The First Pan American Geosynthetics Conference & Exhibition
2-5 March 2008, Cancun, Mexico

The Ongoing Quality Issues Regarding Polyethylene Geomembrane Material Manufacturing & Installation

R.B. Erickson, Vector Engineering, Inc., Grass Valley, California, USA
R.S. Thiel, Vector Engineering, Inc., Grass Valley, California, USA
J. Peters, Vector Chile Limitada, Santiago, Chile

ABSTRACT
Over the past two decades, polyethylene geomembranes have been used successfully in numerous lining applications. Performance is derived largely from the quality of the material and installation, and construction quality assurance (CQA) practices. The purpose of this paper is to clarify critical issues with regard to polyethylene (PE) geomembrane manufacturing and installation, and CQA that are the focus of ongoing discussions within the waste containment industry.

1. INTRODUCTION

Although the geomembrane containment industry has evolved full circle since first required by mandate in the United States, there still exists (and most probably always will) several quality issues related to the long-term performance of geomembranes. Given polyethylene (PE) geomembranes [high density (HDPE) and linear low density (LLDPE)] have become somewhat standard for environmental containment projects, the issues presented in this paper consider only polyethylene geomembranes.

Concerning geomembrane manufacturing, the issues include (1) of generic specifications, (2) degree and uniformity of surface texturing, and (2) carbon black distribution and separation in plane. Specific to installation and CQA, the issues include (1) geomembrane wrinkles, (2) equipment on liners, (3) welded seams and destructive testing, and (4) geoelectric leak surveys. Following is a discussion of each concern.

2. MANUFACTURING ISSUES

2.1 Standard Material Specifications

Generic standard specifications for geosynthetic materials provide designers guidance as to specific values and testing for mechanical, physical, and endurance properties required for performance. Currently, as published by GRI, PGI, and AASHTO, there are 11 industry standards specifications for geosynthetics materials, including geomembranes (6), GCLs (1), and geotextiles (4). At present, there are no standard specifications for drainage geonets/geocomposites or geogrids.

Standard specifications are good in that they provide designers guidance with respect to suggested property values and test frequencies for geosynthetic materials. For example, the Geosynthetic Institute performed the monumental tasks of organizing the geomembrane manufacturers and design community to define the key material performance criteria, omitting antiquated and sometimes time consuming/costly tests no longer relevant to material performance, and bringing all involved to consensus on test values and frequencies of testing.

In general, however, the limitations of standard specifications include the foundation on which they are based tends to commoditize groups of manufactured products. The specifications tend to suggest property values that are at the low end of what is achievable. This results in some values and test frequencies that are essentially the lowest common denominator. This is evident when comparing certain property values between manufacturers' previously or current published values, the lower standard specified values, and actual material conformance test results.

2.1.1 GRI Standard Polyethylene Geomembrane Specifications

GRI Standard Specification GM13 for smooth/textured HDPE geomembranes and GRI-GM17 for smooth/textured LLDPE geomembranes have become the industry standard material specifications used commonly in the Americas. First published in 1997 (GM13) and 2000 (GM17) through the Geosynthetic Research Institute (GRI), they are living documents updated every two years through the institute membership to evolve and keep current with the industry and commercially available products.

GM13 and GM17 define the physical, mechanical, and endurance properties (total 11 properties) for geomembranes ranging in thickness from 0.5 mm (for LLDPE) or 0.75 mm (for HDPE) up to 3.0 mm. The specifications are silent with regard to flat-cast or round-die manufactured products; thus, all properties are synonymous with all commercially available PE geomembrane products manufactured in the Americas. Following find highlights within the standard.

There is some question in the authors' minds if polyethylene materials less than 1 mm thick should even be classified as "geomembranes", rather than simply as tarps. The reason for this is the low durability of materials thinner than 1 mm in thickness, and their susceptibility to puncture in the field. Consideration of this question is outside of the scope of this paper, but it is highlighted as a question to the industry.

2.1.2 HDPE vs. LLDPE

The density of the finished geomembrane is defined as ≥0.940 g/cc for HDPE and ≤0.939 g/cc for LLDPE. The distinguishing difference between HDPE and LLDPE geomembranes is the additional tensile elongation and puncture strength per unit area. LLDPE generally have approximately 50% greater elongation properties with equivalent puncture strength per unit area when compared with HDPE. Thus, LLDPE is well suited for projects that require performance under very high loads (such as leach pads) and applications that may result in large differential settlement and geomembrane deformation over time (such as landfill caps). In general, HDPE membranes should be used in exposed applications as they are slightly more crystalline than LLDPE with slightly improved resistance to UV and heat aging.

