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"Rationale and Background for the GRI-GM13 Specification for HDPE Geomembranes"

by

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Rationale and Background for the GRI-GM13 Specification for HDPE Geomembranes*

Abstract

The Geosynthetic Research Institute (GRI) test method GM13 "Test Properties, Testing Frequency and Recommended Warrant for High Density Polyethylene (HDPE) Geomembranes" sets forth a set of minimum properties that must be met, or exceeded, by both smooth and textured high density polyethylene (HDPE) geomembranes upon being manufactured. In some of the properties, a range is specified. In the context of quality systems and management, this specification is targeted toward manufacturing quality control (MQC).

The properties listed in this specification were obtained by testing multiple commercially available products according to the latest standard test methods established by either the American Society of Testing and Materials (ASTM) or the Geosynthetic Research Institute (GRI). The unique aspect of this specification in comparison to previous HDPE specification is the requirement for long-term performance testing of the geomembranes. Three different tests are specifically designated to challenge the antioxidant package which acts in an essential role in assuring the long-term performance of HDPE geomembranes.

This paper describes the rationale of selecting the relevant test methods and the background for establishing the specified values. Also presented is the frequency of performing the tests and the logic (or illogic) of including a recommended warranty.

Introduction

High density polyethylene (HDPE) geomembranes have been used as liquid and gas barriers in geoenvironmental applications for more than 35 years. The only *generic* specification

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available to aid engineers was published in 1983 by the National Sanitation Foundation (NSF) as Standard No. 54. The standard provided a list of tests together with their corresponding minimum values. Although four revisions were carried out in the intervening years, the standard was still lagging behind the state-of-practice of the HDPE geomembrane industry. For example, only smooth HDPE geomembranes were listed, and many of the specified test methods did not reflect current practice. Some of the tests were even generally considered irrelevant or inappropriate for the currently manufactured HDPE material. Most importantly, the long-term performance of the material was never properly addressed. For a number of interrelated issues, NSF decided to withdraw from the geosynthetic industry by terminating the publication of Standard No. 54 as of the end of 1997.

Considering the above situation, a completely new HDPE specification was needed. In 1994, at the prompting of the U.S. Environmental Protection Agency, a technical task group was formed within GRI consisting of five HDPE resin suppliers and seven geomembrane manufacturers. The group decided that the purpose of the specification was to be directed at manufacturing quality control (MQC) of HDPE geomembranes. This infers that if an owner or specifier has unique or extenuating circumstances for a particular project, modifications in the form of a project specification can be made, however, such changes should be communicated accordingly to the manufacturer.

The new specification covers MQC considerations for both smooth and textured HDPE geomembranes. However, it does not include properties that are related to installation, such as field construction and seaming procedures, seam testing and strength, seam sampling frequency, etc. The specification also presents a recommended warranty, which is focused on the geomembrane material itself, i.e., not the installation. In addition to basic physical and mechanical properties of geomembranes, long-term performance properties are also required. On the other hand, tests that were considered as being irrelevant to MQC or outdated are not included. The majority of the required properties are evaluated by test methods established by the ASTM D35 Geosynthetics Committee. In cases, where no ASTM standards are available, GRI test methods were developed and are included accordingly.

This paper explains the GRI-GM13 Specification, its rationale and background, and its uniqueness with respect to the earlier specification, i.e., to NSF Standard No.54. This is particularly the case for tests that are oriented toward evaluation of the long-term performance of the geomembranes. Also, test data that support the specified value are presented. The minimum physical, mechanical, and chemical properties are listed. In a few cases, a range is specified. Finally, a discussion regarding a recommended warranty is included.

Overview of the Specification

The specification covers HDPE geomembranes with a formulated sheet density of 0.941 g/ml, or greater, in the thickness range of 0.75 mm to 3.0 mm. Tables 1 and 2 are the actual specification tables which include test methods, limiting values, and testing frequencies. Table 1 is for smooth HDPE geomembranes, and Table 2 is for single and double sided textured HDPE geomembranes. The respective values are presented according to seven different sheet thicknesses. The minimum testing frequencies are also defined for each required property. Most of the testing frequencies are based on weight in units of kilograms. The reason for using kilograms instead of number of rolls is to achieve a consistent value between different sheet thicknesses and sheet widths. There are nine notes in each of the tables to further clarify the test conditions and specific requirements. The entire specification, in its latest revision, is available free on the institute's website at http://www.geosynthetic-institute.org/specs.htm.

Discussion of Test Methods Included in the Specification

Many test methods and procedures have been considered for incorporation in this specification. The rationale for including/excluding specific test methods/procedures is presented below.

Excluded Tests. There are as many as sixteen tests that are occasionally included in HDPE specifications, which are omitted from this standard because they are either irrelevant or not appropriate to be used in routine MQC testing. In this section, these test are presented together with the reason for excluding them. Following are the tests that are considered to be irrelevant to the MQC of HDPE geomembranes:

- Volatile Loss - This test is performed according to ASTM D 1203 by measuring the volatile loss at 70°C after 24 hours. However, there are no components in HDPE geomembranes that will evaporate below 100°C. Thus, this test is irrelevant. In a thermogravimetric analysis (TGA), the onset of the weight loss at 470°C corresponds to the decomposition of the polymer chains. Prior to that temperature, no weight loss can be measured, as shown in Halse, et al., (1991).
- Water Absorption - The test is performed according to ASTM D 471 to evaluate rubber characteristics. Due to the high crystallinity and non-polar characteristics of polyethylene, HDPE geomembranes have a hydrophobic characteristic, which has extremely low water absorption. This test is also irrelevant.
- Water Vapor Transmission - This test is performed according to ASTM E 96. The test is not designed to measure sheet materials with thickness like geomembranes, particularly HDPE materials. Both the thickness and relatively high rigidity of the material leads to leakage around the seal of the testing container, leading to large

errors in test results. In addition, the true mechanism for studying the liquid transmission through HDPE geomembrane should be diffusion, as described by Rowe et al. (1996).

