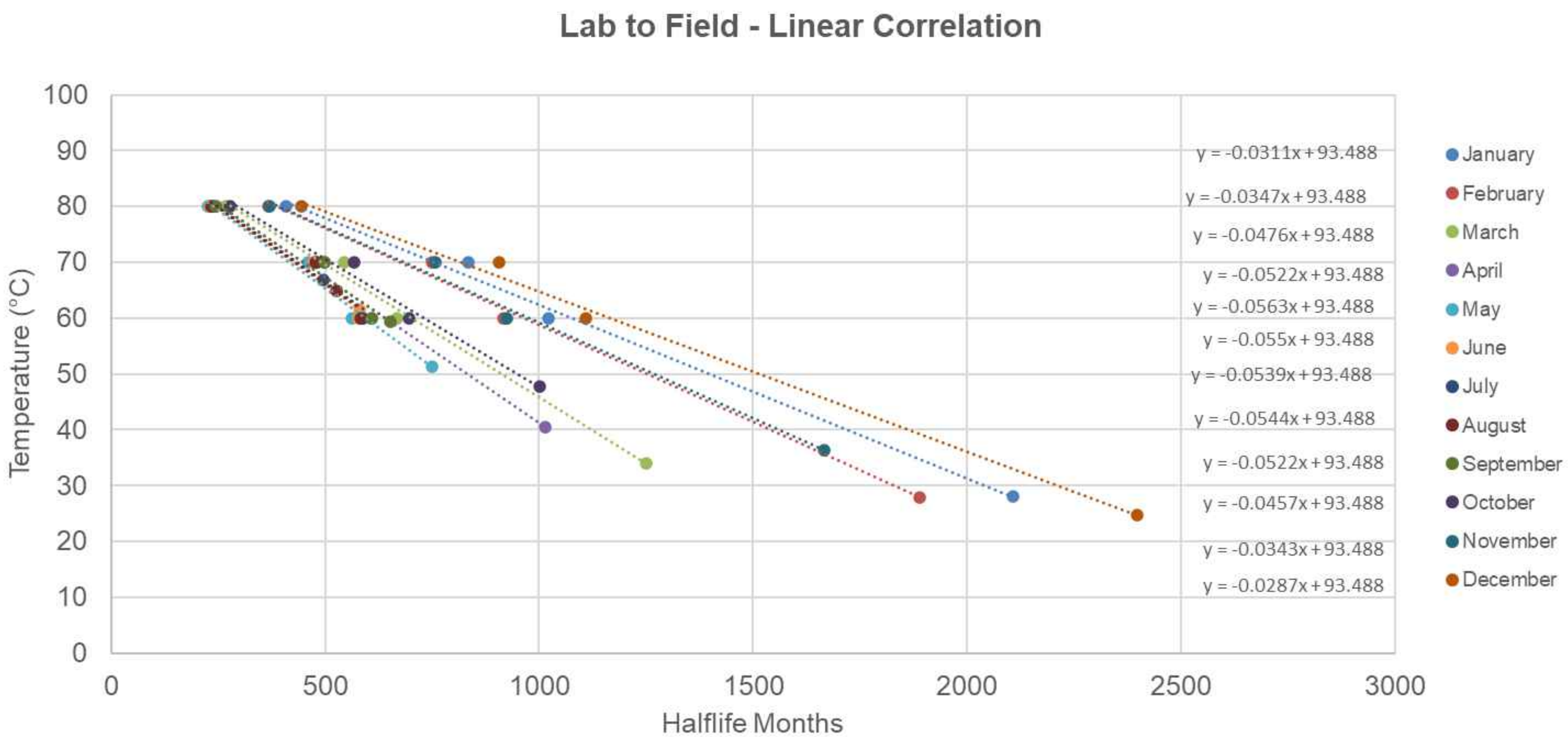
Linear Extrapolations for Half-life Months – Saufley Field Landfill, Pensacola, FL

Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **8**

Kennesaw, GA | November 2022



Notes:

1. Each month was projected down to the turf temperature to get the half-life months. The inverse of half-life months is half-life loss per month. The sum of all the half-life losses for each month in a year is the yearly half-life loss, the inverse of which is the half-life. An example calculation for the Saufley Landfill site is provided in Table 2.
2. Trendline equations are listed in order chronologically from January to December.

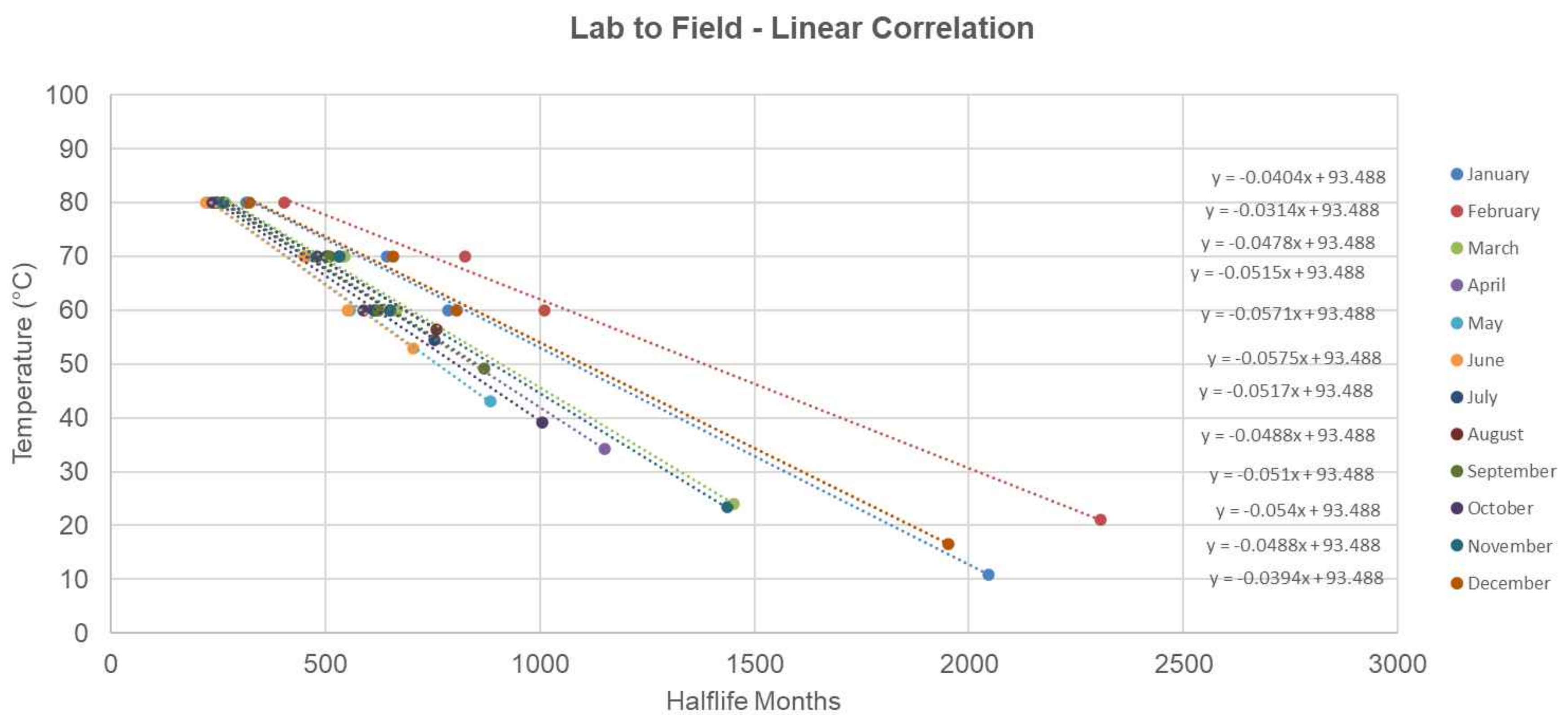
Linear Extrapolations for Half-life Months – New River, Arizona

Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **9**

Kennesaw, GA | November 2022



Notes:

1. Each month was projected down to the turf temperature to get the half-life months. The inverse of half-life months is half-life loss per month. The sum of all the half-life losses for each month in a year is the yearly half-life loss, the inverse of which is the half-life. An example calculation for the Saufley Landfill site is provided in Table 2.
2. Trendline equations are listed in order chronologically from January to December.

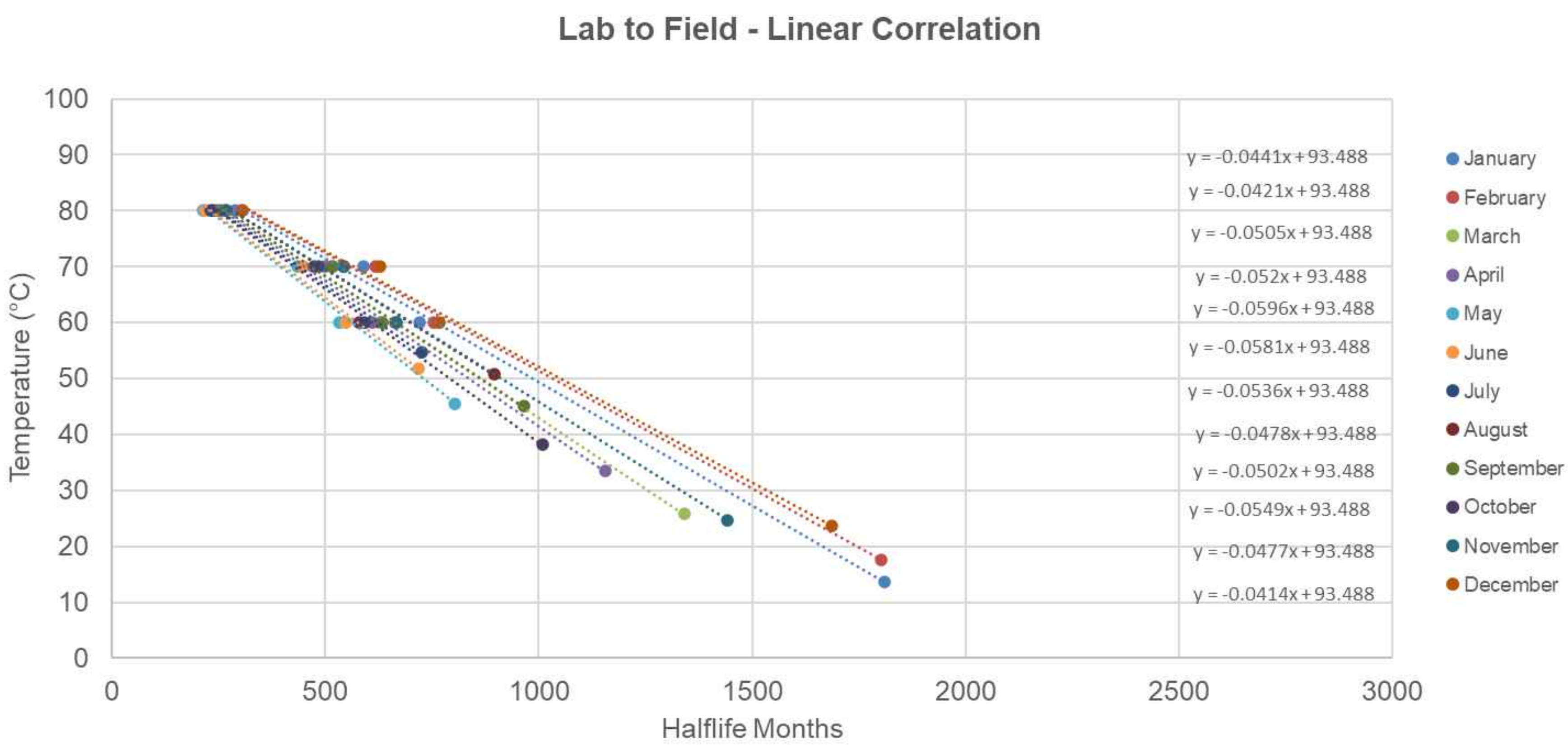
Linear Extrapolations for Half-life Months – Lasalle-Grant Landfill, Jena, LA

Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **10**

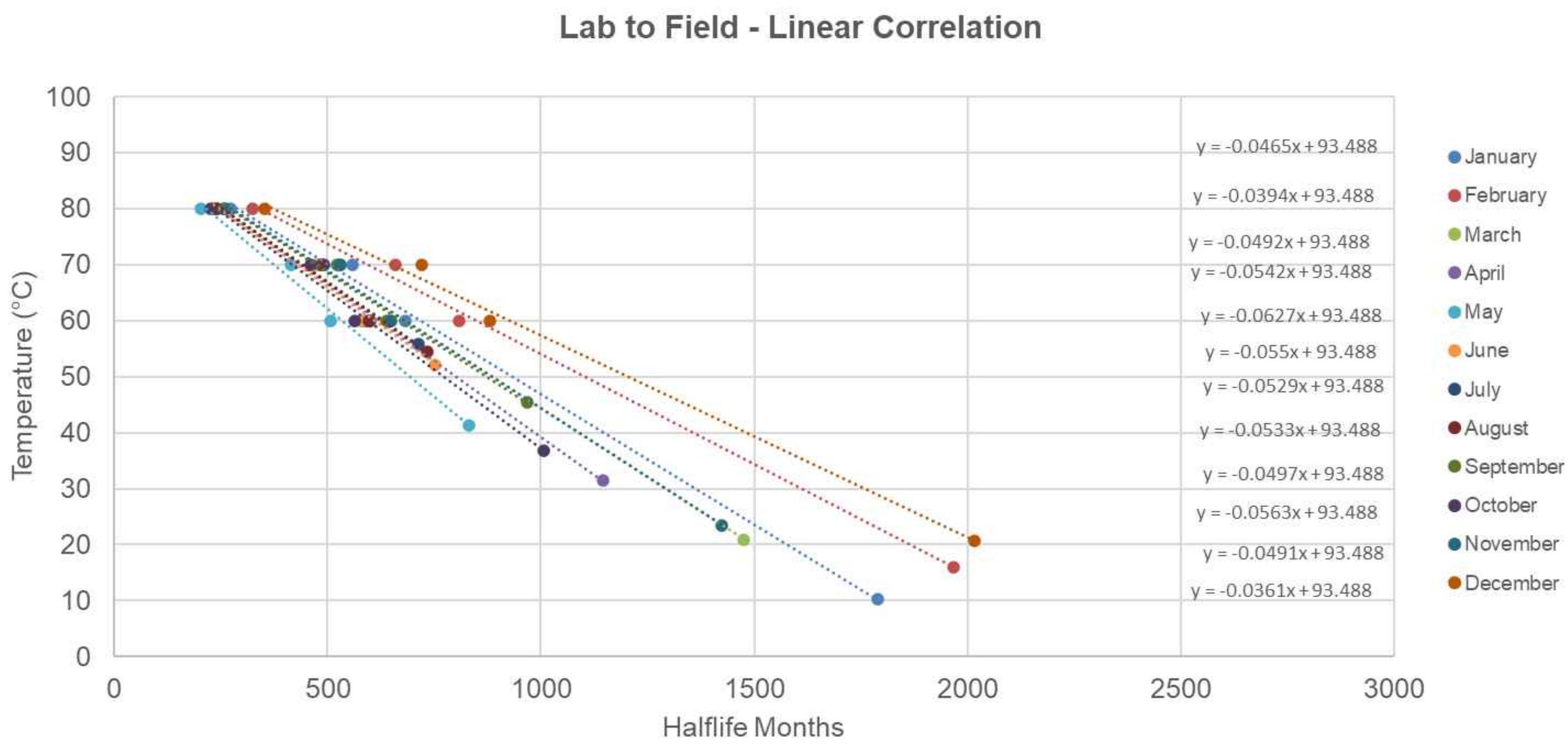
Kennesaw, GA | November 2022



Notes:

1. Each month was projected down to the turf temperature to get the half-life months. The inverse of half-life months is half-life loss per month. The sum of all the half-life losses for each month in a year is the yearly half-life loss, the inverse of which is the half-life. An example calculation for the Saufley Landfill site is provided in Table 2.
2. Trendline equations are listed in order chronologically from January to December.

Linear Extrapolations for Half-life Months – Berkley Co., SC Watershed Geosynthetics – ClosureTurf® UV Assessment	
Geosyntec consultants	Figure **11**
Kennesaw, GA — November 2022	



Notes:

1. Each month was projected down to the turf temperature to get the half-life months. The inverse of half-life months is half-life loss per month. The sum of all the half-life losses for each month in a year is the yearly half-life loss, the inverse of which is the half-life. An example calculation for the Saufley Landfill site is provided in Table 2.
2. Trendline equations are listed in order chronologically from January to December.

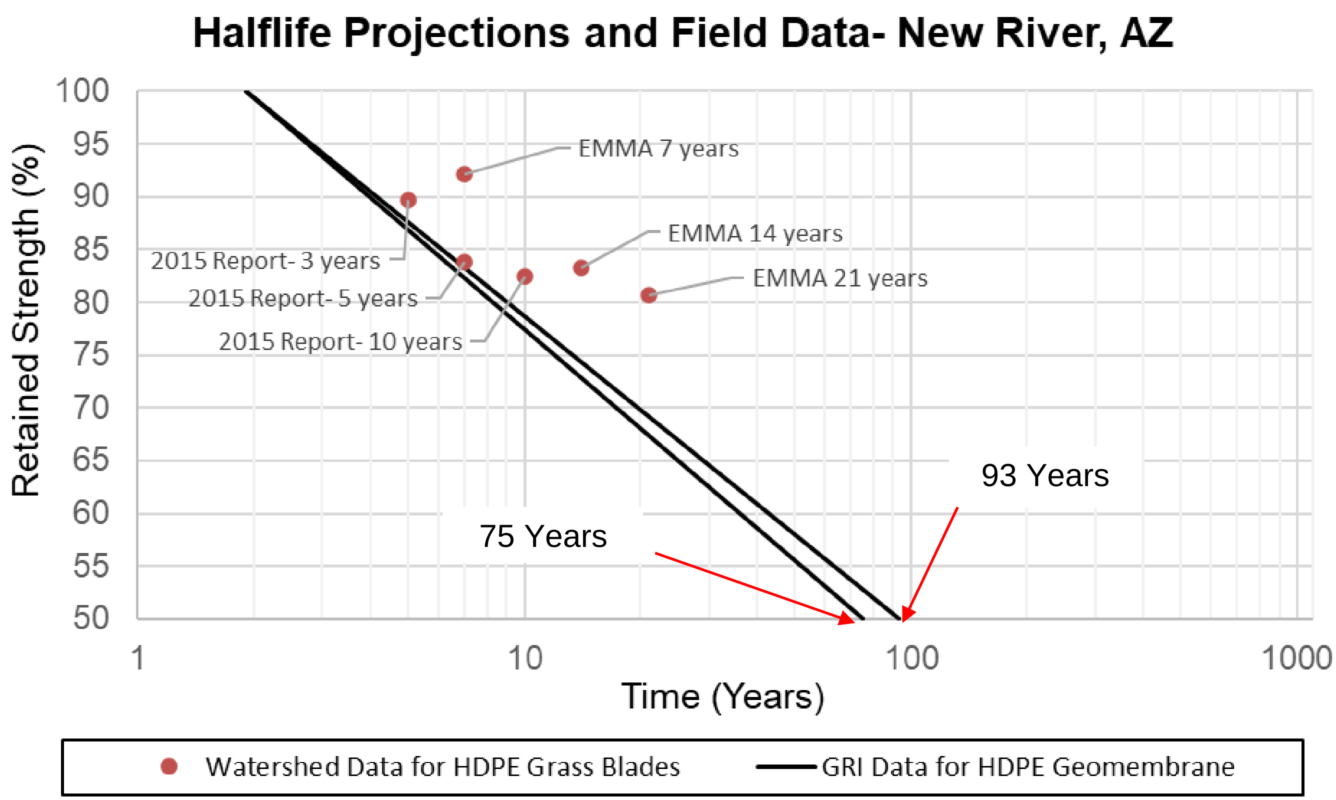
Linear Extrapolations for Half-life Months – Baldwin Co., GA

Watershed Geosynthetics – ClosureTurf® UV Assessment

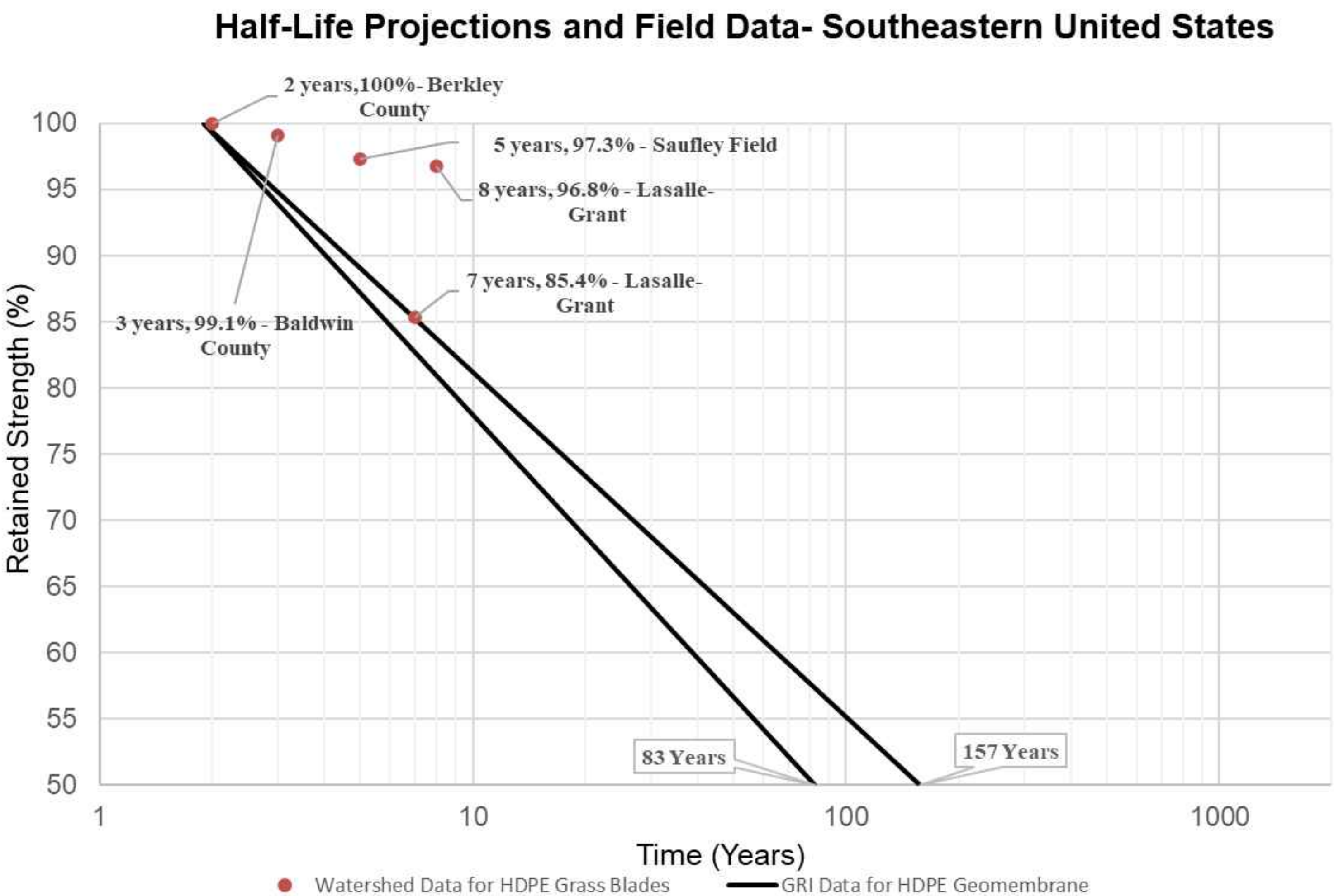
Geosyntec consultants

Figure **12**

Kennesaw, GA | November 2022



Halflife Projections **Upper and Lower Bound Estimates- New River, AZ** Watershed Geosythetics – ClosureTurf® UV Assessment		
Geosyntec consultants		Figure **13**
Kennesaw, GA	November 2022	



Note: The upper and lower bound half-life estimates represent the limits of the estimates for the sites in the Southeastern United States.

Halflife Projections
Upper and Lower Bound Estimates- SE United States
Watershed Geosythetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **14**

Kennesaw, GA | November 2022

2015 Evaluation Report

Geosyntec consultants

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15 May 2015

José Urrutia, P.E.
Vice President of Engineering
Watershed Geosynthetics
11400 Atlantis Place, Suite 200
Alpharetta, GA 30022

Subject: Literature Review and Assessment of ClosureTurf® UV Longevity

Dear Mr. Urrutia:

Watershed Geosynthetics, Inc. (Watershed) has patented an alternative landfill closure system termed, ClosureTurf®. ClosureTurf® consists of high-density polyethylene (HDPE) grass blades tufted through a polypropylene (PP) geotextile backing which overlies Super Gripnet®, an HDPE or linear low-density polyethylene (LLDPE) geomembrane manufactured by AGRU America Inc. The addition of a layer of sand ballast during installation completes the system. The sand ballast provides cover for the lower portion of the HDPE grass blades, the PP geotextile backing, and the Super Gripnet® (Figure 1). The ClosureTurf® system, therefore, is a "hybrid" closure system in the sense that it is neither a traditional soil cover or an exposed geomembrane. ClosureTurf® has been used to close a number of landfills throughout the United States. A select list of sites where it has been used is shown in Table 1. Applications extend to other facilities as well, such as capping of coal ash ponds.

Watershed has requested that Geosyntec Consultants, Inc. (Geosyntec) provide an assessment of the longevity of the ClosureTurf® system with regard to UV degradation. Since ClosureTurf® has elements (i.e., the HDPE grass blades) that are permanently exposed to UV radiation, this assessment will be particularly focused on the exposed portion of the system. However, the UV longevity of the PP geotextile backing and HDPE geomembrane will also be addressed by reference.

Geosyntec's approach to this assessment has been to conduct a literature review of pertinent documents available (journal papers, white papers, presentations, etc.), distill the results of the review, and perform limited analysis. This report concludes with a summary of the review and analysis along with brief discussion for recommendations.