2.1.3 Environmental Stress Crack Resistance

Regarding environmental stress crack resistance (ESCR), many high density polyethylenes may crack when exposed to chemical environments and/or under stress due to the release of stored stresses acquired during the extrusion process. The standard polyethylene resins used for the past 10+ years in North America by the membrane manufacturers for waste containment applications are specially formulated to resist stress cracking. Therefore, stress cracking of polyethylene geomembranes is generally not an issue for established formulations that have been tested and certified by the manufacturers of HDPE. ESCR is typically not an issue for PE geomembranes with resin density below 0.937 g/cc, and stress crack resistance testing is not required by GRI-GM17 for LLDPE geomembranes.

Given that most manufacturers regularly run trials with different resins, including a possible industry trend of higher density resins with improved stress crack resistance, the CQA officer should verify stress crack resistance test results and certifications from the geomembrane manufacturer. The appropriate stress-crack test is specified in GRI-GM13 as ASTM D5397.

2.1.4 Oxidation Induction Time and Endurance Testing

GRI-GM13 and GRI-GM17 greatly expanded the endurance testing requirements for PE geomembranes. The long-term performance of polyethylene is derived primarily from the heat stabilizer/antioxidant package in the resin formulation. The amount of antioxidants in the resin is indirectly measured by the test for oxidation induction time (OIT).

The OIT test exposes geomembrane specimens to an elevated temperature and pressure in pure oxygen and is held constant until complete oxidation and depletion of the resin antioxidants. The time from when oxygen is entered into the differential scanning calorimeter test cell until the onset of oxidation is termed the oxidation induction time, which can be used to determine life expectancy of the geomembrane for a given set of conditions.

There are two types of OIT tests, including (1) standard OIT (Std-OIT) where the specimen is heated to 200ºC under 35 kPa pressure in pure oxygen and held constant through complete oxidation, and (2) high pressure OIT (HP-OIT) test where the specimen is heated to a constant 150ºC under an extremely high pressure (3.4 MPa) in pure oxygen to accelerate oxidation. Thus, the Std-OIT accelerates aging with an extremely high temperature and low pressure, and the HP-OIT test utilizes a lower temperature with a much higher pressure. The Std-OIT test, however, is a shorter test compared with HP-OIT (2 hours vs. 8 hours).

To verify the long-term endurance of PE geomembranes, GM13/GM17 also require OIT testing after long-term oven aging and UV resistance for each resin formulation the manufacturers use. For oven aging and thermal stability, the specimen is placed in a forced air oven at 85ºC for 90 days after which the OIT is tested and compared with the initial OIT to verify a specified minimum OIT retained. Regarding UV resistance, the specimen is placed in a UV fluorescent weatherometer for 1600 hours (67 days) and subsequently tested for OIT to verify the resin maintains a minimum loss of antioxidants.

In buried applications (soil cover), PE geomembrane oxidation and breakdown is extremely slow given the very low oxygen concentration in soils (typically less than 8%). In exposed applications, geomembrane oxidation and depletion of anti-oxidants is accelerated due to UV and heat aging in an oxygen rich environment. GM13 and GM17 clarify that the Std-OIT test not be used for UV resistance testing as it produces unrealistic results given that the typical PE anti-oxidants used are only stable in temperatures up to approximately 165ºC (Std-OIT is conducted at 200ºC). In general, owners and designers should specify the HP-OIT test for exposed applications.

2.1.5 Specifying Materials

Specifiers are encouraged to evaluate material requirements as relate to performance for the specific application they are designing. The required values should be kept in perspective of the GRI standard specifications which can be viewed as a starting point for specifying material values. Other data and sources are available to identify property values for specific conditions.

2.2 Uniformity of Surface Texturing

Smooth liners are limited with regard to interface shear strength performance. Textured geomembranes provide improved frictional characteristics against the adjacent soils or geosynthetics to accommodate greater shear strength requirements. Over the past few years, more attention has been given to the surface profile of textured membranes concerning both the pattern and height of the individual protruding asperities.

There are primarily three types of geomembrane surface texturing processes in the Americas, including co-extruded texture, embossed texture, and, to a lesser extent, spray-on texturing. Each process produces a distinctly different profile with varying sheet friction resistance (e.g. interface shear strength) and tensile properties. Thus, each has its strengths and limitations.

2.2.1 Round-Die Co-Extruded Texture

The process includes co-extruding one or two surface layers with a core layer of polyethylene. Nitrogen gas is injected into the surface layers and allowed to escape after exiting the die, causing roughened and irregular surface asperities. With a fairly aggressive surface asperity profile (generally greater than 0.5 mm high) the friction resistance against soils and geotextiles is quite robust under low normal load conditions arising from the 'Velcro' effect (or hook-and-loop cohesion). Under higher normal loads the 'Velcro-adhesion' effect gives way to a standard Mohr-Coulomb relationship that generally has a y-intercept going through the origin.