- Dimensional Stability - The purpose of this test is to assess the presence of residual stress in the geomembrane. The test is conducted according to ASTM D 1204. The dimensional changes of the specimen before and after incubation in a forced air oven at 100 °C for one hour are measured. The changes are always found to be less than 1 % regardless the type of manufacturing process. This indicates that the magnitude of residual stresses is relatively small in currently produced HDPE geomembranes. Such stress probably does not challenge either the short term or long term performance of the geomembrane. Thus, the test was felt not to be relevant.
- Coefficient of Linear Expansion - The test is performed according to ASTM D 696 to determine the coefficient of linear expansion between -30 °C and +30 °C. The value is an intrinsic property of the HDPE material; e.g., it increases as density of the material decreases and vice versa. Furthermore, for polymeric materials, such a value varies with temperature. It is important for designers to specify the temperature range and then perform the test accordingly. Under such circumstances, the test is no longer an index test, but a performance test. Most importantly, this value has no relevance to the quality of the geomembrane.
- Resistance to Soil Burial - This test is conducted according to ASTM D 3083 to evaluate "Flexible Polyvinyl Chloride (PVC) Plastic Sheeting for Pond, Canal and Reservoir Lining". The purpose of the test is to evaluate the biodegradation of the geomembrane, specifically of the plasticizer component of PVC geomembranes.

There is no plasticizer in HDPE geomembranes. Furthermore, HDPE geomembranes are made from high molecular weight polymers. The test has no relevance to the performance of HDPE geomembranes and should not be included.

- Hydrostatic Resistance - This test is conducted according to ASTM D 751 for "Coated Fabrics". The test is designed to evaluate the burst strength of scrim reinforced geomembranes. The test is not applicable to evaluate HDPE geomembranes due to the lack of a scrim as well as its high elongation.
- Tensile Impact - The test is conducted according to ASTM D 1822, for determining "The Tensile Impact Energy to Break Plastics and Electrical Insulating Materials". This is another index test meant to evaluate the tensile strength of the geomembrane. The unique difference between this test and other mechanical index tests is the high speed of the impacting pendulum. However, geomembranes are seldom subjected to such impacts, hence the test is irrelevant for a MQC specification.
- Brittleness Temperature - This property is measured according to ASTM D 746 to determine "The Brittleness Temperature of Plastics and Elastomers by Impact". HDPE geomembranes are not very sensitive to cold brittle fracture due to their high crystallinity. The brittleness temperature is below - 100°C. Thus, the test does not have relevance to the general usage of HDPE geomembranes. However, if extremely low temperature is to be encountered at a specific site, a complete evaluation on the mechanical behavior of the geomembrane should be performed at the lowest temperature that the site will encounter, not only the brittleness temperature. This is beyond the scope of a MQC specification.

- Various Toxicity Tests - This suite of tests is possibly applicable if the HDPE geomembrane is used in contact with drinking water. If such application is encountered, the geomembrane could be evaluated accordingly. See NSF Standard No.61 in this regard.

Following are tests that were considered to be *not appropriate* as routine MQC tests:

- Ozone Resistance - This property is required in very select applications, e.g., possibly in high elevation applications. Thus, it should not be included in a generic MQC specification. However, if the property is required, the test should be included as an additional requirement.
- Modulus of Elasticity - This value can be readily obtained from the tensile test according to ASTM D 638. Type IV. However, due to the initial nonlinear behavior of HDPE geomembranes, the measurement of elastic modulus is always subjective. A large variation can result even when using an extensiometer; hence, it was considered to be not appropriate.
- Wide Width Tensile - This test is performed according to ASTM D 4885, using a strain rate of 1 mm/min. For HDPE geomembranes, break stress and break strain are generally unable to obtain due to the height limitation of most tensile testing machines. Furthermore, the testing time is very long due to the required slow strain rate and does not adapt to MQC testing. The test, however, should be considered as a performance or design-related test to investigate the behavior of geomembranes under plane strain conditions.
- Multi-axial Tension - This test is performed according to ASTM D 5617, and is considered to be a performance test to model out-of-plane deformation of geomembranes.

Even further, at a pressurization rate of 6.9 kPa/min it is too fast for stress relaxation and negatively biases the material. That said, it could be used but only at a significantly slower pressure rate, Koerner, et al., 2015.

- Field Seam Strengths (Shear and Peel) - As stated in the previous section, this specification is for MQC of the manufactured sheet. It does not include any field installation related requirements.

Revised Tests. There are several tests that are considered relevant in an HDPE specification, but need to *updated and revised* to the current ASTM standards. They are as follows:

- Environmental stress crack resistance (ESCR) - Many past HDPE geomembrane specifications, have ESCR evaluated according to ASTM D 1693, the bent strip test. This test has many disadvantages, such as undefined specimen stress, stress relaxation, large standard deviation, etc. Subsequently, a new stress crack resistance test , the notched constant tensile load (NCTL) test according to ASTM D 5397, was developed and adopted by the industry (Hsuan, et al. 1993). In this specification, the abbreviated version of the NCTL test, the single point-NCTL test (ASTM D 5397-Appendix), is specified to assess the material's ESCR behavior.
- Puncture Resistance - The original test used to assess puncture resistance of HDPE geomembranes has been Federal Testing Material Standard (FTMS 101, Method 2065). The method has been depreciated since federal agencies are encouraging the use of consensus standards. ASTM D 4833 is the replacement test for the evaluation of the puncture resistance of HDPE geomembranes and is used accordingly.

