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Geomembrane Liner Testing Technologies – Present and Developing

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Introduction

The testing of geomembrane liners, caps, and cut-off walls used for solid and liquid waste containment systems, water collection, storage, water distribution systems, wastewater treatment systems, and product storage systems has been developed over the last thirty years or so. However, it is only in the last 15 years that monitoring and testing of installed systems has facilitated an assessment of the longer term performance of geomembranes in these critical applications (Peggs et al. 2004). This information, in turn, has allowed the specification and institution of testing and monitoring procedures during design and construction of new facilities that will further assure the integrity and durability of the next generation of lining systems.

This paper describes the state-of-practice and needed development of geomembrane/liner testing and proposes suggestions for future work. The emphasis is on high density polyethylene (HDPE) geomembranes, since they are the predominantly used polymer for waste containment.

Overview

There are essentially three areas in which testing is performed – on the material itself, on seams, and on the complete liner. There are two types of testing – destructive and nondestructive – the latter being preferred after the liner has been seamed and completed.

It has generally been considered that the seams, particularly field seams, are the Achilles' heel of geomembranes, but this is not necessarily so. Damage (including penetrations) away from the seam can occur while covering the geomembrane with gravel or other materials. Electrical leak surveys (Nosko et al. 1996) have shown that while leaks in seams account for 79% of leaks occurring during liner installation, only 24% of the total number of liner leaks occur during installation. About 73% occur as the liner is covered, of which 68% are stone punctures. Therefore, stone damage, accounting for 50% of total

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damage, is the Achilles' heel of *covered* liners. Seam leaks, which accounting for 19% of the total number of leaks, remain the Achilles' heel of *uncovered* liners.

These analytical results clearly demonstrate where the emphases need to be placed during the design and construction phases for improved liner performance. As result, the International Association of Geosynthetics Installers (IAGI) has developed certification programs for welders and specifications for the installation of geomembranes.

Testing Of Geomembrane Material

Overview

This phase is represented by Quality Control testing during the manufacturing and plant fabrication processes and by Quality Assurance testing on behalf of the owner before or after geomembrane is delivered to the site.

Quality Control Testing

At each stage of manufacturing and fabrication the typical practice is to require a Quality Control (QC) certificate with each batch of incoming material. A few Quality Assurance (QA) conformance tests are performed on the incoming material to assure it meets specifications. During the subsequent stage of processing a series of QC tests are performed to ensure that the product meets the processor's and owner's specifications before the material is shipped. The relevant QC certificate is typically shipped with the material.

QA conformance testing by the design engineer or by an independent construction quality assurance (CQA) contractor, on behalf of the owner, is now frequently being performed at the manufacturing plant, so that any nonconformance is identified and can be remedied before shipping. If conformance testing is performed when material arrives on site, final acceptance is delayed for a few days, or maybe for a week or more if nonconforming material is found and has to be replaced.

Typical testing programs for high density polyethylene (HDPE) geomembrane, the predominant geomembrane at present, are outlined below. While similar principles can be applied to other materials, the same tests do not necessarily apply. The principal difference is that other materials are not susceptible to stress cracking, as is HDPE, in the as-manufactured condition. Other materials include linear low density polyethylene (LLDPE), polypropylene (PP), polyvinyl chloride (PVC), PVC alloys, chorosulfonated polyethylene (CSPE), ethylene propylene diene monomer (EPDM), polyester/polyurethane combinations, bitumen, polyurea, and others.

Resin and Additives

The resin manufacturer will provide the geomembrane manufacturer with a QC certificate listing, at least, density (representative of crystallinity) and melt flow rate (representative of molecular weight) of each "batch" of resin. The meaning of a "batch" varies between manufacturers but is generally considered to be one railcar. The resin manufacturer will not necessarily measure a sample from each railcar but will have sampled the resin after it has been homogenized in storage after the continuous manufacturing process. There is presently a trend to replace the Melt Index with the High Load Melt Index (HLMI) which better describes the chemistry of the present customized resins.

The geomembrane manufacturer will typically measure the same properties on resin samples removed from each compartment of the incoming railcar, perhaps even from the top and bottom of each compartment.

Generally the geomembrane manufacturer receives carbon black in the form of a concentrated masterbatch from a compounder. The compounder will generate a QC certificate showing carbon content and the geomembrane manufacturer will measure the same. Both the resin and the masterbatch contain other additives for ultraviolet and oxidation protection but no testing is performed for these until the geomembrane has been manufactured.