To manufacture a more aggressive textured surface, more surface layer plastic is required to be extruded onto the core geomembrane with elevated levels of dissolved nitrogen. This creates more sporadic and higher asperities but also creates more pronounced stress risers within the sheet which negatively affects the break strength and elongation of the geomembrane. Additionally, as with all PE geomembranes, the more plastic involved with the product (such as a more aggressive textured surface), the higher the material price.

2.2.2 Embossed Texture

The embossed texture profile is created by impressing a pattern on the sheet surface with a patterned roller when the plastic exits the die during manufacturing whereby a structured profile is created. The process creates a very consistent profile of various configurations, including small spikes, dimples, grid patterns, or varying combinations. The manufacturing process does not significantly affect the tensile properties of the sheet to the extent of co-extruded textured geomembranes. However, at low normal loads, some embossed patterns do not create an effective Velcro effect and friction resistance against nonwoven geotextiles/GCLs when compared with co-extruded textured geomembranes. Thus, designer's need to be aware of the great sensitivity that different types of texturing will have at different normal loads.

2.2.3 Spray-On Texture

The spray-on surface profile has a consistency somewhat synonymous with that of sandpaper. The two step process includes spraying atomized polyethylene onto the previously manufactured base smooth geomembrane. The textured profile creates an excellent Velcro effect and friction resistance when in contact with nonwoven geotextiles/GCLs and the base sheet tensile properties are unaffected by the spray-on process. However, given the smaller size and height of the spray-on texture asperities (typically 0.3 mm), the friction resistance against soils is generally reduced when compared with co-extruded and embossed textured geomembranes. Also, the long-term or ultimate performance of the spray-on material under high normal loads needs to be investigated.

2.2.4 Asperity Height vs. Geomembrane Interface Shear Performance

The relationship between asperity height and geomembrane interface shear performance can be misleading as this issue is very complex and has many variables. The variables go beyond the surface profile of the different PE geomembranes and include the variability of direct shear testing (ASTM D5321/D6243) from lab-to-lab, technician-to-technician. The asperity height of the texturing is currently the most commonly specified physical property of PE geomembranes to verify the quality of texturing. It is usually specified for manufacturing quality control purposes with regard to quantifying the desired aggressiveness.

Referring to GRI standard specifications for textured HDPE (GRI-GM13) and textured LLDPE (GRI-GM17) geomembranes, they recommend a MARV value of 0.25 mm for asperity height which, in many applications, may be too low. With increased average asperities, the interface friction resistance generally increases. For embossed textured geomembranes, the consistency of the surface product profile and asperities is a strong advantage of the manufacturing process. Regarding co-extruded textured membranes, the texturing is highly variable and may generally range from 0.25 mm for mild texturing, up to more than 0.80 mm for very aggressive texture.

For example, as shown in Figure 1, when the asperities of the co-extruded surface increased from an average 0.58 mm (23 mil) to 0.75 mm (30 mil), the peak and large displacement interface shear strength against a nonwoven geotextile increased approximately 27% and 30%, respectively. Thus, the pattern and magnitude of the asperities play a key roll in the derived geomembrane shear strength values. Designers can use this to their advantage when specifying geomembrane asperity requirements.

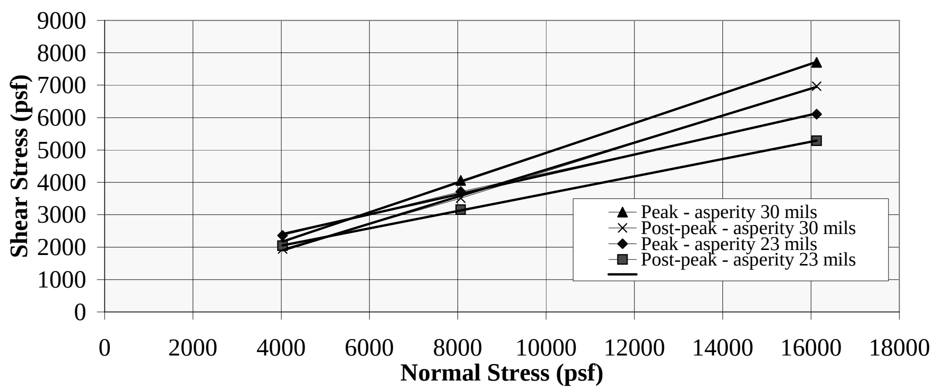

Figure 1. Geomembrane interface shear strength against a nonwoven geotextile (Thiel, 2001).