- Carbon Black Dispersion - This property has traditionally been evaluated using ASTM D 1765 for "Carbon Black Used in Rubber Products". However, the type and amount of carbon black used in rubber products are very large compared to that used in geosynthetics. The function of carbon black in rubber is for reinforcement as well as ultraviolet resistance, and the amount of carbon black content can be as high as 30%. Thus, the applicability of this test to the geosynthetic products is not appropriate. Recently, a new carbon black dispersion test was developed to evaluate geosynthetic products. It uses thin microtome sections viewed under a transmission light microscope at 100 magnification, and compares with reference images. This replacement test is ASTM D 5596, which is required in this specification.

New Tests. Several tests are included in this specification because they are essential in the context of current manufacturing processes, or to assess the durability of the material. The following *new tests* have been incorporated in the specification.

- Core thickness of textured sheet - A new test, ASTM D 5994, was adopted to measure the core thickness of textured HDPE geomembranes. The test uses a pair of tapered gage points, as shown in Figure 1, to probe into the valley(s) of the texturing in order to measure the core thickness.

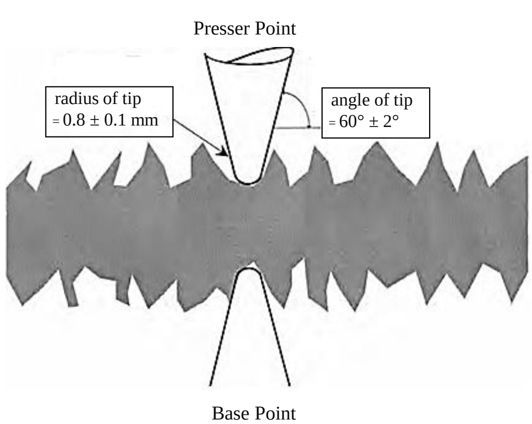

Figure 1 - Core thickness measurement for textured geomembranes.

- Asperity height of textured sheet - For ensuring that there is a minimum roughness on the surface of textured HDPE geomembranes, an asperity height is measured. An index test, ASTM D 7466, was developed to measure the height of textured profile using a depth gauge, as shown in Figure 2.

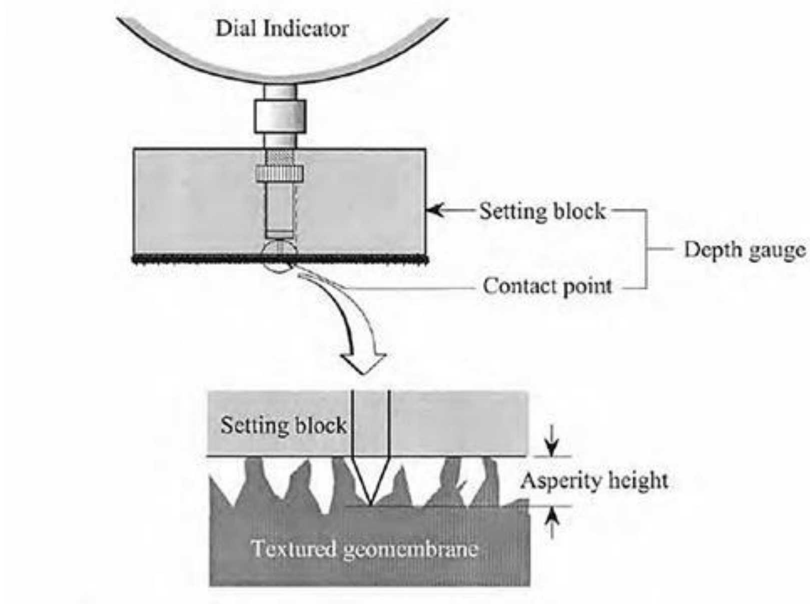

Figure 2 - Asperity height measurement for textured geomembranes.

- Oxidative induction time (OIT) - Both the standard (Std-OIT, ASTM D 3895) and high pressure (HP- OIT, ASTM D 5885) tests are included in the specification. The purpose of including two OIT tests is to provide an option for manufacturers to choose the appropriate test to evaluate their specific antioxidant package. If some of the antioxidant packages have an evaporation temperature lower than 200°C, the Std-OIT test is not the suitable method. For those antioxidant packages, the HP-OIT test is the proper method (Hsuan and Guan, 1997).

- Oven aging -The purpose of oven aging is to challenge the long-term thermal oxidation behavior of the HDPE geomembrane. The incubation procedure is conducted according to ASTM D 5721 in forced air ovens at 85°C for 90 days. Since the initial part of the lifetime of HDPE geomembranes is governed by the antioxidant package, use of oven aging coupled with OIT measurements provides insight into the long-term performance of antioxidant package. This directly reflects on the duration of the geomembrane, Hsuan and Koerner, 1998.
- Ultraviolet (UV) Resistance - For HDPE geomembranes that are exposed to sunlight during their service life, UV resistance is a major property that must be evaluated. The exposure procedure used to assess UV resistance is conducted according to ASTM D 7238 using an UV-fluorescent weatherometer. The exposure time is for 1600 hours, with alternating 20 hour of UV at 75°C followed by 4 hour condensation at 60 °C. Similar to oven aging, the stability of the antioxidant package is assessed using the OIT test. However, only the HP-OIT test should be used.

Specified Material Properties

The properties specified in Tables 1 and 2 can be divided into three categories: physical, mechanical, and endurance. Individual properties will be discussed accordingly in each category. In addition, the frequency for conducting the tests is also prescribed in the tables. Testing frequency for the majority of the properties is based on weight. This is designed to make the required testing consistent for the manufacturer regardless of the thickness, length or width of the geomembrane.