EXECUTIVE SUMMARY

The UV longevity assessment of the ClosureTurf® system (Figure 1) began with a literature review. In general, relatively little published information was discovered regarding exposed HDPE grass blade degradation. The information that is available consists of retained tensile strength test results of HDPE grass blades after exposure (1, 5, 7 and 10 years) at a field test facility in New River, Arizona (Watershed, 2014). Extrapolation of this data by Watershed (2014) resulted in a prediction of 65% retained tensile strength after 100 years of service. In addition, Richgels *et al* (2015) published half-life (i.e., 50% retained tensile strength) predictions of exposed HDPE grass blades using a laboratory data release from the Geosynthetics Institute (GSI) on HDPE geomembrane strips exposed to UV lamp irradiation. Richgels *et al* (2015) obtains an upper bound and lower bound half-life predictions of 247 years and 176 years, respectively. Extrapolation of the field data from New River, Arizona yielded a half-life of 216 years.

Geosyntec checked the calculations shown in Richgels *et al* (2015) and obtained 277 years and 214 years for the upper and lower bound estimates of HDPE grass blade half-life. Differences in the results between Geosyntec and Richgels *et al* (2015) are attributed to rounding. Geosyntec attempted to repeat these calculations for actual performance requirements (i.e., 12.5% of original tensile strength) of the HDPE grass blades rather than a randomly assigned half-life, however the predictions resulted in service lives that were too lengthy to be reasonable. The most likely explanation is that the laboratory data has not degraded enough to allow for service life predictions using 12.5% retained tensile strength. Future data releases from GSI will aid in providing more accurate predictions below the half-life.

Based on Richgels *et al* (2015) predictions, as well as the prediction given in Watershed (2014) it appears that the half-life of the HDPE grass blades exposed to Arizona-like conditions is on the order of 100 years. These results are promising; however additional field test data is needed to improve the half-life predictions, particularly since half-life predictions for exposed HDPE geomembrane are also approximately 100 years (Koerner *et al*, 2015). Understanding the differences in weathering between HDPE grass blades in a synthetic turf and an HDPE geomembrane will provide additional insight into the similar half-life predictions of the two geosynthetics. Finally, the service life of the HDPE grass blades in the ClosureTurf® system should ideally be based on its performance requirements rather than a half-life which will result in a longer service life prediction.

In addition to the HDPE grass blades, there are two unexposed elements of the ClosureTurf® system: (i) the PP geotextile backing for turf component; and (ii) the Super Gripnet® which consist of a HDPE geomembrane (see Figure 1).

Watershed has incorporated UV degradation inhibitors into the PP geotextile backing which, according to Watershed has lead to an improvement in UV resistance by a factor of 14 over the original prediction of 65% retained tensile strength after 100 years (Watershed, 2014). Koerner (2011) has estimated that covered HDPE geomembrane will have a half-life of 446 years at 20 degrees Celsius and 265 years at 25 degrees Celsius.

Therefore, the most critical component of the ClosureTurf® appears to be the exposed HDPE grass blades when it comes to UV degradation. However, degradation of the HDPE grass blades to unserviceable levels can be remediated by replacement of the turf component of the ClosureTurf® system.

BACKGROUND AND LITERATURE REVIEW SUMMARY

In total, Geosyntec has reviewed approximately 40 technical documents to date. The database is a combination of documents provided to Geosyntec by Watershed as well as documents collected by Geosyntec. A complete reference list of the documents in the database can be made available upon request.

In general, relatively little information was found on the topic of exposed HDPE grass blades with respect to degradation due to UV radiation. The documents that were obtained and reviewed are listed below.

1. Field test data provided by Watershed from the New River, Arizona testing facility on the HDPE grass blades (Watershed, 2014).

2. Testing results (Atlas-MTS) discussing the UV longevity of polyethylene and polypropylene grass used for outdoor European athletic facilities.

3. Technical paper by Richgels, *et al.* (2015a) published in the conference proceedings for Geosynthetics 2015 in Portland, Oregon.

4. Presentation by Richgels., C. at the Geosynthetics Conference for 2015 in Portland, Oregon (Richgels, 2015b).

5. Presentation by Diguilio, D. at the Northern New England SWANA Conference on 25 September 2013 (Diguilio, 2013).

The following documents on the topic of HDPE Geomembrane degradation due to UV exposure were reviewed and found to contain useful information regarding this assessment.

1. Geosynthetic Research Institute (GRI) White Paper #6 (Koerner *et al.*, 2011). This white paper contained degradation data (% retained strength and elongation) on laboratory aged samples of 1.5 mm HDPE geomembrane. Aging was completed using a UV Fluorescent device per ASTM D7238 at 70 degrees Celsius (^{o}C).

2. Geosynthetic Institute (GSI) webinar presentation by Koerner *et al.*, (2015). This presentation contained a slide that compared predicted (laboratory vs. field) half-life of geomembranes of various resins, including HDPE, as well as a suggestion for estimating lower bound half-life.

3. Journal paper authored by Rowe *et al.* (2010) published in the Journal of Geotechnical and Geoenvironmental Engineering.

DISCUSSION OF DOCUMENTS AND DATA

The data from the New River, AZ testing facility on the artificial grass component of ClosureTurf® (Watershed, 2014) appears to be the only data set of its kind in our compiled database. The data consists of tensile property testing from field samples exposed to the Arizona environment at approximate exposure periods of 1, 5, 7 and 10 years. At each of the four exposure periods, 20 samples were tested for a total of 80 tests. The average values for tensile strength retained at each corresponding time period is 97%, 90%, 84% and 83%, respectively (Figure 2).

One additional data point was found in the Atlas-MTS document. That data point indicated that approximately 90% of tensile strength of polyethylene grass would be available after 20 years of field exposure assuming average European climatic conditions (temperature, irradiance, etc.). However, the average European irradiance is approximately one-half to one-third that of Arizona (Figure 3) notwithstanding temperature effects. Therefore, the Atlas-MTS data point will be consistent with the data from the New River, AZ facility in the 7 to 10 year time frame once adjusted for the relative levels of exposure and temperature between Europe and Arizona. As such, this data point will not extend the exposure duration covered by the New River, AZ data.

The paper and corresponding presentation by Richgels (2015a, 2015b) utilized the laboratory data released from the GSI on UV degradation of HDPE samples to make upper and lower bound estimates of the field half-life of the HDPE grass blades. The upper bound method utilizes Arrhenius modeling of lab data to project exposure times at half-life to site temperatures combined with ratios of UV irradiance between the laboratory lamp and monthly average irradiance at New River, AZ to develop half-life loss per month. A similar procedure using a linear extrapolation (rather than Arrhenius) was demonstrated for a lower bound estimate. The Watershed (2014) field data set was plotted in between the upper and lower bound estimates. This method is further discussed in the section below titled, "HDPE Grass Blade Service Life Calculations".

Koerner *et al.* (2011) discusses the UV longevity of both exposed and unexposed geomembranes made from various resins, including HDPE based on GSI's laboratory testing program. This document is particularly useful in regard to the ClosureTurf® elements that are considered non-exposed (i.e., the PP geotextile backing for the turf component and the underlying HDPE geomembrane).

The presentation by Koerner *et al.* (2015) includes estimates of half-life of exposed HDPE geomembranes as well as a recommendation for linear data extrapolation as a lower bound limit that was implemented by Richgels (2015b).

PERFORMANCE REQUIREMENTS

The definition of service life of an HDPE (or other resin) geosynthetic (grass blades and geotextiles/geomembranes) typically invokes the half-life criteria. However, the half-life criteria is arbitrary and while useful as a general indicator for comparison it does not directly relate to any aspect of field performance for ClosureTurf® or any other geosynthetic. Therefore it is more appropriate to define the service life in terms of field requirements placed on the material.

HDPE Grass Blades

For the case of the HDPE grass blades on the ClosureTurf® system, tensile strength requirements fall in the range of 2.5 to 3.5 lbs, based on applied loads of pullout forces from equipment operation and water runoff forces (Diguilo, 2013). The ClosureTurf® HDPE grass blades are manufactured with 20 lbs. of tensile strength immediately following the process (Diguilo, 2013). Therefore, without considering a factor of safety, the required tensile strength of the HDPE grass blade is equal to approximately 12.5% to 17.5% of original strength capacity.

PP Geotextile Backing and HDPE Geomembrane

Performance requirements for the PP geotextile backing and HDPE geomembrane depend on more site-specific parameters (e.g., steepness of slopes, seismicity, etc.) than the HDPE grass blades. Therefore until a parametric study is completed which will define the performance requirements over a range of expected conditions, the half-life will have to be used as a benchmark for degradation of the PP geotextile and HDPE geomembrane.

HDPE GRASS BLADE SERVICE LIFE CALCULATIONS

In order to develop a prediction for the longevity of the HDPE grass blades with respect to UV degradation, Geosyntec implemented the method found in Richgels (2015a, 2015b) for two levels of retained tensile strength. The first level is the 50% of tensile strength, or half-life, criterion that is commonly used as a benchmark for geosynthetic service life. Geosyntec performed this calculation to compare our results with the results presented by Richgels (2015a, 2015b). Once the half-life estimates were calculated, Geosyntec attempted to repeat the calculations using a retained tensile strength of 12.5% of an HPDE grass blade.

Half-Life Estimation (50% of Retained Strength)

The assessment utilized by Richgels (2015a, 2015b) begins with a laboratory data release from GSI (Figure 4). The data includes retained tensile strength of HDPE samples that have been incubated under a UV lamp at elevated temperatures, which accelerates the UV weathering process in accordance with ASTM D7238.

As mentioned, the GSI data includes samples tested at three elevated temperatures: (i) 80 degrees Celsius (^{o}C); (ii) 70^{o}C; and (iii) 60^{o}C. The testing program appears to have originally included only the 70^{o}C data, with the 80 ^{o}C and 60^{o}C testing added at a later date (therefore, weathering is not as advanced). The 70^{o}C data set has reached approximately 66%, while the 80^{o}C and 60^{o}C data sets have reached approximately 78% and 86%, respectively. Nonetheless, logarithmic extrapolations to 50% retained strength were performed for each data set. The amount of exposure time (on a log scale) corresponding to the 50% retained strength plotted vs. the inverse of the corresponding temperature (80^{o}C, 70^{o}C and 60^{o}C) is shown in Figure 5. Figure 5 allows for extrapolation to find the laboratory exposure time required to achieve 50% retained strength at temperatures lower than the test temperatures (i.e., actual field temperatures).

Once the curve is defined relating any temperature to a level of laboratory lamp exposure, the remaining task is to develop a relationship between laboratory exposure and field exposure for a particular site. In this case, the testing site in New River, AZ where Watershed has performed tests on HDPE grass blades, was selected.

Richgels (2015a, 2015b) presents monthly averages at the site for: (i) peak turf temperature; and (ii) irradiance as a fraction of the laboratory lamp irradiance. Using these two values for a given month combined with the Arrhenius model, an estimate of half-life loss per month is obtained. Summation of the half-life lost per month over a year yields the annual half-life loss. The inverse of the annual half-life loss is the predicted half-life in years. Using this method, Richgels obtains a half-life of approximately 247 years, while Geosyntec obtained a half-life of 277 years using the same data (Table 2). The difference is attributable to rounding errors in the logarithmic projections.

Following the suggestion of Koerner *et al.* (2015), Richgels (2015b) treated the results of the half-life mentioned above as an upper bound estimate. For the lower bound estimate, Koerner *et al.* (2015) suggests performing a linear extrapolation of the laboratory data to lower field temperatures, rather than using the Arrhenius model.

With the linear extrapolation, the ratio of monthly irradiance to laboratory lamp irradiance is scaled linearly to calculate the number of months required to reach half-life at 80C, 70C and 60C. Linear extrapolations per month are made from the elevated temperatures to the corresponding peak turf temperature in that month. The resulting half-life loss per month is summed to obtained half-life loss per year. The inverse of that result is the half-life in years. Richgels (2015b) calculates a half-life of 176 years using this linear model. Geosyntec's calculation using the same data resulted in a half-life of 214 years (Table 3 and Figure 6). The difference in the calculations is approximately the same as with the calculation using the Arrhenius (logarithmic) model.

Figure 7 shows the calculated upper (Arrhenius - logarithmic) and lower (linear) bound curves calculated by Richgels (2015b) along with the field data on the HDPE grass blades provided by Watershed (2014). As shown in Figure 7, the trend line fit to the field data falls in between the upper and lower bound curves produced by Richgels (2015b). Note that the first point from the field data at approximately 1 year is omitted from the trend line. This is because the first data point is assumed to be within the anti-oxidant phase of degradation rather than the polymer oxidation stage as suggested by Rowe *et al.* (2010). Additional discussion regarding the stages of degradation for polyolefin materials can be found in CUR 243 (2012).

Service Life Estimation Based on Performance Requirements (12.5% of Retained Strength)

Geosyntec repeated the calculations discussed above for the estimation of half-life, but extrapolated the GSI laboratory data down to 12.5% rather than 50% at 80C, 70C and 60C. Upper bound

(Arrhenius – logarithmic) and lower bound (linear) estimates were 2,500 years and 2,043 years, respectively.