For projects where the minimum GRI-GM13/17 asperity requirement will meet the shear requirements, standard GRI specifications may be specified. When a more aggressive geomembrane surface is required, an average asperity should be specified (minimum average roll value, MARV) with an absolute minimum value attached to further define an expected surface texture and friction resistance.

The asperity values and associated shear requirements should be specified with the manufacturers' standard products in mind, understanding the potential limitations of a specially manufactured product and process. Where standard texturing may provide sufficient interface strength, the product can be selected with the understanding that a standard product will cost less with fewer potential delays during the manufacturing/shipping procurement process. Although more aggressive products may be potentially available, designers should keep in mind designing around the strengths as well as the limitations of geosynthetic products, in this case with regard to interface shear strength.

2.2.5 Project Specific Direct Shear Testing

Designers often use published literature values or previously obtained test results for shear strength requirements. In such cases, experience and judgment may assist in selecting shear strength parameters for the preliminary design. It is recommended that material specific testing be performed with regard to final project specifications and conformance testing requirements.

As discussed above, the variation in co-extruded geomembrane texturing can have a significant effect on interface shear strength. Designers unaware of this issue may test a manufacturer's sample and obtain passing results, and subsequently use GRI-GM13/GM17 as a texturing specification. This may provide an extremely low result that may not achieve the same interface shear strength as the sample provided for initial testing by the manufacturer. Regarding embossed material, there will likely be less variability between samples, but variability in the direct shear test will always exist between labs.

For projects where slope stability is a concern, site specific direct shear testing should always be conducted and results derived from site-specific conditions and product testing. For CQA purposes, representative test samples of the specific geomembranes tested can be retained by the CQA firm for a direct comparison between the tested material and geomembranes delivered to the site.

2.3 Carbon Black Distribution and Separation In Plane

Separation in plane (SIP) of textured HDPE geomembranes is typically observed as a result of destructive seam peel testing on the 25 mm uniform strip specimens. The separation is an internal failure/peeling of the geomembrane and may travel within the sheet for a considerable distance (Figure 2). The issue of separation in plane failure within HDPE geomembranes was first discussed in 2001 (Smith, 2001) and has since been given increasing attention. Table 1 summarizes the documented observations and conclusions regarding SIP to date.

Figure 3. SIP in 25 mm wide HDPE co-extruded texture geomembrane specimens in single and multiple failure planes.

Table 1. Literature comments on separation-in-plane (SIP) (GSI, 2005).

Reference	Date	Observed Occurrences	Cause(s)	Conclusion
Smith in Mining Record	July/August 2001	- HDPE $\geq$ 1.5 mm (not LLDPE)	- rapid cooling - high plant temp - improper mixing - all of above	- materials defect - long-term concerns - no consensus
Nobert in Poly-Flex Newsletter	August 2001	- HDPE $\geq$ 1.5 mm (not LLDPE) - mainly blown film - fast testing rates - mainly XMD - HDPE and MDPE (not LLDPE or VLDPE)	- rapid cooling (skin-core effect)	- artifact of rapid testing - not a material defect - not a seam defect
Allen in Smith memo	August 2001	HDPE and fPP	- poor CB dispersion - improper mixing	- n/c
Struve in GFR	March 2003	- all GM types - thicker GMs - blown film mainly	- certain master batches - contaminants - temp. gradients - cooling conditions - rapid testing rates	- low density carrier resin in master batch - resins with excessive low density “tails”

As summarized in Table 1 (GSI, 2005), it is difficult to definitively say what the specific problem(s) underlying SIP can be attributed as there currently is no industry consensus. SIP is a problem which arises every couple years, generally resulting from the PE geomembrane manufacturing process, cooling conditions, certain resins or mater batches (carbon black/carrier resin additive), or any combination there of. This is not an industry wide issue but a product specific manufacturing issue that has occurred, albeit seldom, in North and South American manufactured HDPE co-extruded texture geomembranes. It has been observed primarily in co-extruded textured HDPE geomembranes with thickness 1.0 mm and greater.

Currently, the industry seam testing and strength requirements (GRI-GM19) allows for SIP as it is a “sheet related issue”, not a “weld related failure”, which is true. Currently the industry standard specifications for HDPE (GRI-GM13) and LLDPE geomembranes (GRI-GM17) are silent on the issue of SIP as well as most PE geomembrane material specifications.