Table 1 – High Density Polyethylene (HPDE) Geomembrane - Smooth

Properties	Test Method	Test Value							Testing Frequency (minimum)
		0.75 mm	1.00 mm	1.25 mm	1.50 mm	2.00 mm	2.50 mm	3.00 mm	
Thickness - mils (min. ave.) • lowest individual of 10 values	D5199	nom. (mil) -10%	nom. (mil) -10%	nom. (mil) -10%	nom. (mil) -10%	nom. (mil) -10%	nom. (mil) -10%	nom. (mil) -10%	per roll
Density (min.)	D 1505/D 792	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	90,000 kg
Tensile Properties *(1)* (min. ave.) • yield strength • break strength • yield elongation • break elongation	D 6693 Type IV	 11 kN/m 20 kN/m 12% 700%	 15 kN/m 27 kN/m 12% 700%	 18 kN/m 33 kN/m 12% 700%	 22 kN/m 40 kN/m 12% 700%	 29 kN/m 53 kN/m 12% 700%	 37 kN/m 67 kN/m 12% 700%	 44 kN/m 80 kN/m 12% 700%	9,000 kg
Tear Resistance (min. ave.)	D 1004	93 N	125 N	156 N	187 N	249 N	311 N	374 N	20,000 kg
Puncture Resistance (min. ave.)	D 4833	240 N	320 N	400 N	480 N	640 N	800 N	960 N	20,000 kg
Stress Crack Resistance *(2)*	D 5397 (App.)	500 hr.	500 hr.	500 hr.	500 hr.	500 hr.	500 hr.	500 hr.	per GRI GM-10
Carbon Black Content - %	D 4218 *(3)*	2.0-3.0%	2.0-3.0%	2.0-3.0%	2.0-3.0%	2.0-3.0%	2.0-3.0%	2.0-3.0%	9,000 kg
Carbon Black Dispersion	D 5596	note *(4)*	note *(4)*	note *(4)*	note *(4)*	note *(4)*	note *(4)*	note *(4)*	20,000 kg
Oxidative Induction Time (OIT) (min. ave.) *(5)* (a) Standard OIT — or — (b) High Pressure OIT	 D 3895 D 5885	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	90,000 kg
Oven Aging at 85°C *(5), (6)* (a) Standard OIT (min. ave.) - % retained after 90 days — or — (b) High Pressure OIT (min. ave.) - % retained after 90 days	D 5721 D 3895 D 5885	 55% 80%	 55% 80%	 55% 80%	 55% 80%	 55% 80%	 55% 80%	 55% 80%	per each formulation
UV Resistance *(7)* (a) Standard OIT (min. ave.) — or — (b) High Pressure OIT (min. ave.) - % retained after 1600 hrs *(9)*	D 7238 D 3895 D 5885	 N. R. *(8)* 50%	 N.R. *(8)* 50%	 N.R. *(8)* 50%	 N.R. *(8)* 50%	 N.R. *(8)* 50%	 N.R. *(8)* 50%	 N.R. *(8)* 50%	per each formulation

(1) Machine direction (MD) and cross machine direction (XMD) average values should be on the basis of 5 test specimens each direction
Yield elongation is calculated using a gage length of 33 mm
Break elongation is calculated using a gage length of 50 mm
(2) The yield stress used to calculate the applied load for the SP-NCTL test should be the manufacturer's mean value via MQC testing.
(3) Other methods such as D 1603 (tube furnace) or D 6370 (TGA) are acceptable if an appropriate correlation to D 4218 (muffle furnace) can be established.
(4) Carbon black dispersion (only near spherical agglomerates) for 10 different views:
9 in Categories 1 or 2 and 1 in Category 3
(5) The manufacturer has the option to select either one of the OIT methods listed to evaluate the antioxidant content in the geomembrane.
(6) It is also recommended to evaluate samples at 30 and 60 days to compare with the 90 day response.
(7) The condition of the test should be 20 hr. UV cycle at 75°C followed by 4 hr. condensation at 60°C.
(8) Not recommended since the high temperature of the Std-OIT test produces an unrealistic result for some of the antioxidants in the UV exposed samples.
(9) UV resistance is based on percent retained value regardless of the original HP-OIT value.