These estimates of service life are simply too large to be reasonable. A likely explanation is that the samples tested at 80C, 70C and 60C have not degraded enough to produce accurate predictions at 12.5% retained strength. As previously mentioned, the data for 80C has reached 78% retained strength; the data for 70C has reached 66% retained strength; and the data for 60C has reached 86% retained strength. Therefore, the extrapolation for each of these data sets to 50% retained strength will be much more accurate than extrapolations to 12.5%. In addition, small uncertainties in log-based extrapolations will greatly influence results.

For these reasons, it is not practical or useful at this time to quantitatively assess service life in terms of actual performance requirements when those requirements are substantially below the half-life. There is some value, however in a qualitative use of performance requirements in comparisons with half-life estimates (i.e., to establish the factor of safety remaining at 50% degradation).

SUMMARY AND CONCLUSIONS

Geosyntec's literature review of approximately 40 documents yielded few sources of UV degradation data for exposed HDPE grass blades. Relevant data that was found included the field test data from the New River, AZ testing facility provided by Watershed (2014) and one data point from Atlas-MTS. The Atlas-MTS data point indicated that HDPE grass blades in average European climatic conditions would retain approximately 90% of its original strength after 20 years of field exposure. Taking into account the differences in temperature and UV irradiance between New River, AZ and European averages, the data point is consistent with the New River, AZ test data in the 7 to 10 year range.

Following the method presented in Richgels (2015a, 2015b) for HDPE grass blades, Geosyntec calculated an upper bound half-life of 277 years compared with Richgels 247 years using the Arrhenius (semi-log) extrapolations to site temperatures and ratio of laboratory lamp to field irradiance. Geosyntec calculated a lower bound half-life based on linear temperature extrapolations, as suggested by Koerner *et al.* (2015), of 214 years compared with 176 years obtained by Richgels (2015b). The differences between Geosyntec and Richgels calculations were attributed to rounding. As shown in Figure 7, the field data from New River, AZ suggests a half-life of 216 years when considering only the last three data points (i.e., polymer oxidation stage).

Another prediction of HDPE grass blade degradation is included in Watershed (2014) using the same (New River, AZ) field data. That prediction of retained tensile strength at 100 years of service life is 65%.

Therefore, it appears that the half-life of the HDPE grass blades will be on the order of 100 years based on the existing field data set and extrapolation methods found in the literature and presented herein. The results are promising; however additional field test data is needed to improve the half-life prediction, particularly since the half-life predictions for exposed HDPE geomembranes are also approximately 100 years (Koerner, 2015). Half-life predictions presented herein will also need to be revisited when additional labratory data is released from the GSI testing program.

Geosyntec attempted to calculate the service life of the HDPE grass blades using 12.5% of retained strength, rather than an arbitrarily assigned half-life. However, the calculation resulted in unreasonably long service life. This result is likely due to uncertainties in extrapolating the laboratory data released from GSI down to the 12.5% retained strength level. The data release has degraded to 78%, 66% and 86% for the 80 °C, 70 °C, and 60 °C test temperatures. Therefore, extrapolations to 50% may be warranted while extrapolations to 12.5% may not be until additional lab data is available. That being said, it should be recognized that half-life, or 50% of retained strength, has a factor of safety of 2.8 to 4.0 when considering the tensile capacity performance requirements of HDPE grass blades.

With regard to the unexposed elements of the ClosureTurf® system, Watershed (2014) indicates that the retained tensile strength of the PP geotextile backing prior to the addition of UV inhibitors is 65% after 100 years. This estimate is based on exhumed samples of the geotextile from the LaSalle-Grant Landfill in Louisiana. According to Watershed (2014), the addition of proprietary UV inhibitors to the PP geotextile backing has led to an improvement in UV resistance by a factor of 14. The final geosynthetic in the ClosureTurf® system is the covered HDPE geomembrane. Koerner (2011) estimates that the half-life of a covered HDPE geomembrane is 446 years at 20C, and 265 years at 25C. Furthermore, the degradation of the unexposed elements of the ClosureTurf® system invoke the half-life criteria. As discussed with regard the exposed HPDE grass blades, actual performance requirements should ideally be used to determine system longevity. However, the existing testing programs need to be allowed to degrade further before projections to lower values are made.

It is worth reiterating that applications of ClosureTurf® in areas of the United States where the UV irradiance and the temperatures are lower will result in longer half-life predictions than discussed above. In some cases (e.g., the Northeastern States), the differences will likely be quite large when compared with Arizona.

Finally, once UV degradation of the most susceptible component of ClosureTurf® (i.e., the exposed HDPE grass blades) does result in a tensile break, replacement of the HDPE grass and PP geotextile backing can be performed.

CLOSING

Geosyntec appreciates the opportunity to assist Watershed in the development of its ClosureTurf® products. Questions and comments may be directed to either of the undersigned at 678-202-9500.

Sincerely,

Will Tanner, P.E.
Project Engineer

Ming Zhu, Ph.D., P.E.
Senior Engineer

Attachments: References
Tables
Figures

Copies to: Bill Gaffigan (Geosyntec)
Mike Ayers (Watershed)

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TABLES

Table 1. Selected Sites where ClosureTurf® has been Installed.

Select ClosureTurf® Installations				
Installation	**Type**	**Acres**	**State**	**Year**
Progressive - Weatherford	Public – MSW	8.5	Texas	2010
Progressive - Timberland	Public - MSW	4	Louisiana	2011
Crazy Horse (Salinas SWA – Monterey)	City – MSW	65	California	2012
Saufley Landfill (Escambia)	Public – C&D	22.5	Florida	2012
Georgia Pacific	Independent	70	Georgia	2013
Berkeley County Landfill	City - MSW	12	South Carolina	2013
Lanchester Landfill (Chester)	City - MSW	7	Pennsylvania	2013
Tangipahoa Parish	City – MSW	22	Louisiana	2013
Sandtown – (Berkeley County)	City – MSW	4	Delaware	2013
Si-County Landfill	EPA – Region 6	5	Texas	2014
Holcim Cement Landfill (Kiln Dust)	Independent	46	New York	2015

Table 2. HDPE Grass Blade Upper Bound Half-Life Calculations (Geosyntec)

Month	UV Lamp On[1] (hrs/day)	Peak Turf Temp[2] (C)	Peak Turf Temp (K)	Peak Turf Temp (1/K)	Reaction Rate[3]	Lab Half-Life[4] (lamp hrs)	Field Equivalent[5] (days)	Field Equivalent[6] (months)	Half Life Loss per Month[7]
January	4.00	27.99	301.14	0.0033	-15.67	6385286	1596322	51494	1.94196E-05
February	4.94	27.96	301.11	0.0033	-15.67	6401982	1296604	46307	2.15949E-05
March	6.13	33.94	307.09	0.0033	-15.11	3632197	593012	19129	5.22755E-05
April	6.94	40.58	313.73	0.0032	-14.50	1983742	285945	9531	0.000104915
May	7.25	51.21	324.36	0.0031	-13.58	792646	109330	3527	0.000283544
June	7.31	61.52	334.67	0.0030	-12.75	344593	47124	1571	0.00063662
July	6.94	66.82	339.97	0.0029	-12.34	228887	32993	1064	0.000939599
August	7.00	64.80	337.95	0.0030	-12.50	267230	38176	1273	0.000785841
September	6.94	59.43	332.58	0.0030	-12.91	406208	58553	1889	0.000529439
October	5.88	47.74	320.89	0.0031	-13.88	1062504	180852	5834	0.000171411
November	4.56	36.38	309.53	0.0032	-14.88	2899472	635501	21183	4.72069E-05
December	3.69	24.68	297.83	0.0034	-15.99	8826208	2393548	77211	1.29515E-05
Lab	20							Yearly Half-life Loss[8]	0.003604818
								Half-life[9] (years)	277.41

Notes:

(1) UV Lamp On (hours per day) is given in Richgels (2015a, 2015b).
(2) Peak Turf Temps for New River, AZ given in Richgels (2015a, 2015b).
(3) Reaction Rate is calculated from the regression curve shown in Figure 4 for the upper bound (logarithmic) case.
(4) Lab half-life in hours is equal to 1/e^(Reaction Rate).
(5) Field equivalent (days) is calculated by dividing the lab half-life in hours by the UV lamp on hours per day.
(6) Field equivalent in days is converted to months using the given days in that particular month.
(7) Half-life loss per month is the inverse of the corresponding field equivalent in months.
(8) The yearly half-life loss is the sum of each individual months half-life loss.
(9) The half-life in years is the inverse of the yearly half-life loss.

Table 3. HDPE Grass Blade Lower Bound Half-Life Calculations (Geosyntec)

Month	UV Lamp On(1) (hours/day)	Months @ 80 C(2)	Months @ 70 C(2)	Months @ 60 C(2)	Peak Turf Temp(3) (C.)	Half-life Months (from Regression)	Half-life Loss per month
January	4.00	692	1507	3078	27.99	6948	0.000143933
February	4.94	620	1352	2761	27.96	6256	0.000159849
March	6.13	452	984	2010	33.94	4059	0.00024637
April	6.94	412	898	1834	40.58	3213	0.000311281
May	7.25	382	832	1698	51.21	2248	0.000444747
June	7.31	391	852	1740	61.52	1580	0.000633027
July	6.94	399	869	1775	66.82	1237	0.00080834
August	7.00	395	861	1759	64.80	1371	0.000729293
September	6.94	412	898	1834	59.43	1826	0.000547629
October	5.88	471	1026	2095	47.74	3070	0.000325779
November	4.56	627	1365	2788	36.38	5321	0.000187929
December	3.69	750	1635	3339	24.68	7945	0.000125871
Lab	20					**Yearly Half-life Loss**	0.00466405
						Half-life (years)	214.41

Notes:

(1) UV Lamp On (hours per day) is given in Richgels (2015a, 2015b).

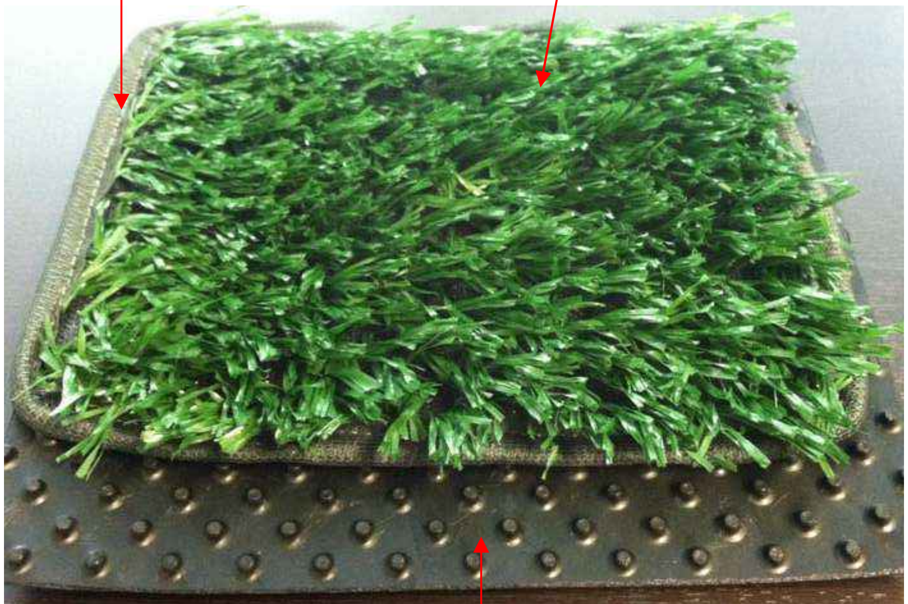
(2) The months required at each temperature is calculated using the regressions from Figure 4 for each temperature, projected down to half-life, then dividing the lamp-hours at half-life by the UV lamp on hours per day for a given month. Once this calculation is done for 80, 70 and 60 C, a linear regression (as shown in Figure 5) is used to obtain the half-life months at the corresponding peak turf temp.

(3) Peak turf temperatures given in Richgels (2015a, 2015b).

FIGURES

PP Backing

HDPE Grass Blades



AGRU Super Gripnet
HDPE Geomembrane

Sand Ballast Infill

Note: The sand ballast infill is not shown in the sample photo on the left, but is shown in a field application photo on the right.