As currently specified through industry guidance and specifications, SIP continues to be allowable if all other criteria are met. Within ASTM subcommittee D35.01, the task group on Carbon Black Dispersion/Distribution is under development to study carbon black distribution and SIP. Note that carbon black dispersion (dispersion of carbon black agglomerates) is distinctively different than carbon black distribution (mixing of the base resin and the carbon black). This is a positive step to further identify the underlying cause(s) and potential long-term adverse effects on geomembrane performance with regard to internal creep and SIP. However, given the typical progress of some industry venues which include a cross section of manufacturers and designers, such as ASTM, answers to current questions and concerns may take some time to obtain.

2.3.1 The Manufacturing End of SIP

Clarifying SIP in co-extruded textured HDPE geomembranes is obviously a problem that requires additional clarification as well as a procedure for resolution, when it occurs, from a manufacturing as well as a CQA standpoint. This includes identifying the critical strains at which potential SIP failures may occur in the field under site specific conditions.

From forensic testing of geomembranes exhibiting SIP, most all failed products exhibited carbon black and base PE resin ‘streaks’ caused by poor mixing and distribution of the carbon black masterbatch within the base HDPE resin. Therefore, SIP failures are likely attributed in part to changes in the masterbatch loading of carbon black (typically 25% to 50%) combined with the type of resin and molecular weight of the masterbatch carrier resin. For products which exhibit SIP, Struve (2003) proposed a very straight forward verification test in which the manufacturer can evaluate the root cause of SIP. It includes the following procedure.

- Make absolutely no changes to the operating conditions except stop the masterbatch feed;
- Allow the extruder to purge itself of black material and run natural HDPE resin;
- When the black has substantially disappeared from the sheet test for SIP (typically within two hours it will disappear);
- Add back the original masterbatch and test for SIP (will most probably reappear);
- Add a “better” masterbatch known not to cause SIP, verify SIP does not appear.

This procedure takes only a few hours of manufacturing time and eliminates all hypothetical discussions about the relative excellence (or not) of various masterbatches or other causes of SIP. There have been some HDPE geomembrane resins that, by themselves, exhibit SIP but no current standard resins used for waste containment exhibit SIP. However, the above test can also be used to evaluate the base resin as well as the masterbatch (Struve, 2003).

Thus, manufacturers have a verification process to immediately commence evaluating the root cause of SIP and very quickly make corrective actions to potentially eliminate further failing material. Given the potential for the masterbatch formulation to result in or contribute to SIP, it is suggested that only qualified masterbatch formulations that exhibit extruded sheet properties absent of SIP be approved for manufacturing. This masterbatch specification should include a maximum percent carbon black, gradation of carbon black, along with the density, molecular weight, and polymer type of the carrier resin.

The requirement for the masterbatch specification would be consistent with current specifications for the base polyethylene resin which typically specifies the polymer type, density, percent antioxidants/heat stabilizers, and percent reclaimed polymer. Development of a masterbatch resin specification should be a focus of the ASTM Carbon Black Dispersion/Distribution task group as well as all PE geomembrane manufacturers.

2.3.2 The CQA End of SIP

Given that SIP has been observed most commonly during 25 mm wide specimen destructive testing of seam peel strength, additional field tensile strip testing should be conducted on non-seam geomembrane specimens. These specimens can very easily be cut from destructive seam samples and field tested with a tensiometer as part of the CQA program. No frequency is suggested, but periodic testing will confirm the presence or absence of geomembrane SIP behavior.

3. INSTALLATION AND CQA ISSUES

3.1 Geomembrane Wrinkles

The problem of PE geomembrane wrinkles continues to be a major concern regarding the geomembrane installation and long-term performance of composite (geomembrane-clay/GCL) lining systems. The excessive expansion and contraction of LLDPE or HDPE geomembranes is a primary drawback regarding PE when compared with PVC, EPDM, or flexible polypropylene (fPP) geomembranes.

Installed polyethylene geomembranes will always have wrinkles with increasing temperatures and contraction/bridging over subgrade with decreasing temperatures. In the Americas, there will most probably never be a PE membrane installation absent of wrinkles or bridging. To install a wrinkle/bridge free geomembrane, it would require a much larger installation crew, temperature controlled canopies or enclosed tents, extensive CQA, a construction schedule three times a typical installation schedule, and the budget to pay for it.

Installation and soil covering of PE geomembranes installed with predominantly no wrinkles have been accomplished in Europe, but include the manpower, equipment, and budget to accomplish it. In the Americas, however, geomembrane products and installation are viewed by many owners as a commodity and most projects are constructed on tight budgets. The objective during most geomembrane installations is to minimize, and many times accommodate, wrinkles to the extent possible within the construction schedule, observation of the CQA monitor, and budget. And, as a result, many times quality installations are achieved.