Table 2 – High Density Polyethylene (HDPE) Geomembrane - Textured

Properties	Test Method	Test Value							Testing Frequency (minimum)
		0.75 mm	1.00 mm	1.25 mm	1.50 mm	2.00 mm	2.50 mm	3.00 mm	
Thickness mils (min. ave.) • lowest individual for 8 out of 10 values • lowest individual for any of the 10 values	D 5994	nom. (-5%) -10% -15%	nom. (-5%) -10% -15%	nom. (-5%) -10% -15%	nom. (-5%) -10% -15%	nom. (-5%) -10% -15%	nom. (-5%) -10% -15%	nom. (-5%) -10% -15%	per roll
Asperity Height mils (min. ave.) *(1)*	D 7466	0.40 mm	0.40 mm	0.40 mm	0.40 mm	0.40 mm	0.40 mm	0.40 mm	every 2nd roll *(2)*
Density (min. ave.)	D 1505/D 792	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	0.940 g/cc	90,000 kg
Tensile Properties (min. ave.) *(3)* • yield strength • break strength • yield elongation • break elongation	D 6693 Type IV	11 kN/m 8 kN/m 12% 100%	15 kN/m 10 kN/m 12% 100%	18 kN/m 13 kN/m 12% 100%	22 kN/m 16 kN/m 12% 100%	29 kN/m 21 kN/m 12% 100%	37 kN/m 26 kN/m 12% 100%	44 kN/m 32 kN/m 12% 100%	9,000 kg
Tear Resistance (min. ave.)	D 1004	93 N	125 N	156 N	187 N	249 N	311 N	374 N	20,000 kg
Puncture Resistance (min. ave.)	D 4833	200N	267 N	333 N	400 N	534 N	667 N	800 N	20,000 kg
Stress Crack Resistance *(4)*	D 5397 (App.)	500 hr.	500 hr.	500 hr.	500 hr.	500 hr.	500 hr.	500 hr.	per GRI GM10
Carbon Black Content (range)	D 4218 *(5)*	2.0-3.0 %	2.0-3.0 %	2.0-3.0 %	2.0-3.0 %	2.0-3.0 %	2.0-3.0 %	2.0-3.0 %	9,000 kg
Carbon Black Dispersion	D 5596	note *(6)*	note *(6)*	note *(6)*	note *(6)*	note *(6)*	note *(6)*	note *(6)*	20,000 kg
Oxidative Induction Time (OIT) (min. ave.) *(7)* (a) Standard OIT — or — (b) High Pressure OIT	 D 3895 D 5885	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	 100 min. 400 min.	90,000 kg
Oven Aging at 85°C *(7), (8)* (a) Standard OIT (min. ave.) - % retained after 90 days — or — (b) High Pressure OIT (min. ave.) - % retained after 90 days	D 5721 D 3895 D 5885	 55% 80%	 55% 80%	 55% 80%	 55% 80%	 55% 80%	 55% 80%	 55% 80%	per each formulation
UV Resistance *(9)* (a) Standard OIT (min. ave.) — or — (b) High Pressure OIT (min. ave.) - % retained after 1600 hrs *(11)*	D 7238 D 3895 D 5885	 N.R. *(10)* 50%	 N.R. *(10)* 50%	 N.R. *(10)* 50%	 N.R. *(10)* 50%	 N.R. *(10)* 50%	 N.R. *(10)* 50%	 N.R. *(10)* 50%	per each formulation

(1) Of 10 readings; 8 out of 10 must be ≥ 0.35 mm, and lowest individual reading must be ≥ 0.30 mm; also see Note 6.
(2) Alternate the measurement side for double sided textured sheet
(3) Machine direction (MD) and cross machine direction (XMD) average values should be on the basis of 5 test specimens each direction.
Yield elongation is calculated using a gage length of 33 mm
Break elongation is calculated using a gage length of 50 mm
(4) The SP-NCTL test is not appropriate for testing geomembranes with textured or irregular rough surfaces. Test should be conducted on smooth edges of textured rolls or on smooth sheets made from the same formulation as being used for the textured sheet materials.
The yield stress used to calculate the applied load for the SP-NCTL test should be the manufacturer's mean value via MQC testing.
(5) Other methods such as D 1603 (tube furnace) or D 6370 (TGA) are acceptable if an appropriate correlation to D 4218 (muffle furnace) can be established.
(6) Carbon black dispersion (only near spherical agglomerates) for 10 different views:
9 in Categories 1 or 2 and 1 in Category 3
(7) The manufacturer has the option to select either one of the OIT methods listed to evaluate the antioxidant content in the geomembrane.
(8) It is also recommended to evaluate samples at 30 and 60 days to compare with the 90 day response.
(9) The condition of the test should be 20 hr. UV cycle at 75°C followed by 4 hr. condensation at 60°C.
(10) Not recommended since the high temperature of the Std-OIT test produces an unrealistic result for some of the antioxidants in the UV exposed samples.
(11) UV resistance is based on percent retained value regardless of the original HP-OIT value.

Physical Properties. This category includes thickness, asperity height, density, and melt index. It should be noted that melt index (MI) is not included in the table, but is described in the main text of the specification.

- Thickness - For all geomembranes, the nominal thickness of the geomembrane is the obvious target value. For smooth sheet, the average thickness must be the nominal value; however, the lowest individual of 10 values can be -10% due to variation of the material and testing. For textured geomembranes, the average core thickness can be 5% less than the nominal thickness of the sheet. This was a difficult decision to make and attests to the variation in blown film process, which is relatively difficult to control when aggressive texturing is required. Based on the ASTM interlaboratory test data, the coefficient of variation of core thickness for double sided textured geomembranes was ±3.6%. Regarding the lowest individual value, the lowest for eight out of ten values can be -10%, and the lowest for any of the ten values can be -15%. The ASTM interlaboratory test data showed that the lowest individual was -19% for double-sided textured geomembranes. The test frequency for this property is every roll of geomembrane.
- Asperity Height - This is an index property, and is only applicable to textured geomembranes. The property has no known correlation to the interfacial shear strength behavior of the geomembrane, e.g., as determined using ASTM D 5321 direct shear testing. Similar to the thickness test, ten measurements are required across the width of the geomembrane. The minimum average value should be 0.40 mm. Since this is new test, details of the lowest value within the ten measurements have not been established. The test frequency of this property is every second roll. If

the sheet has double sided texturing, the measurement side is performed on an alternating basis.

- Density - A minimum value of 0.940 g/ml is required for the as-formulated manufactured geomembrane, see ASTM D 883. It should be recognized that the virgin resin has a lower density value than the formulated material. An appropriate equation used to estimate resin density from formulated sheet density is listed in ASTM D 3350, and is given in Equation (1). The test frequency for density is per every 90,000 kg of resin.

$$D_r = D_p - 0.0044 \times C \qquad (1)$$

where: D_r = density of virgin resin (g/ml)

D_p = density of formulated product (g/ml)

C = carbon black content (%)

- Melt Index - The difference between melt flow index values per ASTM D 1238 for HDPE geomembrane made from blown film versus flat extrusion methods is significant. Since both manufacturing methods are appropriate, a range was considered, but it is so broad as not to be meaningful. Thus, a specific value is left off the tables, but included as a comment in the text of the specification.