Geomembrane Material

The QC tests performed by the manufacturer on the finished product vary between those specified in National Sanitation Foundation International Standard 54, 1993 (NSF54 1993) which was withdrawn in April 1997, and those listed in the Geosynthetic Research Institute standard GRI GM13 Rev 6, June 2003. GRI GM13 also lists the frequencies at which the tests are performed. The latter is a QC testing regimen. It is not a set of material specifications.

The following items within GRI GM13 should be noted. The stress cracking resistance test is ASTM D5397 “Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test”, not the ASTM D1693-01 bent strip test. Hsuan et al. (1992) have shown that the bent strip test is completely inappropriate for present HDPE resins – the stress relaxes before cracking can be initiated, therefore all modern resins behave about the same, and are acceptable. Only the ASTM D5397 test, with its constant load, defines the differences between the various resins - differences that can be a few orders of magnitude. The D1693 test should never be performed again on HDPE geomembranes.

The carbon black dispersion test (ASTM D5596-03) requires the preparation of a thin-slice microsection for viewing in the microscope. Only this method presents a carbon dispersion that is unchanged from the as-manufactured condition. At present, there is some question as to the interpretation of “agglomerates” in this standard particularly as to whether it includes all black shapes. However, the present standard only considers those features that are related to carbon dispersion, not other agglomerates

Oxidative induction time (OIT) is used to evaluate changes due to thermal and ultraviolet radiation exposure. Nevertheless, manufacturers still present changes assessed by the measurement of uniaxial tensile properties (ASTM D638-02a). While the use of OIT is still a subject of some debate, there is no doubt that if tensile testing is used, the parameters that should be monitored are the break properties, primarily the break elongation, not the yield properties. The break elongation most effectively reflects changes to the surface of the material where changes initially occur and where failures usually initiate. A faster tensile test or an impact test might be even more effective.

The debate on the use of OIT to monitor changes in performance centers on whether a test at an elevated temperature is meaningful in relation to much lower service and testing temperatures where different additives to those providing protection at higher temperatures might be active. Hence the inclusion of the lower temperature, longer term oven aging and ultraviolet resistance tests in GRI GM13. These tests are crucial for geomembranes that are to be left exposed. The oven aging test will become more important in the higher temperature environments in aerobic bioreactor landfills.

Quantifying the roughness of surface textures/structures is very difficult – GRI GM13 simply specifies a minimum asperity height, but with no requirement for asperity distribution or geometrical profile. Asperity height is relatively easy to measure when the texture (better described as a structure) is added as a secondary process to the geomembrane but is more difficult on primary process random textures. The relative merits of randomly-textured and geometrically structured profiles have not yet been adequately discussed. Each will have advantages in different lining systems.

For textured sheet the stress cracking test requires that the test be performed on the smooth sheet at the edges of the rolls. However, such a test will not assess any effect of the texturing process on the stress cracking resistance of the basic sheet. When this is required, and also when the effect of seaming is required, the test must be performed on unnotched sheet according to the BAM method (Thomas and Woods-Deschepper 1992) at a temperature of 80°C and a stress of 4 MPa. Typically a break time exceeding 700 hr is required.

While puncture resistance is a required QC parameter, it is an acknowledged engineering design fact that puncture strain is a far more meaningful parameter for in-situ performance. Because uniaxial tensile strength, both at yield and rupture, is provided as a fundamental strength parameter, it may be more appropriate to provide an index puncture strain parameter as a means of further assuring material quality. This introduces the differences between index testing used for QC and QA compared to performance testing to obtain parameters useful for assessing the performance of the material while in service.

A uniaxial tensile test does not reproduce the tensile performance of a geomembrane in the field because the installed liner is likely to be stressed biaxially, being restricted from contracting sideways to produce the necking that occurs in a uniaxial test. To evaluate field performance, a large diameter specimen (600 mm) is typically subjected to a biaxial pneumatic burst test by incrementally increasing the pressure. The measurement of strain, and whether pressure should be increased continuously or incrementally are items needing further investigation.