Often there is no specific CQA standard in specifications with regard to wrinkle management, excepting the basic requirements of ‘minimizing wrinkles’ or ensuring the liner is in ‘intimate contact’ with the subgrade. Wrinkles in geomembranes present an array of potential problems related to the installation and soil cover scheduling, damage, and long-term performance of the drainage and lining systems. Polyethylene geomembrane wrinkle/bridging problems include:

- Increased potential for damage from installation traffic and soil covering;
- Interruption of drainage above the liner in caps;
- Shortened time frames for welding and soil covering;
- Geomembrane bridging (or trampolining) at the toe of slopes;
- Long-term strains in the liner material that may be detrimental to its life, or may cause localized stresses in unfavorable locations;
- Reduced ability for full coverage of geoelectric surveys which may not be able to detect holes on wrinkles;
- Loss of intimate contact against the underlying clay/GCL in composite lining systems.

Geomembrane wrinkles are both a regulatory concern which should be addressed through geomembrane installation specifications and proper construction quality assurance oversight. Wrinkle management plans should be included into all PE geomembrane installation specifications that provide realistic guidance specific to geomembrane wrinkles. The plan should include some or all the following guidelines. The authors use the following guidelines.

- Limit maximum wrinkle height to 75 mm to 150 mm during covering (lesser height for bottom liners);
- No geomembrane wrinkles should be folded over;
- Selective scheduling of soil placement during periods with lower ambient temperature, such as night time;
- When the wrinkles reach 75 mm – 150 mm vertical height, soil placement operations should be stopped;
- Physically remove wrinkles by walking them out or dividing wrinkles directly ahead of soil covering; prevent wrinkles from folding over on high-normal load applications;
- Mechanically remove fishmouths >150 mm by cutting, overlapping, flattening, and extrusion welding a patch over the affected geomembrane, minimum 160 mm patching past the edge of the damage);
- Utilizing white surfaced HDPE or LLDPE geomembranes to reduce sheet temperatures and potentially reduce wrinkling up to 40% (similar to fPP geomembranes);
- Conduct geoelectric leak surveys after geomembrane installation and soil covering to identify and repair all potential damage to the liner;
- Continual observation of the liner cover soil operations by the CQA monitor to ensure compliance with the maximum wrinkle height, wrinkles are not folded and covered, and no geomembrane damage occurs;
- Evaluate alternate materials to polyethylene (including PVC, EPDM, and fPP). This, however, would sacrifice the performance and potential cost advantages of HDPE or LLDPE geomembranes.

Minimizing wrinkles through a formal CQA wrinkle management program can greatly reduce problems resulting from geomembrane wrinkles or bridging. The program should provide specific guidance to the CQA monitors, installation crew, and earthworks contractor as to what is and is not acceptable during geomembrane installation and soil covering.

Additionally, a geoelectric dipole leak survey after geomembrane installation and soil covering can be utilized as a very effective and cost efficient CQA tool. Geoelectric leak surveys are discussed in Section 3.4.

3.2 Equipment on Liners

Currently, the EPA/600/R-93/182 – Section 3.3.4.1 states that "... small pneumatic tire lifting units with maximum tire inflation pressure of 40 kPa (6 psi) are allowable equipment on the liners". This mandates that all-terrain-vehicles (ATV's) or specially adapted units with low ground contact pressure are the only acceptable equipment to deploy liners directly on top of previously installed geosynthetics. The guidelines to this rule for operating equipment on geosynthetic lining or drainage systems include the following.

- No sudden stops/starts;
- No tire spinning;
- Maximum tire pressure 28-42 kPa;
- Only smooth and clean tires;
- 90° entrance and exits;
- No excessive turning;
- No driving over wrinkles;
- One person per vehicle; and
- No vehicles on slopes.

The US EPA installation guidelines are focused on protecting the liner system from damage due to oversized vehicles, poor installation techniques, and promoting safe work procedures. In situations where no equipment is expressly allowed on the liner, EPA guidance recommends that geomembrane positioning of rolls using a steel cable spanning the width of the deployment area and a block and tackle system should be utilized.

Major areas of concern for operating equipment directly on geosynthetics include:

- Damage to geomembranes due to puncture or tearing;
- Displacement of bentonite in an underlying GCL; and
- Damage to geonet/geocomposite drainage layers due to potential geonet strand roll over or compression.

Where alternative equipment to low ground pressure vehicles are proposed, approval for direct travel on the liner should only be after verification of the equipment bearing pressure, conformance with the project specifications, and certified approval by the geosynthetics manufacturer of the liner.