<u>Mechanical Properties</u>. This category includes tensile properties, tear resistance, and puncture resistance.

- Tensile properties - The test is performed according to ASTM D 638 Type IV using dumbbell shaped specimens. Four test parameters are required: yield stress, break stress, yield elongation, and break elongation. The minimum average value of these four parameters refers to both machine and cross machine directions with 5 test specimens being required in each direction. The minimum yield stress for both smooth and textured geomembranes is 15,000 kN/m^2 and the break stress is 27,000 kN/m^2. In the specification, these values are presented in units of “N/m” by multiplying the stress by the nominal thickness of the geomembrane. Regarding the elongation, the minimum yield elongation for smooth and textured sheets is 12% using a gage length of 33 mm. The break elongation for smooth and textured geomembranes is 700% and 100%, respectively. The gage length used to determine the break elongation is 50 mm. The relatively low break elongation for textured geomembranes is for textured sheet manufactured by the blown film co-extruded texturing process.   The test frequency for these tensile properties is every 9,000 kg.

- Tear resistance - The minimum average tear resistance is 125 kN/m for both smooth and textured geomembranes. Data in the tables are presented in units of “N” by multiplying the above value by the nominal thickness of the geomembrane. The test frequency is every 20,000 kg.
- Puncture resistance - This value is evaluated according to ASTM D 4833. The minimum average puncture resistance is 320 kN/m. Data in the table are presented in units of “N” by multiplying the above value by the nominal thickness of the geomembrane. The test frequency is every 20,000 kg.

It should be noted that the required value for the above three mechanical properties varies linearly with thickness. It is assumed that the thickness of the geomembrane has no influence on the fundamental stress, or strength, of the geomembrane. Generally, the strength of the bulk material increases slightly with thickness due to the increase in crystallinity in bulkier products. However, the actual correlation is not well defined, and is strongly dependent on the processing method. As a conservative approach, strength values obtained from thinner geomembranes are used in the calculation for greater geomembrane thicknesses.

Endurance Properties. This category includes stress cracking resistance, carbon black content and dispersion, OIT, oven aging, and UV resistance. The majority of the properties in this category are new with respect to previous specifications. They are essential in assuring the long-term performance of the geomembrane.

- Stress cracking resistance - This property is evaluated using the SP-NCTL test. The pass/fail criterion is indicated in Table 3, according to GRI-GM10.

Table 3 - Specification for SP-NCTL Test According to GRI-GM10 (Revision 4, Jan. 2015) (where F_t = failure time)

Test Condition	Yield Stress (ASTM D638)	Number of Test Specimens	Passing Criteria	Action if Failure Criterion is not Reached
A	manufacturer's mean value via MQC testing	5	4 out of 5 with $F_t \geq 500$ hr (noncomplying specimen with $F_t \geq 250$ hr)	Retest using condition B
B	manufacturer's mean value via MQC testing	5	4 out of 5 with $F_t \geq 500$ hr (noncomplying specimen with $F_t \geq 250$ hr)	Perform full NCTL test via ASTM D 5397 with $T_t \geq 250$ hr
C	manufacturer's mean value via MQC testing	30	$T_t \geq 250$ hr	Reject sheet(s)

The original 100 hours failure time of the SP-NCTL test defined in Table 3 was deduced from data which included fourteen commercially available as-manufactured geomembranes and seven field cracked geomembranes (Hsuan et al., 1993; Hsuan and Koerner, 1995). In 2014 it was raised to 500 hours.

- Carbon black content - The test is performed according to ASTM D 1603, with a specified range from 2 to 3 %. The 3% carbon black value is the maximum capacity level above which no significant improvement in ultraviolet resistance occurs, Accorsi and Romero (1995). The specification also allows other testing methods, such as ASTM D 4218 (muffle furnace) or the microwave technique to evaluate carbon black content if an appropriate correlation to D 1603 can be established.
- Carbon black dispersion - The specification for this property is based on viewing ten microtome slides, which are taken from various locations along of the width geomembrane. The image that is observed under 100x of a transmission light microscope is compared with patterns that are shown on the reference chart. Nine of ten views should be in Category 1or 2 and one can be Category 3 to assure the uniformity of the carbon black in both dispersion and distribution.
- Oxidative induction time - Either the Std-OIT test or the HP-OIT test can be used to evaluate this property. The purpose of permitting either test is to allow for the selection of the appropriate test for the particular antioxidant package used in the formulation. Certain antioxidant packages are not suitable to be evaluated by Std-OIT (Thomas and Ancelet; 1993 Hsuan and Guan, 1997).

  Since these two OIT tests are relatively new, a GRI interlaboratory test program was undertaken in order to establish the variability of the test and to determine the typical OIT values for current commercially available geomembranes. Eight HDPE geomembranes were included in the test program. Three were smooth and five were textured geomembranes. They all contained different antioxidant packages. The thickness of the geomembranes was 1.0 mm. Five laboratories participated in the testing.

The result of the Std-OIT testing is shown in Table 4. Samples A to F, show a Std-OIT value range from 115 to 183 minutes. The coefficient of variation of these six, samples ranges from 6% to 16%. It should be recognized that this percentage incorporates the variability of the material, test and equipment. Since the majority of the tested geomembranes (the notable exceptions being G and H) shows a Std-OIT value above 100 minutes, the value of 100 minutes was selected to be the minimum required value for Std-OIT. For perspective, an antioxidant package of a HDPE geomembrane with Std-OIT value of 80 minutes was predicted to have a lifetime of 200 years at 20°C under soil burial conditions (Hsuan and Koerner, 1998). Thus, the 100 minute seems to be acceptable for a screening test, although the long-term performance of the antioxidant must be assessed using an aging procedure, which will be discussed later.