Another performance parameter of interest is the puncture protection of a geomembrane afforded by a cushion geotextile. Geotextiles are typically selected based on their mass per unit area in the range of 350 to 600 g/m^2. Frequently field trials are performed on a built-up cross section of the liner in a small test pad then by moving a heavy piece of equipment around on top of the test pad. The geomembrane is exhumed then examined for signs of puncturing and tested for changes in uniaxial mechanical strength. Typically, in North America, unlike in Europe, no consideration is given to the elastic recovery of indentations that occur when the geomembrane is exhumed nor is any consideration given to the stress cracking resistance of HDPE geomembranes in evaluating the significance of the indentation that occurs in service on the long-term durability of the geomembrane. Whether or not the geomembrane is punctured at the time of the test is only part of the problem. The other part is whether the damage that occurs in service will significantly shorten the life of the geomembrane.

Two types of quasi-performance laboratory tests are performed to assess the puncture protection of geomembranes. In one, a large disc of geomembrane is hydrostatically deformed over three truncated cones standing varying heights above a sand subgrade. The critical cone height at which the geomembrane is first punctured is determined. This is representative of the strain tolerance of the geomembrane. In the second test the geomembrane sample is deformed over stones to be used in the field. Whether or not puncture occurs is determined. One point of discussion in these tests is whether a geomembrane being deformed over the profile or the stones replicates the stones being pressed into the geomembrane with a firm subgrade in the field. In Europe, the latter type of test, known as the cylinder test is performed with a deformable plate under the geomembrane that records the strains developed in the geomembrane during the test. Local strains are not allowed to exceed 0.25%. It has been proposed by Shercliff (1996) that California Bearing Ratio puncture resistance (ASTM D6241-99) is a more realistic parameter than mass per unit area for assessing puncture protection.

Recently a regulator and a design engineer in the United States have attempted to limit both maximum local and global strains in HDPE geomembranes to 1% in one project and to 0.25% in another project. This would make designing with HDPE geomembranes extremely difficult, if not impossible. A re-assessment of maximum allowable strains in HDPE, LLDPE and PP geomembranes has been performed by Peggs et al (2005) for the specific case of a geomembrane used as the cap of old waste and the bottom liner for new waste in a vertical expansion. Proposed maximum allowable strains (MAS) are shown in Table 1.

TABLE 1: Proposed maximum allowable strains (MAS)

Material	Proposed MAS
Smooth HDPE (SCR <1500 hr)	6%
Smooth HDPE (SCR >1500 hr)	8%
Structured HDPE	6%
Textured HDPE	4%
LLDPE (Density >0.935 g/cm3)	10%
LLDPE (Density <0.935 g/cm3)	12%
Structured LLDPE	10%
Textured LLDPE	8%
Polypropylene	15%

These are proposed as conservative MAS values.

Another major performance test is the direct shear test for the determination of interface shear strength or friction angle. This also is a performance test and should be conducted with the field interface of interest with each component backed by a component with the same deformation characteristics as that in the field and under the worst-case moisture conditions. Typically this test is performed on specimens with a 300 mm square contact area with a linear displacement. Some tests are still performed on specimens with a 100 mm square contact area, and some with a torsional displacement (Stark and Poeppel 1994). To be conservative the post-peak “residual” shear strength is typically used rather than the peak shear strength, even though interface movement initially occurs at the peak value. Discussions on peak versus residual shear strengths can be found in the proceedings of the 15th GRI conference (GRI-15 2001)

In HDPE geomembranes the most significant long-term performance parameter is the stress cracking resistance. This is typically specified, as in the GRI GM13 standard, to be a minimum of 300 hr (recently increased from 200 hr) in the single point test (ASTM D5397) performed at 30% of the room temperature yield stress. There is no reason why this minimum value should not be increased depending on the criticality of individual liner applications. A liner used to contain hazardous waste should have a far higher stress cracking resistance than a golf course pond liner. The stress cracking resistances of the available HDPE resins might vary by a factor of 500 to 1000.

When the chemistry of the contained liquid is undefined, it is advisable to perform a chemical resistance test of the proposed geomembrane in the site-specific liquid. The United States Environmental Protection Agency (EPA) Method 9090 (EPA 1987) was used for many years but this has been superseded by separate ASTM methods for immersion (D5322-98) and testing of the different geosynthetics – ASTM D5747-95a for geomembranes. Bulk mechanical properties are predominantly used to evaluate the attack of the chemical. However, many of these tests do not reflect changes to the surface layers of the test specimens, the place where chemical attack starts, and most frequently where mechanical failure initiates. The test procedure should include a stress cracking test in the test liquid for polyolefin geomembranes. In addition to tensile elongation at break, impact, and fast tensile tests, degradation in the surface layers can be best monitored by microstructural analytical techniques such as Fourier Transform Infrared Analysis (FTIR), Gel Permeation Chromatography (GPC), and Differential Scanning Calorimetry (DSC). However, one of the remaining concerns is that no guidance is provided as to what are acceptable and unacceptable changes in the various parameters. It should be noted that HDPE geomembranes show virtually no change in properties when exposed to typical municipal solid waste leachates.