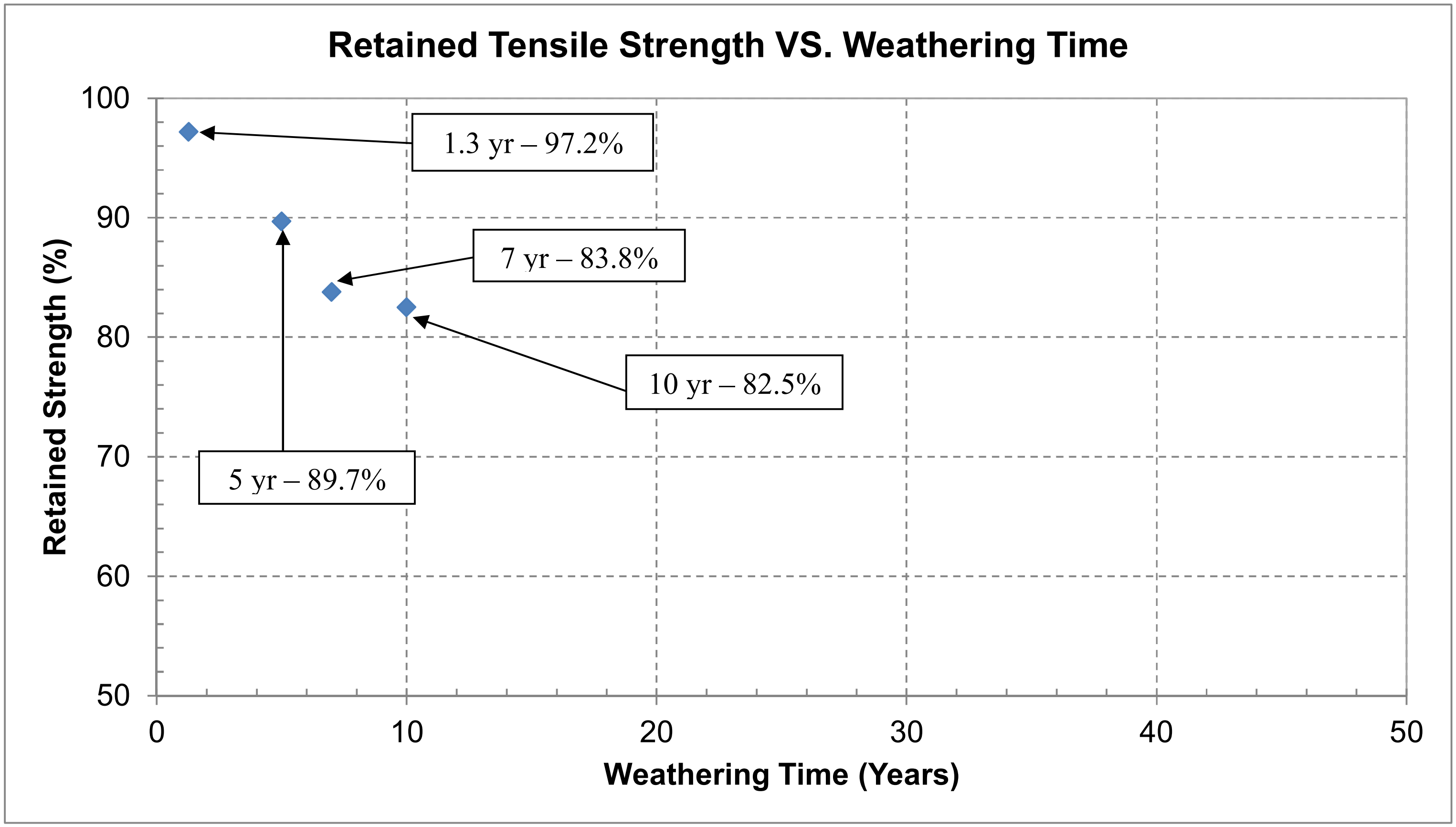
ClosureTurf® Components

Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **1**

Kennesaw, GA | 23-April-2015



Notes:

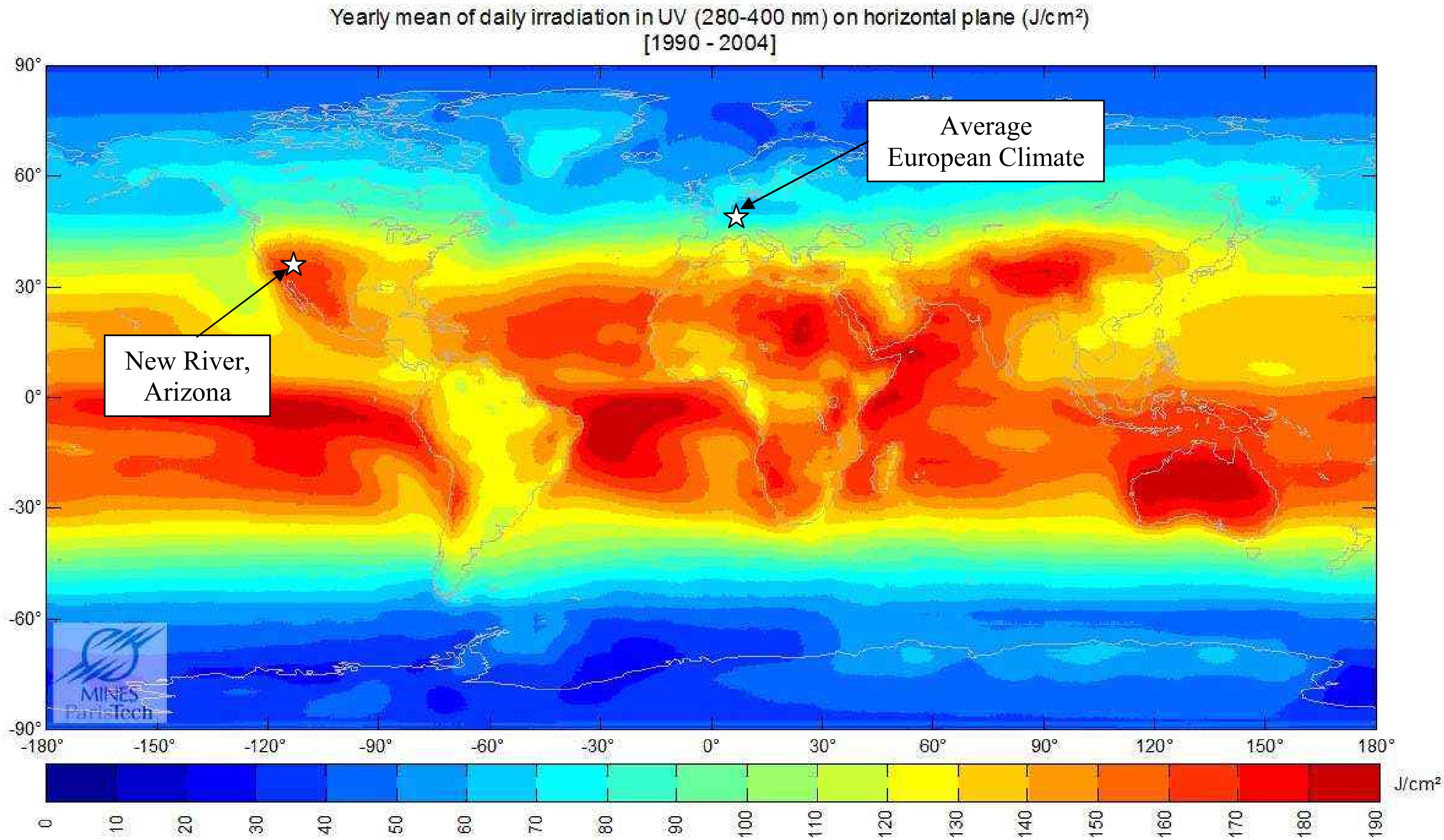
1. The first data point at Weathering Time of 1.3 years is considered to be within the initial stage of UV degradation (i.e., anti-oxidant depletion), rather than polymer oxidation which is represented by the final three data points.
2. Each data point represents the average result of 20 tensile break tests.

Field Test Data (Watershed, 2014)
New River, AZ Atlas Testing Facility
Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **2**

Kennesaw, GA | 25-April-2015



$1\ J/cm^2 = 4.755\ ft\text{-}lbs/in^2$

Yearly Irradiation in the Ultraviolet Range

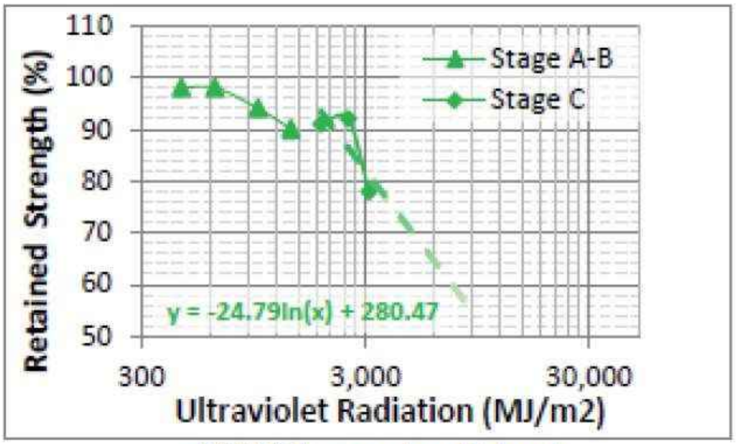
Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

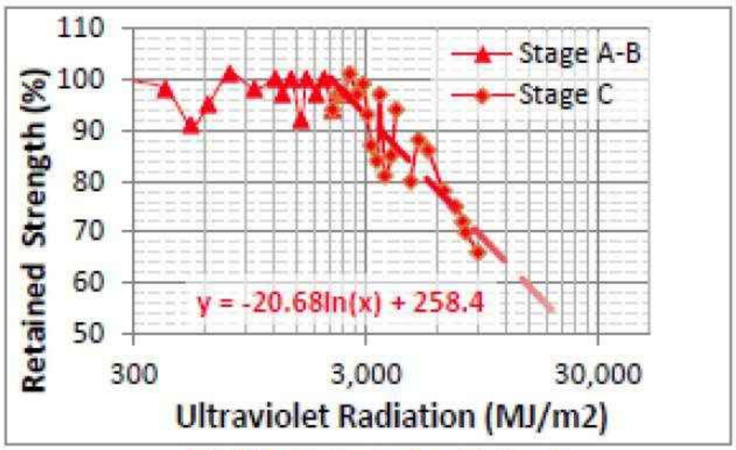
Figure 3

Kennesaw, GA

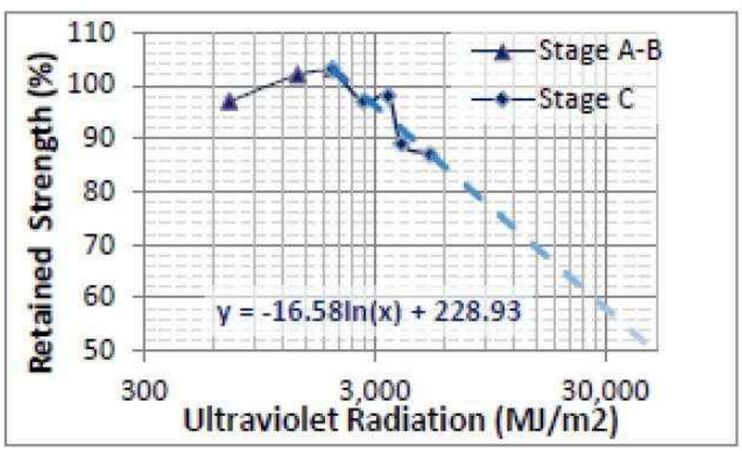
23-April-2015



a) 80°C Temperature Dataset



b) 70°C Temperature Dataset



c) 60°C Temperature Dataset

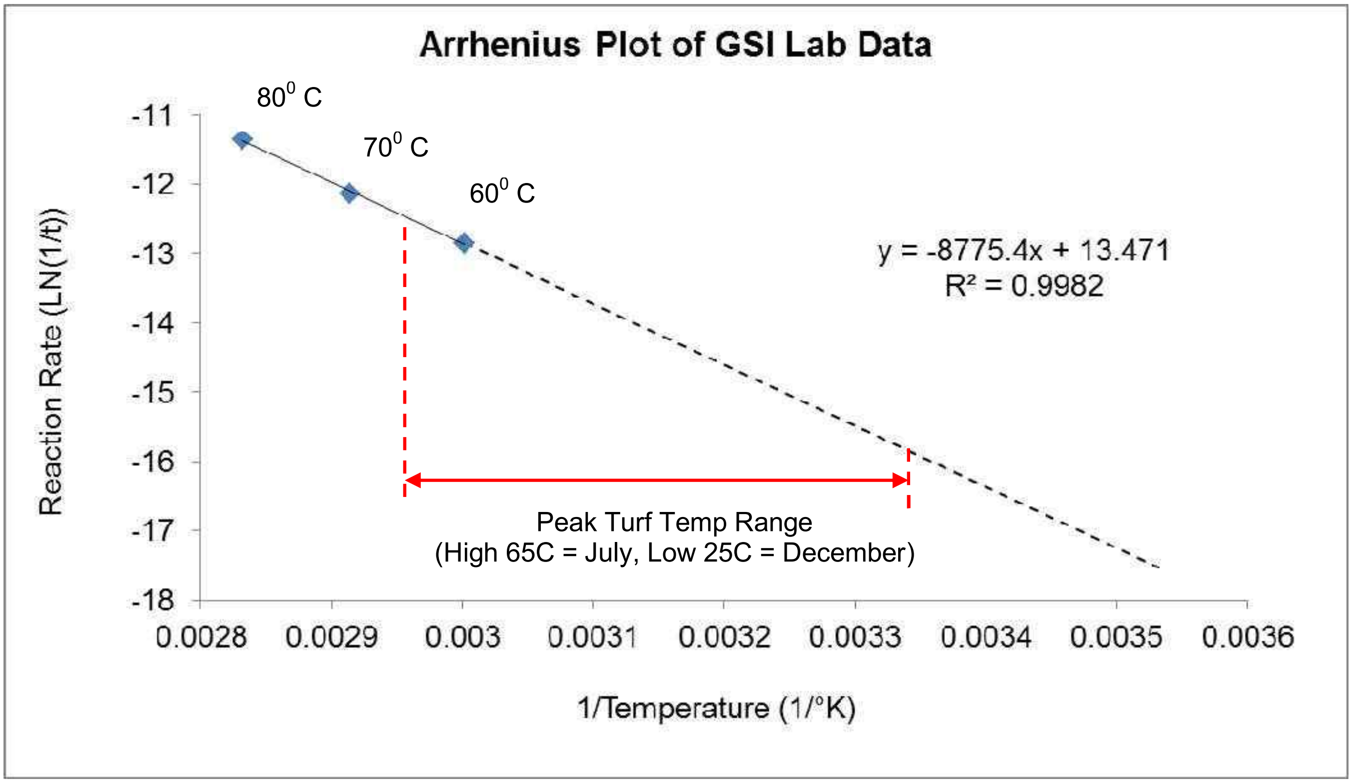
GSI Data Release - Three Stage Oxidation of HDPE for Different Temperatures