Allowable equipment travel directly on geosynthetics must be evaluated on a project by project basis and should be guided by the type of application, potential damage to the underlying geosynthetics, and the project specifications. In some applications, however, ATVs may not be suitable for direct travel due to poor subgrade. If the installation equipment is observed to damage any underlying geosynthetic components, it should be removed from the liner and an alternative method of installation used.

To evaluate equipment for direct travel on the liner, a simple test pad demonstration with a sacrificial liner may be conducted. Damage to geosynthetics by equipment during installation will always be a continued concern. However, a proper CQA plan and oversight can greatly reduce damage.

3.3 Welded Seams and Destructive Testing

The issue of welding PE seams and CQA testing continues to be of major concern and debate regarding installed PE membranes. Contrary to the wide perception that welded PE geomembrane seams are a commodity, PE seaming is a very technical operation which requires expertise by the installer and vigilance on the part of the CQA monitor.

There is an abundance of technical literature available regarding geomembrane welding and related topics given the numerous nuances associated with skillful welding. Managing the many variables related to fusion and extrusion welding forms the basis of the technical nature of welded seams. The many variables include:

- Type of wedge or extrusion welding machine;
- Speed, temperature, and pressure of the wedge welding machine(s);
- Operator skill and training;
- Seam cleanliness and overlap;
- Ambient temperature and changes in weather conditions;
- Smooth or textured material and surface oxidation; and
- Geomembrane wrinkles.

Given the many variables and the operator skill required for welding polyethylene geomembrane seams, it is not surprising that the industry continues to have an approximate failure rate of 1% of all welded seams. This translates to 1 meter of failed seam for every 100 linear meters of welded seam. This appears to be a high a tolerance for failed seams but is also a reflection of the technical nature of welding PE seams, required expertise and quality assurance by the geomembrane installer (as shown in Figure 4), and the continued requirement for CQA oversight.

When comparing PE fusion/extrusion welded seams with other types of seaming methods, such as solvents and tapes, the alternate methods are simpler and more consistent. However, they do not offer the seam strength and integrity of a properly welded PE seam. Although developments will continue with regard to the type of welding equipment and the base geomembrane material, the current method of extrusion/wedge welding PE geomembrane seams will continue as long as PE membranes are installed. And, in the absence of effective CQA oversight and/or poor on-site installation welding techniques, failures of welded PE geomembrane seams will persist.

The most notable development by PE geomembrane manufacturers to facilitate fusion welded seams are smooth edge/weld edge textured geomembranes. Smooth geomembranes are much easier to clean compared with textured membranes and greatly improve the integrity of welded seams of textured geomembranes. They are produced by several manufacturers and are typically offered with a minimal up charge when compared to conventional textured geomembranes with texturing all the way to each edge. When possible, smooth edge textured geomembranes should be specified.

The requirement of one destructive seam test for every 150 linear meters of weld dates back to the late 1980s but still remains the industry standard. Given the variability of geomembrane welding and CQA monitoring, many times the sampling frequency and CQA discretion result in creating holes in perfectly good seams. The CQA monitor should be smart in selecting the location of destruct samples by taking samples at the beginning or end of seams, or a seam intersection that will require patching. This should never translate to a welded area that looks questionable; it is the obligation of CQA oversight to identify all potential installation problem areas. Intervals should be flexible depending on the quality of installation.

Testing of thermally bonded polyethylene geomembranes should be conducted in accordance with GRI-GM19. It addresses sampling, seam peel and shear values, and pass/fail criteria of HDPE and LLDPE geomembrane seams. The installer and CQA expertise must be factored into any alternative to the current standard test frequency of destructive seam testing, such as increasing or decreasing the test frequency. For example, GRI-GM14 is a guide that presents how a CQA organization can modify intervals for taking geomembrane destructive seam samples using the method of attributes, a statistical model for selecting frequency. The purpose of the guide is to reward good seaming performance by taking fewer destructive samples, and to penalize poor seaming performance by taking additional destructive samples.

3.4 Geoelectric Geomembrane Leak Surveys

Geoelectric leak surveys are increasing in acceptance and are required as part of many CQA programs for geomembrane installations. It is essentially a state-of-the-practice method for testing the integrity of installed liners, both exposed geomembranes and membranes with soil cover. It is a test program that may be utilized in addition to geomembrane seam testing to address the effectiveness and questions surrounding destructive geomembrane seam testing.

Geoelectric leak location methods include impressing a voltage across the geomembrane and detecting the points where electrical current flows through holes and defects. The development of the electrical leaks surveys of geomembranes was started by the US EPA in 1980 with the first surveys of intact membranes conducted in 1985. Since that time, the technology has evolved resulting in a proven technology that is effective in locating and repairing damage to geomembranes after liner construction and covering (Thiel et al., July 2003).