Quality Assurance

Once the performance tests have been used to identify the appropriate geomembrane material for the specific application, and the correct material specifications and index QC tests have been identified, the next phase of testing is QA testing. Construction QA testing is frequently performed in the field but, as indicated previously, is more effectively performed in the manufacturing plant before material is shipped to the site. Then, barring a transportation accident, the material can be used immediately after it arrives on site. This is not an opportunity to reproduce the QC testing program but should simply be used for spot check testing. Frequently the full range of specification tests is performed about every 9,000 m^2 of geomembrane. This is not necessary because a selection of key tests that reflect the fundamental quality of the product and its key performance parameters is all that is needed. Thickness across the full roll width will be measured, remembering that the edges of blown film (round die) extruded geomembrane are very close to one another in the manufacturing process. The most extreme distances are a half roll width apart.

Density (crystallinity) and Melt Index (molecular weight) may be measured every 19,000 m^2, but carbon dispersion and carbon content might be measured every 9,000 m^2 on geomembranes that are to be left exposed. On buried geomembranes it may not be considered necessary to measure carbon parameters because such sheets will not be exposed to ultraviolet radiation. However, carbon dispersion is significant in that large agglomerates can be the stress concentrating initiation sites for stress cracking. Therefore, it is advisable to confirm this parameter. Uniaxial tensile break parameters will assess the surface and internal homogeneity of the geomembrane perhaps every 9,000 m^2 while OIT will assess the additive content each 23,000 m^2. Single point stress cracking tests can be performed once on each type of resin in the shipment. Actually these tests would all be performed at the defined frequency on each type of resin in the shipment. Only geomembranes made from one type of resin should be used on a project.

Generally it should not be necessary to test HDPE geomembranes for low temperature brittleness, environmental stress cracking resistance by the bent strip test, soil burial performance, ozone resistance, and even uniaxial yield strength parameters, although yield parameters are a by-product of determining break properties.

When geomembranes are to be left exposed in locations where they may experience a wide range of material temperatures (which will be wider than the ambient temperature range) it may be appropriate to measure the coefficient of linear thermal expansion (CTE) in order to effect proper wave/wrinkle management. Standard specifications provide an average CTE between -30°C and 30°C, but the curve shows increasing expansion rates at temperatures up to maximum field temperatures of about 90°C. Test should therefore be performed up to this temperature. The average CTE may be 100% higher than it is between -30 and 30°C.

Geomembrane seams

There have always been two components to geomembrane seam testing – destructive and nondestructive. The former is undesirable in a liner that should not contain holes, particularly when approximately one meter of double wedge seam is cut out for testing and is patched using about three meters of inferior extrusion welding. Consequently the frequency of destructive sampling is typically limited to once per 150 m of seam per welding machine/operator combination. Note that seams made by each machine/operator combination must be tested each 150 m. This frequency may be increased or decreased depending on the test results according to the Method of Attributes described in GRI GM14 (1998). If seams are providing good test results the frequency of testing can be reduced, but if poor results are being obtained, the testing frequency is increased. However, it does seem inappropriate to increase the frequency of hole cutting and to increase the amount of extrusion seaming in poorly made seams. Obviously, a major objective of seam testing is to preclude the need for destructive testing. The International Association of Geosynthetic

Installers has recently published a white paper authored by Robert Koerner and George Koerner of the Geosynthetic Institute (2004) rationalizing a reduction in destructive testing providing other nondestructive methods, geomembrane edge preparation, and personnel accreditation protocols are implemented.

Nondestructive testing is typically performed by air pressure testing double track fusion seams, vacuum box testing single track extrusion and fusion seams, spark testing extrusion seams particularly short detail-oriented (e.g. pipe boot) seams, and air lance testing single track chemical and fusion seams. Such tests evaluate only the continuity of seams, not, except indirectly, the bond strength of the seam. Thus, they only identify leaks through the seam or adjacent geomembrane. They do not identify flaws that may become leaks under service stresses, nor leaks that may occur during the first loading of the lining system. Air pressure tests do not identify penetrations that sometimes occur along the outside edge of double track seams under the free flap.