Watershed Geosynthetics – ClosureTurf® UV Assessment

Geosyntec consultants

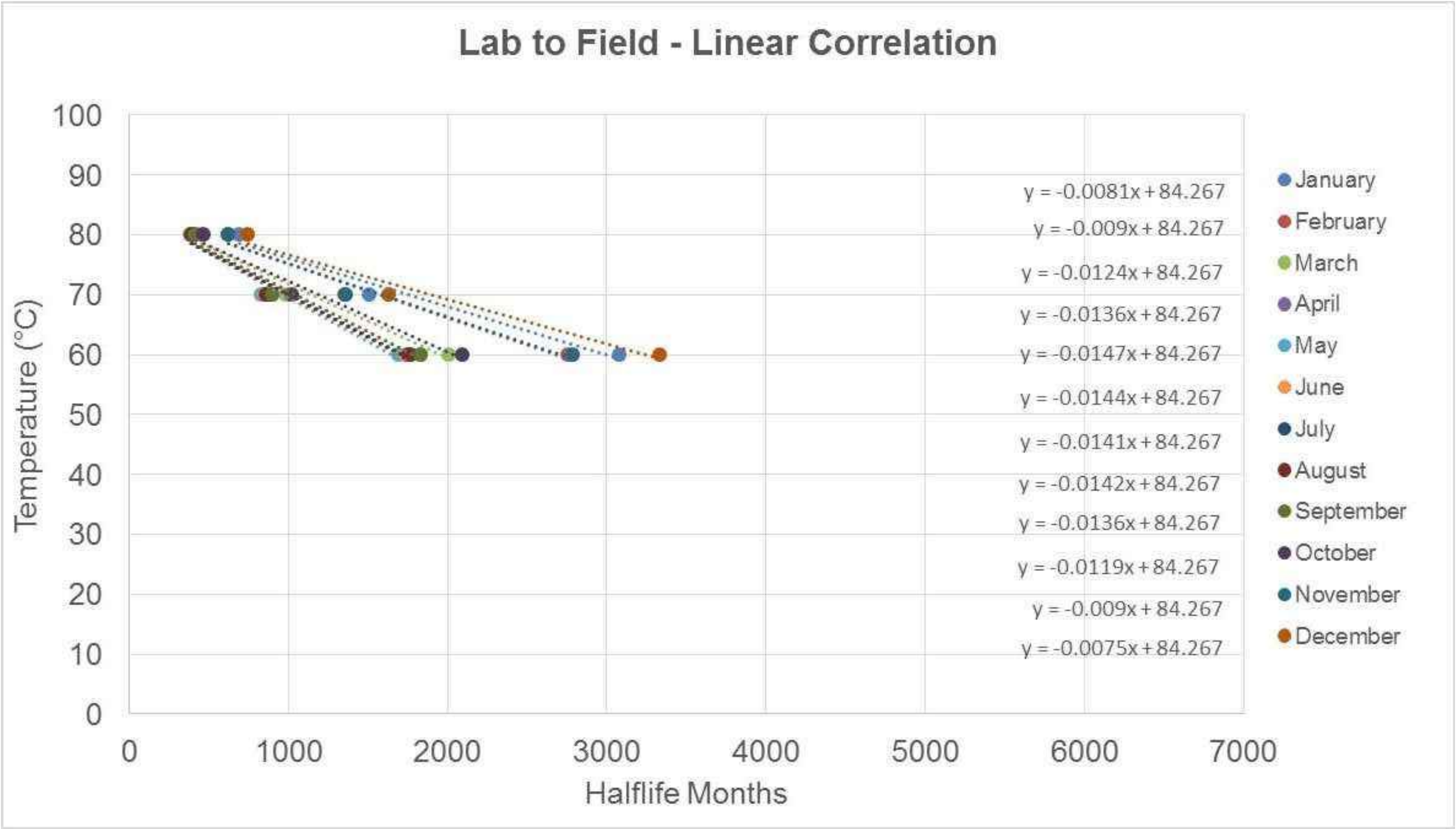
Figure 4

Kennesaw, GA | 23-April-2015



Note: Richgels (2015b) mentions that the use of peak turf temperature is conservative since it only occurs for approximately one hour per day.

Arrhenius Plot of Lab Data Watershed Geosynthetics – ClosureTurf® UV Assessment		
Geosyntec consultants		Figure 5
Kennesaw, GA	23-April-2015	



Note: Each month was projected down to the peak turf temperature given in Table 3 to get the half-life months. The inverse of half-life months is half-life loss per month. The sum of all the half-life losses for each month in a year is the yearly half-life loss, the inverse of which is the half-life.

Linear Extrapolations for Half-life Months

Watershed Geosythetics – ClosureTurf® UV Assessment

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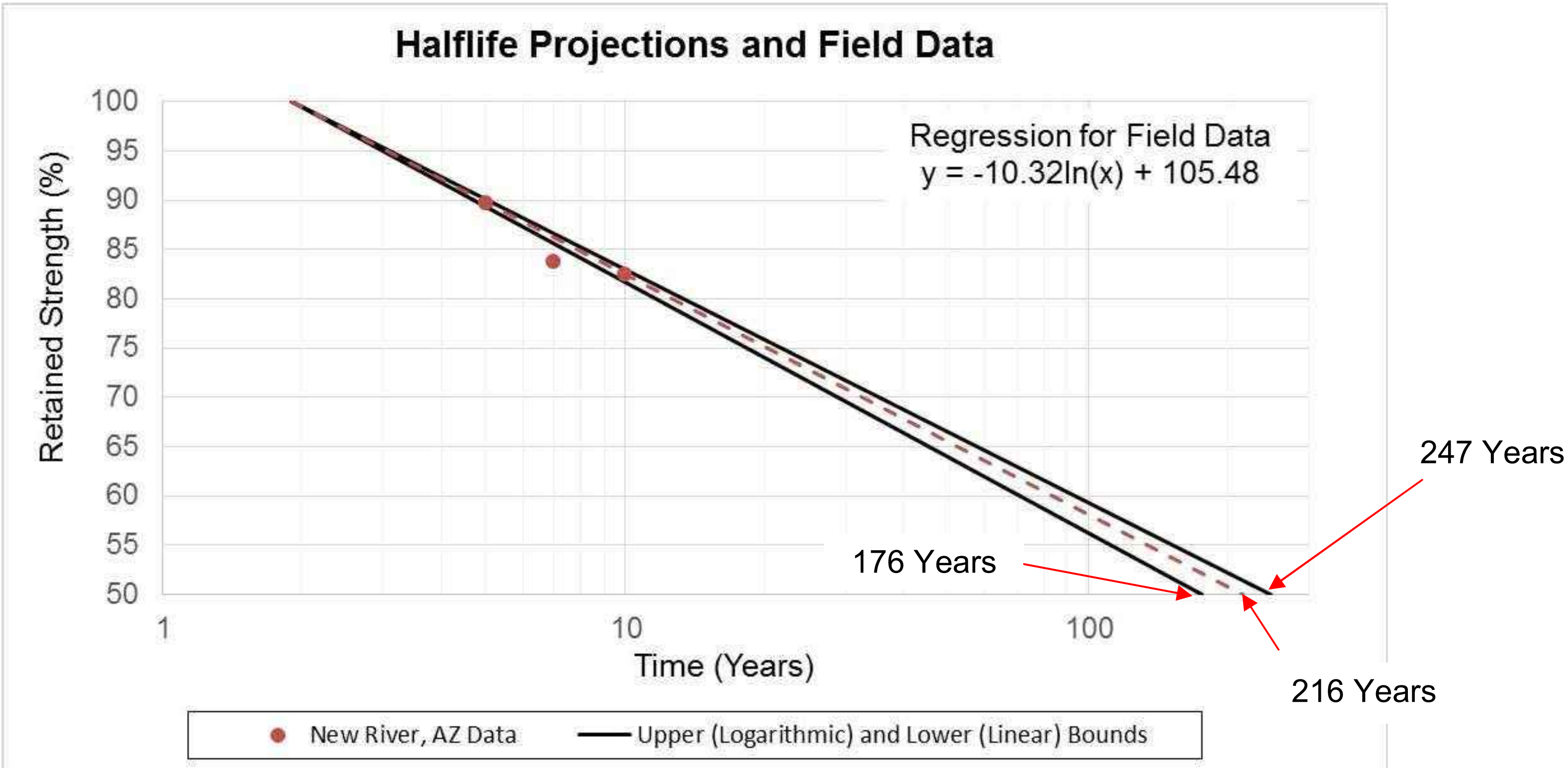
Figure 6

Kennesaw, GA | 23-April-2015



Note: Geosyntec calculated an upper bound half-life of 277 years and a lower bound half-life of 214 years using the same data and method. Difference between Geosyntec and Richgels calculations are attributed to rounding.

Halflife Projections (Richgels, 2015a, 2015b)
Upper and Lower Bound Estimates
Watershed Geosythetics – ClosureTurf® UV Assessment

Geosyntec consultants

Figure **7**

Kennesaw, GA | 23-March-2015

Appendix I
Example Calculation for Pull-Out Resistance of ClosureTurf for Thermal Effects

EXAMPLE CALCULATION FOR PULL-OUT RESISTANCE OF CLOSURETURF FOR THERMAL EFFECTS

PURPOSE

The pull-out resistance of a ClosureTurf termination along a 3H:1V sideslope is evaluated for a 3-foot deep and 2-foot wide anchor trench. The factor of safety against pull-out is estimated by calculating the tensile force induced by thermal contraction of the geomembrane component of ClosureTurf (i.e., 50-mil Super GripNet or MicroDrain) and the resisting forces along the proposed anchor trench.

METHOD

The factor of safety against pull-out of the ClosureTurf geomembrane component of the anchor trench was evaluated based on a force equilibrium analysis as the ratio of the sum of the resisting forces, $F_{resisting}$, to the sum of the driving forces, $F_{driving}$, as follows:

$$FS_{pull\ out} = \frac{\sum F_{resisting}}{\sum F_{driving}} \tag{1}$$

<u>Driving Forces</u>

The driving force consists of the tensile force caused by thermal contraction of the geomembrane component after installation, calculated as follows:

$$T_t = J * \alpha * \Delta T \tag{2}$$

where:

T_t	=	tensile force due to thermal contraction of geomembrane component [pounds per foot (lb/ft)];
J	=	elastic modulus of HDPE geomembrane component (lb/ft);
α	=	coefficient of thermal expansion for HDPE geomembrane component [inverse degrees Fahrenheit (1/°F)]; and
ΔT	=	temperature change of geomembrane component after installation (°F).

The elastic modulus (J) for the geomembrane component (i.e., Super GripNet or MicroDrain) is not provided in the manufacturer product data sheets; therefore, the elastic modulus was estimated from the tensile yield strength (σ_y) and corresponding yield strain (ε) reported in the product data sheets as follows:

$$J = \frac{\sigma_y}{\varepsilon} \tag{3}$$

where:

J = elastic modulus of geomembrane component (lb/ft);

σ_y = tensile strength at yield for 50-mil HDPE Super GripNet and MicroDrain (i.e., 110 lb/in. = 1,320 lb/ft); and

ε = tensile strain at yield for 50-mil HDPE Super GripNet and MicroDrain (i.e., 13%).

The elastic modulus for the geomembrane component was calculated to be approximately 10,000 lb/ft using Equation 3.

The coefficient of thermal expansion (α) for the geomembrane component was estimated as 6.7×10^{-5} / °F based on typical values for HDPE geomembranes. Tensile force due to thermal contraction of the geomembrane component (T_t) was calculated for a temperature change (ΔT) conservatively selected as 100°F. The tensile force calculation is presented below.

Resisting Forces

For the ClosureTurf termination, the analysis of resisting forces was performed based on a frictionless pulley system (Qian et al. 2002), which allows the geomembrane component to be considered as a continuous member along its entire length. The resisting forces against pull-out were calculated as the frictional forces between both sides of ClosureTurf and the adjacent materials along the anchor trench, as shown in Figure I-1.