Table 4 - STD-OIT Values (in minutes) Obtained from Different Laboratories

Sample	Std-OIT Value from Different Laboratories					Average OIT	Variation Coefficient (%)
	Lab. 1	Lab. 2	Lab. 3	Lab. 4	Lab. 5		
A (S)	132	126	116	134	127	127	6
B (T)	134	108	99	117	119	115	11
C (T)	187	126	162	167	194	167	16
D (S)	202	175	174	201	165	183	9
E (T)	198	129	176	199	189	178	16
F (S)	182	176	162	156	184	172	7
G (T)	64	42	54	73	60	59	20
H (T)	61	45	52	70	57	57	17

Note: S = smooth sheet
T = textured sheet

For Samples G and H, their Std-OIT values are well below 100 minutes. There are two possibly reasons causing such low values. One is an insufficient amount of antioxidant. The other is the particular type of antioxidant package, which may not be suitable to be evaluated by the Std-OIT test. Under this situation, the HP-OIT test should be performed on these materials to verify the cause.

For the HP-OIT test, there were only two laboratories involving in interlaboratory testing. The results are shown in Table 5. The two sets of data are very similar, however, the variability of the test and material cannot be quantified based on the sparse data. Samples A to F show the HP-OIT value ranging from 334 to 1068 minutes. The HP-OIT to Std-OIT ratio for five out of six geomembranes is in the range of 2.5 to 3.3, not considering samples C, G, and H. This seems to suggest that the five geomembranes may contain similar antioxidant types but of different proportions. The antioxidants are probably a blend of phosphites and hindered phenols, since similar ratio values were observed in HDPE geomembranes that contain similar antioxidant packages (Hsuan and Guan, 1997). In contrast, a high HP/Std-OIT ratio is obtained in Samples C, G, and H, due to their high HP-OTT values. Thus, these three geomembranes are most likely to contain different types of antioxidant package than the other five, but not necessarily the same among them.

Table 5 - HP-OIT Values (in minutes) and HP/Std OIT Ratio

	HP-OIT Value		Average HP-OIT	Average Std-OIT	HP/Std Ratio
	Lab. 1	Lab. 4			
A (S)	331	336	334	127	2.6
B (T)	335	333	334	115	2.9
C (T)	1195	940	1068	167	6.4
D (S)	520	512	516	183	2.8
E (T)	593	575	584	178	3.3
F (S)	436	428	432	172	2.5
G (T)	269	292	281	59	4.8
H (S)	275	258	267	57	4.7

Note: S = smooth sheet
T = textured sheet

Before establishing the minimum HP-OIT value, the purpose of including the test should be clarified. It is to provide an alternative test for evaluating antioxidant packages that are sensitive to the high testing temperature used in the Std-OIT test, e.g., the situation occurring in Samples C, G, and H. The minimum required value must be higher than the HP-OIT value that is obtained from the antioxidant package with Std- OIT of 100 minutes. Thus, the HP-OIT value was determined by multiplying 100 minutes by the average HP-OIT/Std-OIT ratio of five geomembranes that contain phosphites and hindered phenols. The average HP-OIT/Std-OIT ratio is 2.8, which results in a HP-OIT value of 280 minutes. Since the specification value must be higher than that, it was arbitrarily agreed to use 400 minutes. Geomembranes that pass Std-OIT test most likely will not pass the HP-OIT test. Furthermore, there is no known correlation between the proposed Std-OIT and HP-OIT values. However, geomembranes must pass one of the two OIT requirements. Based on the specified value, geomembrane samples G and H do not fulfill the OIT requirement due to an insufficient amount of antioxidants. The frequency of OIT testing (by either method) is every 90,000 kg.

- Oven aging - The OIT value discussed above is designed as an index test to verify the existence of antioxidant after high temperature exposure. In itself, it does not reflect on long-term performance of the antioxidant insofar as the lifetime of the geomembrane. A performance challenge to the antioxidant package is required to ensure the durability of the geomembrane. For assessing the thermal-oxidation of the antioxidants, forced air oven aging is a simple and consistent incubation environment, although it is recognized that such environment does not simulate true field conditions. The temperature of the oven is elevated to 85°C in order to shorter the testing duration. Incubated samples are retrieved after 90 days for OIT measurement. The percent- retained value cannot be less than 55% for Std-OIT or 80% for HP-OIT testing. These values are established based on data from the GRI interlaboratory test program described in the previous section. Four laboratories participated in the 90 day incubation study for the Std-OIT test. The results are shown in Table 6. The average OIT retained value is 65% regardless the type of antioxidant package. The lowest measured value is 56%. Thus, the specification value was set at a minimum retained value of 55%.

Table 6 - Std-OIT Retained Percent Values in 85°C Forced Air Oven After 90 Days

Sample	Std-Retained Values form Different Labs (%)				Average Retained (%)
	Lab. 1	Lab. 2	Lab. 3	Lab. 4	
A (S)	68	54	47	54	56
B (T)	61	54	60	56	58
C (T)	75	58	63	60	64
D (S)	70	57	67	60	64
E (T)	75	84	67	55	70
F (S)	66	56	71	53	62
G (T)	83	94	73	75	81
H(T)	75	56	61	72	66
			Average Retained (%)		65
			Coefficient of Variation		12%

Note: S = smooth text
T = textured sheet

For the HP-OIT test, only one laboratory was involved. The results are shown in Table 7. The average value is 85%. However, since only one laboratory participated, a more conservative value was set in the specification, i.e., 80% minimum OIT retained. It should be noted that the Sample C is below the specified HP-OIT value, but passes the Std-OIT value. The antioxidant package of this geomembrane probably contained thiosynergists (sulfate compounds) which exhibit a rapid decrease of HP-OIT value in the early stage of incubation, but then stayed constant (Hsuan and Guan, 1997). For this antioxidant package, the Std-OIT is the more appropriate test method.