Testing can be performed on exposed liners as well as liners covered with soil or water. Using either a water lance (exposed membranes, ASTM D 7702) or dipole (soil/water covered membranes, ASTM D 7007) methods, up to 100% of the installed lined area can be non-destructively tested for the presence of leaks/defects. These state-of-the-practice technologies, combined with qualified CQA oversight during geomembrane installation, offer a very powerful and cost-effective CQA tool to improve the quality of liner installations.

Approximately 73% of damage to geomembranes is caused due to soil covering resulting in larger geomembrane holes and tears (Forget et al., 2005). Therefore, dipole geoelectric surveys will significantly reduce the potential for environmental contamination risks. The dipole geoelectric leak survey is a technology that can identify and subsequently remediate damage to geomembranes caused during installation and soil covering. Incorporating a dipole geoelectric leak survey into a geomembrane CQA plan is an effective and cost efficient tool to greatly improve the lining system integrity and environmental containment. Geomembrane geoelectric leak surveys go beyond current industry CQA programs and seam testing technologies.

There are several qualified firms that perform geoelectric leak surveys at a very reasonable cost, typically less than $0.70/sq meter in the US. Geoelectric surveys are a state-of-the-practice CQA tool that should be considered as part of any CQA program for any critical geomembrane containment project.

4.0 CONCLUSIONS

Over the past two decades, polyethylene geomembranes have been used successfully in numerous lining applications. Performance is derived largely from the quality of the material and installation construction quality assurance (CQA) practices. This paper clarifies the current critical issues with regard to polyethylene (PE) geomembrane manufacturing and installation CQA that are the focus of ongoing discussions within the waste containment industry.

Concerning geomembrane manufacturing, the issues include (1) the strengths and limitations of generic specifications and clarification of select testing requirements, (2) degree and uniformity of surface texturing and specifying surface texturing, and (3) carbon black distribution, separation in plane, and expanding specifications to address SIP. Specific to CQA, the issues discussed include (1) geomembrane wrinkles and development of wrinkle management plans, (2) equipment on liners and evaluating equipment parameters, (3) welded seams and the technical nature of PE welding and destructive testing, and (4) state-of-the-practice geoelectric leak surveys.

REFERENCES

Daniel, D. E. and Koerner, R. M. (1993), Quality Assurance and Quality Control for Waste Containment Facilities, *U.S. EPA Technical Guidance Document,* EPA/600/R-93/182, 305 pgs. (Also available from ASCE Press, Reston, VA, USA).

Forget, B, et al. (2005). Lessons Learned from 10 Years of Leak Detection Surveys on Geomembranes, *Sardinia Symposium*, Sardinia, Italy.

Geosynthetic Institute (2005). Commentary on Separation-in-Plane (SIP) in Geomembrane Testing, *The GSI Newsletter/Report,* Vol.19, No.2, Folsom, PA, USA.

Geosynthetic Research Institute (2006). Test Methods, Test Properties and Testing Frequency for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes, *GRI Test Method GM13*, Geosynthetic Institute, Folsom, PA, USA.

Geosynthetic Research Institute (1998). Selecting Variable Intervals for Taking Geomembrane Destructive Seam Samples Using the Method of Attributes, *GRI Test Method GM14*, Geosynthetic Institute, Folsom, PA, USA.

Geosynthetic Research Institute (2006). Test Methods, Test Properties and Testing Frequency for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes, *GRI Test Method GM17*, Geosynthetic Institute, Folsom, PA, USA.

Geosynthetic Research Institute (2005). Seam Strength and Related Properties of Thermally Bonded Polyolefin Geomembranes, *GRI Test Method GM19*, Geosynthetic Institute, Folsom, PA, USA.

Norbert, J. and Yazdani, G. (2001). Separation in the Plane of the Sheet: Is it a Seam Failure? Poly-Flex Document, Grand Prairie, TX, USA.

Smith, M.E. (2001). SIP in Leach Pad and Tailings Pond Liners: An Acceptable Condition? *The Latin American Mining Record,* Vol. 8, No. 4.

Struve, F. (2003). Separation in Plane (SIP), *Geotechnical Fabrics Report,* Vol. 21, No. 2, Roseville, MN, USA.

Thiel, R.S. (2001). Peak vs. Residual Shear Strength for Landfill Bottom Liner Stability Analysis, *15th Annual GRI Conference*, Geosynthetic Institute, Folsom, PA, USA.

Thiel, R., Darilek, G. Laine, D. (2003). Cutting holes for testing vs. testing for holes*, Geotechnical Fabrics Report*, Vol. 21, Roseville, MN, USA.