The frictional forces that act along flat planes of ClosureTurf were calculated as the product of the normal force acting on the plane and the tangent of the interface friction angle between the ClosureTurf component and the adjacent material. For forces F_1 and F_2, the normal force was taken as the weight of the overlying soil. For forces F_3 and F_4, the normal force was estimated as the at-rest lateral earth pressure at mid-depth within the anchor trench.

The frictional forces F_1 through F_4 were calculated according to Equations 4 through 7, respectively, below and act in the direction shown in Figure I-1.

$$F_1 = \gamma_{at} * d_{at} * w_{at} * \tan(\delta_U) \quad (4)$$

$$F_2 = \gamma_{at} * d_{at} * w_{at} * \tan(\delta_L) \quad (5)$$

$$F_3 = 0.5 * \gamma_{at} * d_{at}^2 * K_0 * \tan(\delta_U) \quad (6)$$

$$F_4 = 0.5 * \gamma_{at} * d_{at}^2 * K_0 * \tan(\delta_L) \quad (7)$$

where:

γ_{at} = unit weight of anchor trench backfill material [pounds per cubic foot (pcf)];

d_{at} = depth of anchor trench [feet (ft)];

w_{at} = width of anchor trench (ft);

δ_U = interface friction angle between turf and overlying anchor trench backfill material (degrees);

δ_L = interface friction angle between geomembrane component and underlying material (degrees);

K_0 = coefficient of at-rest earth pressure [i.e., 1-sin(ϕ)]; and

ϕ = friction angle of anchor trench backfill material (degrees).

The interface friction angle between the geomembrane component and the underlying material (δ_L) was taken as the internal friction angle of ClosureTurf provided in the manufacturer product data sheets (i.e., 35 degrees). The interface friction angle between the turf and the overlying backfill material (δ_U) is expected to be lower than δ_L, because the grass blades provide a lower frictional resistance on the upper side of ClosureTurf. For this calculation, δ_U was estimated as two thirds of δ_L (i.e., 23.3 degrees).

CALCULATIONS

The tensile force due to thermal contraction of the geomembrane component was calculated using Equation 2:

$$T_t = 10{,}000 \times 6.7\text{x}10^{-5} \times 100 = 67 \text{ lb/ft} \tag{2}$$

The resisting frictional forces acting along the anchor trench were calculated using Equations 4 through 7 for a 3-ft deep and 2-ft wide anchor trench (i.e., d_{at} = 3 ft, w_{at} = 2 ft), as shown below. Typical values of unit weight of backfill (γ_{at}) of 125 pcf and friction angle of 32 degrees were used for this calculation.

$$K_0 = 1 - \sin(\phi) = 0.47$$

$$F_1 = 125 \times 3 \times 2 \times \tan(23.3) = 323 \text{ lb/ft} \tag{4}$$

$$F_2 = 125 \times 3 \times 2 \times \tan(35) = 525 \text{ lb/ft} \tag{5}$$

$$F_3 = 0.5 \times 125 \times (3)^2 \times 0.47 \times \tan(23.3) = 114 \text{ lb/ft} \tag{6}$$

$$F_4 = 0.5 \times 125 \times (3)^2 \times 0.47 \times \tan(35) = 185 \text{ lb/ft} \tag{7}$$

The sum of resisting forces acting along the anchor trench was calculated, as follows:

$$\sum F_{resisting} = 323 + 525 + 114 + 185 = 1147 \text{ lb/ft}$$

The sum of resisting forces was compared to the tensile yield strength of the geomembrane component:

$$1147 < 1320 \quad \text{O.K.}$$

The factor of safety against pull-out was calculated using Equation 1, as follows:

$$FS_{pull\ out} = \frac{1147}{67} = 17.1 \tag{1}$$

SUMMARY AND CONCLUSIONS

The factor of safety against pull-out of a ClosureTurf termination was calculated for a 3-ft deep and 2-ft wide anchor trench. The factor of safety against pull-out is calculated as 17.1, and therefore, the ClosureTurf termination is not expected to pull out of the anchor trench due to forces induced by thermal contraction.

REFERENCES

Qian, X., R.M. Koerner, and D.H. Gray. 2002. *Geotechnical Aspects of Landfill Design and Construction*. Prentice-Hall Inc.

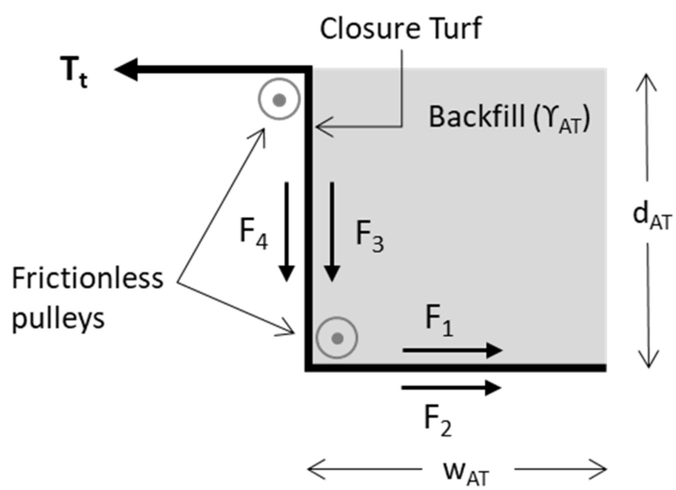


Figure I-1. ClosureTurf Termination within Anchor Trench

Appendix J
ClosureTurf Deep Freeze Test Results

Can you drive on WatershedGeo's ClosureTurf when it is frozen?

George R. Koerner Ph.D., P.E. & CQA
Geosynthetic Institute (GSI) 475 Kedron Ave. Folsom, PA 19033 U.S.A.

Date: September 25, 2018

Introduction

Any engineered barrier should be challenged as to its performance when placed in extreme climates. It is for this reason that we were asked to investigate the performance of WatershedGeo's ClosureTurf when exposed and stressed under extremely cold conditions. This material has been placed in a location where emergency vehicles will need to traffic the material in the depth of winter. Several owners are asking, "will this material hold up under traffic, in such conditions?" This concern is applicable to many locations in the continental United States and has greater significance in Canada and Alaska.

The effects of driving on WatershedGeo's ClosureTurf when it was frozen was studied at the Geosynthetic Institute (GSI) in September of 2018. Samples in the form of 300 mm (12 in.) by 300 mm (12 in.) squares were exposed repeatedly to temperature cycles between -60°C to +20°C. After five thermal cycles, the specimens experienced vehicle traffic and then were observed for damage in the cold condition. After visual inspection, the samples were tested for tensile properties and compared to baseline results. Please note that this mechanical testing was conducted at standard laboratory temperature after the materials reached temperature equilibrium.

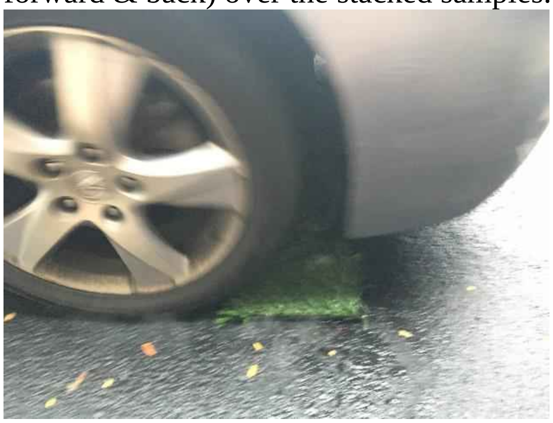
It should be clearly stated that this is not a freeze-thaw study. That issue has been investigated by several researchers which include, but are not limited to, the U.S. Bureau of Reclamation, EPA, Comer et. al. (1996) Hsuan et. al. (1994), LaFleur, et. al., (1984) and Rollin et. al., (1984). All these studies show that the geomembrane component of the closure system and their seams performed extremely well even after hundreds of freeze-thaw cycles. The work by Zimmie and LaPlante (1990) shows that compacted clay liners (CCL) do not fair well when exposed to the same extreme conditions.

Summary of Procedure

1. A sandwich of turf and geomembrane coupons are exposed to five (5) repetitive cycles of freezing via immersion in a dry ice bath at (-60 Degree Celsius) and then thawing at room temperature. Each exposure lasts for one-hour of freezing followed by an hour of thawing. The process is shown in the figures below.



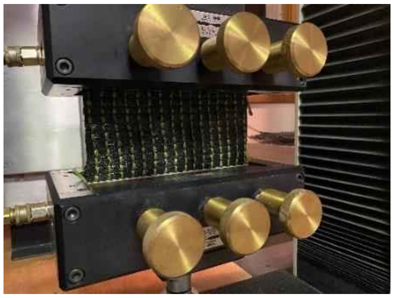
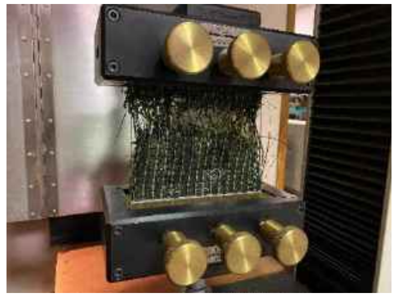
2. After the fifth quench, the samples were trafficked by a 1 ton, 26 psi tire pressure, 8” wide wheel rubber tire vehicle. The vehicle made two passes as shown in the figures below (i.e., forward & back) over the stacked samples.




3. After the exposure described above, the samples were observed for damage. As can be seen in the figures below, neither the turf nor the geomembrane was damaged. The only observed difference between the before and after specimens was that the spikes on the underside of the geomembrane were bent over from trafficking.



4. The expose and unexposed samples were also tested for retained tensile properties. As can be seen in the figures below the turf was tested via ASTM D4595 “Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method” and the geomembrane specimens were tested via ASTM D4885 “ Standard Test Method for Determining Performance Strength of Geomembranes by the Wide Strip Tensile Method.”

Three specimens from the centrally located areas of the exposed and unexposed turf and geomembrane coupons were used to determine the tensile properties and calculate the average value for comparison purposes. Pictures of the turf tested before and after failure are shown above. Photographs of the geomembrane testing during different stages of elongation are shown below.

Results

Average exposed coupon results were compared to the unexposed results. As can be seen in the tabular results below, there were no statistical differences between the before and after exposure wide width tensile test results for either the turf or the geomembrane. This holds true for the strength and elongation characteristics of both materials.

Turf Before Exposure

Spec. Number	Break Load (lbs)	Break Strength (ppi)	Break deflection (in)	Break Elongation (%)
1-MD	2025	**253**	1.14	**29**
2-MD	2311	**289**	1.23	**31**
3-MD	2193	**274**	1.19	**30**
Ave.		**272**		**30**
Std.		18.0		1
Cv		6.6		4

Turf After Exposure

Spec. Number	Break Load (lbs)	Break Strength (ppi)	Break deflection (in)	Break Elongation (%)
1-MD	2112	**264**	1.25	**31**
2-MD	2240	**280**	1.29	**32**
3-MD	2138	**267**	1.16	**29**
Ave.		**270**		**31**
Std.		8.5		2
Cv		3.1		5

Geomembrane before exposure

Spec. Number	Yield Load (lbs)	Yield Strength (ppi)	Yield deflection (in)	Yield Elongation (%)	Break Load (lbs)	Break Strength (ppi)	Break deflection (in)	Break Elongation (%)
1-MD	887	**111**	0.26	**7**	1255	**157**	28.1	**703**
2-MD	894	**112**	0.28	**7**	1311	**164**	29.9	**748**
3-MD	899	**112**	0.3	**8**	1274	**159**	29	**725**
Ave.		**112**		**7**		**160**		**725**
Std.		0.8		1		3.6		23
Cv		0.7		7		2.2		3

Geomembrane after exposure

Spec. Number	Yield Load (lbs)	Yield Strength (ppi)	Yield deflection (in)	Yield Elongation (%)	Break Load (lbs)	Break Strength (ppi)	Break deflection (in)	Break Elongation (%)
1-MD	879	**110**	0.32	**8**	1341	**168**	30.2	**755**
2-MD	901	**113**	0.31	**8**	1229	**154**	29.5	**738**
3-MD	882	**110**	0.34	**9**	1315	**164**	30	**750**
Ave.		**111**		**8**		**162**		**748**
Std.		1.5		0		7.3		9
Cv		1.3		5		4.5		1

Conclusions

Like all performance simulation testing, this humble experiment is not completely representative of the entire field conditions. This procedure is only intended to induce property changes associated with the end use conditions due to extreme cold and vehicular traffic. It is not a survivability nor a long-term durability study. It also does not proport to model field conditions such as differential settlement or the case of yielding subgrade under closure systems when trafficked. In addition, note that rather small unrestrained pieces of the materials were exposed to traffic on rigid asphaltic pavement. The evaluation is limited; however, it is still considered relevant based on the actual conditions tested.

With all the above written, we again ask the question; “Can you drive on WatershedGeo’s ClosureTurf when it is frozen?” We believe the answer is **yes**, cautiously in a pinch with light ground pressure, rubber-tired equipment.