Table 7 - HP-OIT Retained Percent Values in 85°C Forced Air Oven After 90 Days

Sample	HP-OIT Retained (%)
A (S)	89
B (T)	88
C (T)	50
D (T)	95
E (T)	89
F (S)	91
G (T)	89
H (S)	91
Average	85

Note: S = smooth sheet
T = textured sheet

- Ultraviolet (UV) resistance - For exposed geomembranes, the material's UV resistance is obviously a critical property. The UV-fluorescent weatherometer was selected to simulate UV degradation of the geomembrane. Such devices are simple to use, small in size, require little maintenance and are relatively inexpensive, e.g. compared to the Xenon arc weatherometer. The incubation condition per ASTM D 7238 requires 20 hours UV cycle at 75°C followed by 4 hours condensation at 60°C. The incubation duration of the exposure is 1600 hour elapsed machine time. Three laboratories completed the Std- OIT test and two the HP-OIT test. The results indicate that the Std-OIT gives extremely variable percentage retained values, as shown in Table 8. In contrast, (with the exception of C) the HP-OTT retained values are more well behaved. It is suspected that different antioxidants may have their structure altered under UV exposure, subsequently becoming more sensitive to the high testing temperature used in the Std-OIT test. A detailed investigation on the chemical structure of the antioxidants is required to fully understand the mechanisms involved. In the meantime, only the HP-OIT is recommended to be used in the UV resistance test. The average HP-OIT retained value was initially set at 60%, however, there is a large different in each of the tested geomembranes between the two sets of data. The variability is probably caused by the inconsistency of UV incubation. Thus, the minimum retained percentage is redefined at 50%. Similar to the oven aging, Sample C shows a very low HP-OIT value of 17%. The value remained unchanged even after 2400 hr incubation. This unique HP-OIT response of the thiosynergist type of antioxidants must be carefully examined. Geomembranes that contain this type of antioxidant package typically show a HP- OIT/Std OIT ratio ranging from 6 to 9.

Table 8 - Std-OIT and HP-OIT Percent Retained Values After Incubation in the UV Weatherometer for 1600 Hours

Sample	Std-OIT Retained Value (%)			HP-OIT Retained Value (%)	
	Lab. 1	Lab. 2	Lab. 3	Lab. 1	Lab. 2
A (S)	46	57	15	86	84
B (T)	9	13	12	64	44
C (T)	10	12	6	17	18
D (S)	29	16	9	73	67
E (T)	37	13	14	75	62
F (S)	20	13	11	80	64
G (T)	7	12	19	39	52
H (S)	14	34	16	71	91
Average	22	21	13	63	60

Note: S = smooth sheet
T = textured sheet

Warranty

Material warranties often accompanying a geomembrane specification is similar to that given in the roofing industry. Roofing membranes in flat roofs are usually exposed to the site-specific environment. As such, UV light, coupled with high temperature, must be accommodated. These two factors are arguably the most aggressive actions that cause the degradation of polymeric materials. Clearly, a 20-year warranty on a roofing membrane (and by logical extension to exposed geomembranes in applications like uncovered reservoir liners, canal liners, and floating covers) is a worthwhile pursuit. The vast majority of geomembranes, however, are covered and backfilled. Twenty year warranties do not even begin to challenge the potential lifetime for HDPE geomembrane durability. Depletion of antioxidants alone should reach 200 years depending on site temperature, and this is only the first stage in the aging process, e.g., see Hsuan and Koerner, 1998. Thus, to request a 20 year warranty from a HDPE manufacturer for a covered or backfilled geomembrane is clearly within the materials capability but represents a questionably relevant document at best. Quite possibly, it also represents a financial burden to the manufacturer from an insurance perspective. Far better than a material warranty would be an extended installation warranty which places an emphasis on both construction quality control (CQC) and construction quality assurance (CQA) organizations and their personnel. Nevertheless, owners/specifiers/regulators continue to request material warranties, and following the GRI-GM13 specification the suggested time period is for 5-years, which represents a compromise between having a document for archival purposes and a minimum financial burden with respect to insurance costs on the part of the manufacturer.

Summary and Conclusion

With HDPE geomembranes (as with all geosynthetics) material modifications and upgrading by the manufacturing/resin/additive community is an ongoing process. As such, any specification must be reviewed and modified (as required) on a regular basis. GRI-GM13 requires such a review every 24-months, or sooner. The information presented in this paper represents the development of the original document dated June 17, 1997. Over the intervening years, the specification has seen twelve revisions and this white paper reflects the major quantitative changes. The most recent version can be found on the Institute's website at www.geosynthetic-institute.org/specs.htm.

To the authors' knowledge, all North American (and most worldwide) HDPE geomembrane manufacturers can produce HDPE geomembranes in accordance with this specification. In order for the specification to be fully effective, however, the owner/specifier/regulatory communities must adopt and require it use. To be sure, the relative rigidity of the test methods, test values, and frequency of testing is more stringent than past generic specifications or even individual manufacturers specifications. However, if the balance of relevant test methods, achievable property values, and appropriate long-term performance is the goal of a HDPE geomembrane user, GRI-GM 13 should be seriously considered for adoption and use.

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