References

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Zimmie, T.F., and La Plante, C. (1990)"The Effects of Freeze-thaw Cycles on the Permeability of a Fine-Grained Soil," Proc., 22nd Mid-Atlantic Ind. Waste Conf., Drexel Univ., Philadelphia.

Appendix K
ClosureTurf Fire Resistance Test Report

RICHGELS ENVIRONMENTAL SERVICES

June 15, 2020

Jose Urrutia
Vice President of Engineering
Watershed Geosynthetics.
11400 Atlantis Place
Suite 200
Alpharetta, GA 30022

RE: CLOSURETURF FIRE TEST CT AND CT-HD

Dear Jose:

Richgels Environmental Services (RES) had initially investigated the fire resistance of ClosureTurf CT in June 2015. RES' concern at the time was the State of California had declared wildfire as a "reasonable foreseeable" risk for solid waste landfill surfaces after wildfire events at landfills resulting in destruction of landfill gas collection systems and other supporting infrastructure. The most recent occurrence at Butte County's Neal Road Landfill in 2018 during the Camp Fire (destroyed the town of Paradise, CA). The American Society for Testing and Materials (ASTM) test Method E108 *Standard Test Methods for Fire Tests of Roof Coverings* is designed to test asphalt composite roofs for fire resistance. Section 10 of this test method is similar to field conditions such as large brush or trees adjacent to landfill surfaces from which burning embers could fall thus igniting grasses on the landfill surface.

Thus, this method was chosen to assess fire resistance of both the CT and CT-HD versions of ClosureTurf (data sheets attached). This investigation performed the Burning Brand Test (Section 10 of ASTM E108**)** conducted with 3 different brand sizes, Class A, B and C. The Class A brand is 12 inches square in length, width and nominally 3 inches in depth. The Class B brand is 6 inches square and nominally 3 inches in depth. The Class C brand is a 2-inch cube. The CT test was performed in California in June 2015. After development of the denser CT-HD version, its fire test was conducted in August 2018 under my supervision at Watershed Geo's Research and Development Laboratory in Louisiana.

Test Preparation

Brands for both the Class A and Class B tests were constructed using nominal 1x1 (¾ " x ¾" finished) pine stock and fastened together with 3d finishing nails. Strips were spaced ¼" apart using a ¼" template to provide consistent strip spacing. The Class A brand was built with 36 each 12" long strips. Class B brand was built with 18 each 6" long strips. The Class C brand was made with a 1-1/2" long piece of 2x2 pine stock with perpendicular saw kerfs on opposite sides per ASTM E108 specifications. The completed brands were oven cured overnight. ASTM E108 specifications recommend curing the brands in an oven for 24 hours at an oven temperature between 105°F and 120°F. Home ovens only go as low as 150°F, so the brands were just cured overnight (Figure 1). All brands were judged as nearly "bone dry," which was confirmed by their ignitability (below).

The test site subgrade was stripped of vegetation and bladed smooth with a straight shovel before placing 50-mil, LLDPE Super Gripnet geomembrane samples. ClosureTurf test pads were prepared using dimensions specified in ASTM E108 – 4'-4" by 3'-4." All test pads received 60 pounds of commercially available sand that met ASTM C33 specifications (Figure 2). Sand was poured evenly over the pads and raked in place per recommended construction practice. This is an equivalent application of 4.2 psf, less than the ClosureTurf manufacturer's recommended sand ballast application (5 psf).

Assuming a sand unit weight of 120 pcf,, sand applied at a rate of 5 psf would spread to approximately 0.5 inches deep. An application rate of 4.2 psf would be 0.42 inches. The thickness difference of 0.08 inches would expose that much more of HDPE grass tufting hence is considered conservative for the purposes of this examination.

Figure 1

Figure 2

Test Execution

The Class A brand was ignited over charcoal and propane outdoor grills for the CT and CT-HD tests respectively. Each large face was exposed to the ignition source for 30 seconds. Each side face was exposed for 45 seconds each. The final exposure of the brand faces per ASTM E108 procedures were not done as the brands were fully aflame and the pine stock was beginning to be consumed. The total ignition time was four minutes.

After the prescribed ignition time, the fully aflame brands were placed on the turf samples (Figure 3). Turf blades melted to the top of the sand ballast in proximity of the burning brand, yet the turf did not ignite nor self-propagate flame away from the brand in either test. A slight wind developed during testing fanning flames to one side.

Figure 3

ClosureTurf CT

ClosureTurf CT-HD

The Class B brands were also ignited over outdoor grills as described above for the Class A brands. Each face was placed on the grill for 30 seconds. Each side face was exposed for 30 seconds each. As with the Class A brands, the Class B brands were fully aflame after the last side face was placed against the grills. Total ignition time was 3 minutes.

The Class C brands were ignited over the grills as described above. Four of the brand faces were placed on the grills for 30 seconds for a total of 2 minutes ignition time.

The Class A brand finished burning with open flame approximately 30 minutes after placement. No fire propagation away from brand in the CT nor CT-HD tests occurred. The same was true for the Class B and C brand tests.

Post Test Inspections

The Class A and B brands were nearly entirely consumed. (Figure 4) Only a few pieces of brand were left after fire test completion. Grass tufts in both the CT and CT-HD samples were melted up to 6 inches away from the Brand A (Figure 5) edge in the melt zone. Ballast sand was discolored under the brand within burn zone.

The Class B brands were also nearly entirely consumed. Only a few pieces of brand were left after fire test completion. Grass tufts were melted up to 4 inches away from the brand edge as shown in Figure 6. Sand discolored under brand but retained natural color within melt zone.

The melt zone around the Class C brand was up to 4 inches in the longest dimension (Figure 7).

Figure 4

Brand A Closure CT

Brand A ClosureTurf CT-HD

Figure 5

Figure 6

Brand B ClosureTurf CT

Brand B ClosureTurf CT-HD

Figure 7

Brand C ClosureTurf CT

Brand C ClosureTurf CT-HD

Upon peeling back the turf component of the tested samples, it was found the turf had melted on to the SGN and was essentially consumed by the fire within the burn zone of all the Class A and B tests. The SGN drainage studs were intact up to the boundary of the brand and melted down to the geomembrane sheet within the burn zone. The woven geotextile beyond the burn zone – or under the melt zone - was undamaged as shown in Figure 8.

Figure 8

The entire system was pulled back to observe if the fire had burned through the SGN for both tested samples.

The underside of the SGN displayed observable effects from the fire but was not broached. The SGN burn zone boundary for results typical to all Class A and Class B tests is shown in Figure 9. Some of the soil and organic debris beneath the burn zone was dry and adhering to the SGN. Spikes beneath the burn zone were gone, while spikes in areas immediately neighboring the burn zone were intact.

The Class A brand burn zone damage to the SGN was essentially the dimensions of the brand – 12” x 12”.

Figure 9

Figure 10

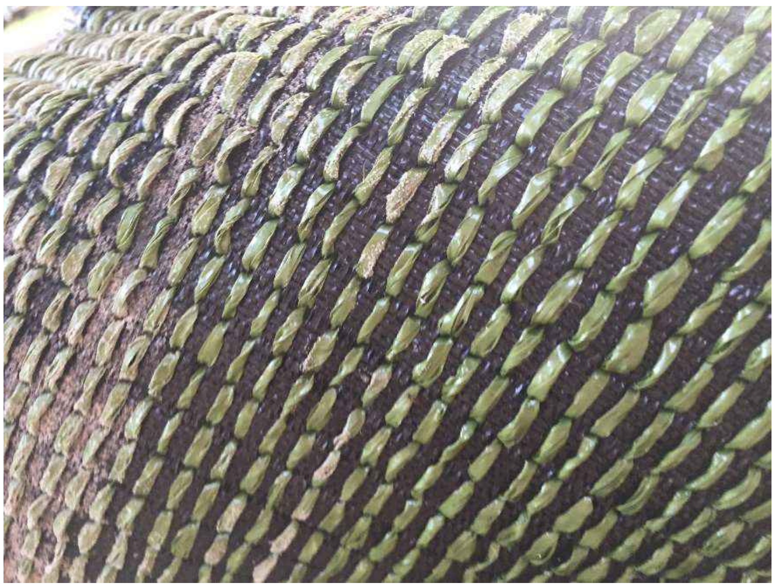
Sand discoloration beneath the burn zone was also observed in the Class B brand test. The underside of the SGN displayed observable melting from the fire but was not broached (Figure 10). Again dry soil and organic debris was found adhering to the SGN underside.

The Class B brand melt zone was slightly larger than the dimensions on the brand – 7-1/2” 7-1/2” for the CT test. For both the Class A and B tests, studs in the immediate vicinity of the burn zone were completely intact. Studs with the burn zone were flattened.

Class C brands were stuck to the underlying grass tufts after the fire had gone out. The CT test brand was not fully consumed by the fire. Note sand discoloration under the brand and minor melting of nearby grass tufts in Figure 7.

For both tests, Class C brands displayed no melting effect on the woven geotextile component in the turf (Figure 11) There were no observable impacts to the SGN either.

Figure 11



Conclusions

1. ClosureTurf exposure to fire is contained to the vicinity of the fire source. It does not spread.
2. None of the ASTM burning brand tests burned through the SGN component of ClosureTurf. This is important when considering active gas control maybe near site perimeter where burning embers may fall.

These results are relevant to concerns in California with respect to wildfire. Wildfire danger is a regulated consideration for closed landfills with surface infrastructure such as landfill gas (LFG) collection wells and piping. California considers wildfire a reasonably foreseeable event for which site owners must provide corrective action cost estimates. Vegetated surfaces provide fuel for fire propagation to other combustible structures such as LFG collection systems. This corrective action requirement could be coming to other states. Use of ClosureTurf as a final cover system should reduce these concerns and related financial burdens for corrective action financial liabilities.

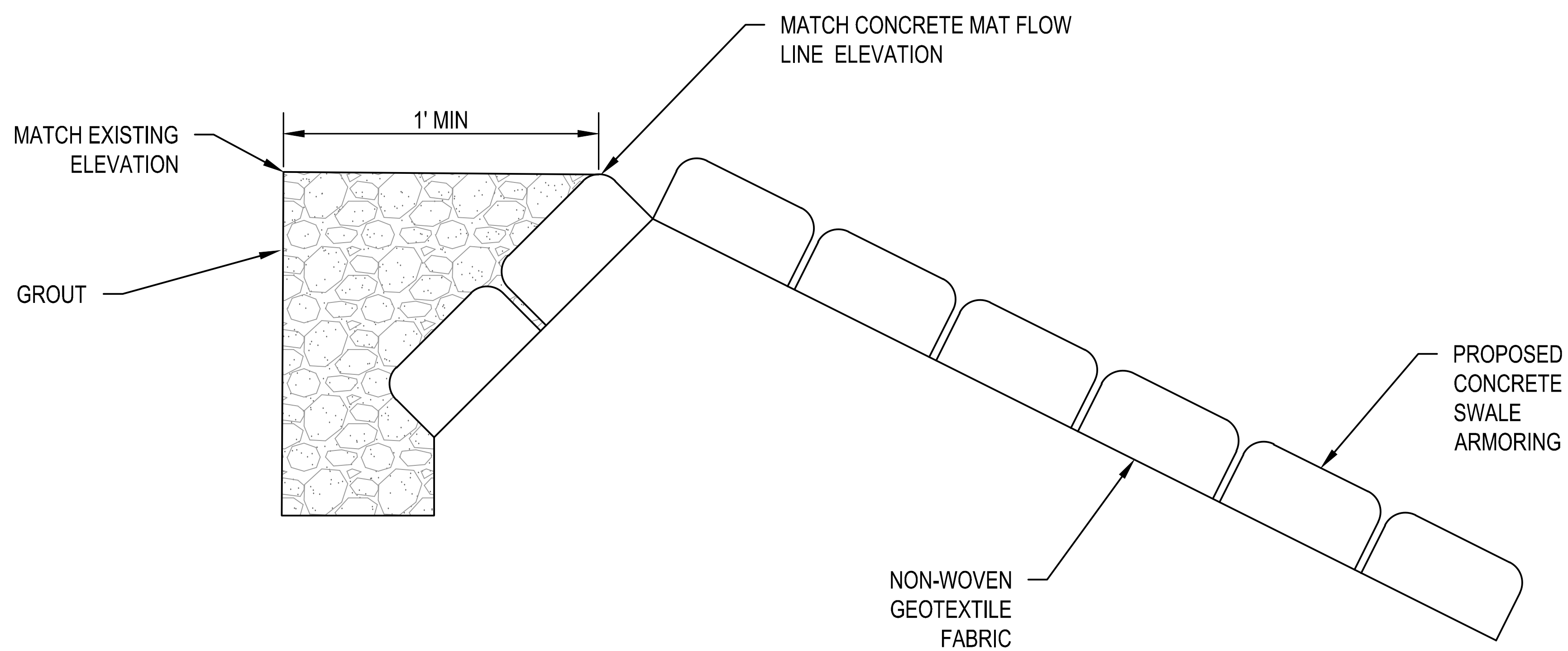
If you have any questions, please call or email the undersigned.

Very Truly Yours

Chris Richgels, PE

Richgels Environmental Service

Attachment C
Example Detail



EXAMPLE CONCRETE MAT DETAIL