It is interesting to note that vacuum box testing is done using soap solutions which may be capable of initiating environmental stress cracking in HDPE geomembranes. Rarely is the soap removed from the seam area. The role of the soap in contributing to the higher incidence of stress cracking failures in extrusion seams has not been determined. Stress cracking typically occurs at the edge of the extrusion bead, most likely at the boundary between the originally oriented extruded sheet microstructure and the more isotropic melted and solidified weld zone material.

Geomembrane seam specimens are *destructively* assessed by performing peel and shear tests and monitoring some combination of peel strength, shear strength, shear ductility, and peel separation. Typically, five specimens are tested in peel and five in shear. Peel tests demonstrate the quality of the interfacial bond. Shear tests, it is often claimed, demonstrate that the seam is “stronger” than the geomembrane. That is, in fact, not so because most project specifications require the seam shear strength to exceed only 90% to 95% of the geomembrane strength. Thus the presence of the seam reduces the strength of the geomembrane. The shear test is actually used to demonstrate that the welding process (mechanically and thermally) has not adversely affected the ductility of the adjacent geomembrane.

The ductility of the geomembrane can be adversely affected by overheating, deep grinding, gouges, and the orientation of such flaws. Peel separation, which can, contrary to popular opinion, occur in the field, may introduce crazing, the precursor of stress cracks, in the separated surfaces thereby reducing the stress cracking resistance of HDPE geomembrane seams. Until the stress cracking resistance of the basic geomembrane is better quantified, it is safer to assume that any geomembrane is susceptible to stress cracking and to avoid any amount of peel separation.

Typically the shear strength of a seam is required to be >90% of the yield strength of the geomembrane, while peel strengths are often required to be >70% and >60% of yield strength for fusion and extrusion seams respectively. However, the new GRI.GM19 (2005) specification for geomembrane seams requires both fusion and extrusion seams to have the same peel strength. The yield strength that is referenced is not well defined. It is usually taken as the manufacturer’s specified value, which is assumed to be the equivalent of the Minimum Average Roll Value (MARV), the value that 95% of samples will meet.

Infrequently it is taken as the measured value of the actual on-site geomembrane. This is not recommended because it is not known whether the geomembrane material/specimen is at the high or low end of the population strength distribution. If the geomembrane is at the high end many seam samples may be unnecessarily rejected.

However, Peggs (1996) has shown that peel and shear strength measurements do not demonstrate that a good weld has been achieved. Due to the small cross sectional area of the geomembrane components on each side of the seam compared to the large area of seam bonding, test specimens will always fail in the geomembrane when bonding efficiency exceeds between 8 and 20%, depending on thickness. Therefore, even the peel test cannot demonstrate that proper welding (material mixing and solidification) has occurred. There is, therefore, little point in measuring peel and shear strengths. In shear tests, adequate elongation of the adjacent geomembrane should be demonstrated, and in peel tests the amount of peel separation should be confirmed to be zero. The latter is not necessary if it can be shown that peel separation does not introduce crazing in the upper separated surface.

There are two damaging processes that can occur at seams – mechanical and thermal. Mechanical damage is typically excessive grinding gouges. Thermal damage is overheating, resulting in oxidation and melting notches.

Both may be evidenced by low ductility breaks in both shear and peel testing. Inadequate bonding can only (by conventional testing) be evidenced in the peel test. Therefore, it should ultimately be possible to demonstrate adequate bonding of the seam, and adequate ductility in the adjacent geomembrane by performing only peel tests. This may be somewhat problematic with present higher density resins due to their relatively low ductility in bending, but as resin formulations are improved to provide better stress cracking resistance, the thicker geomembranes should fail in a ductile mode when bent during peeling. This is presently a requirement of peel testing in Germany.

Four out of five test specimens are typically required to meet specifications for the complete sample to be considered acceptable; rarely are all five required to meet specifications. This is a 20% failure rate. There are many lining systems and features, such as cast-in liners and liner anchorages, where every millimeter of a seam can be under a peel stress. Experience has shown that such seams can, and do, fail at the 20% failure region. Even when repaired, adjacent failures have occurred later when the seam is subsequently loaded in service. Such failures occur when the peeling force is imposed as a wedge force between the bottom flap of the seam and the top geomembrane; a mode of loading that is not induced by conventional peel testing. Therefore, if the bond strength is only 25% efficient, a conventional peel test will show acceptability, but a wedge separation force might easily cause separation of the poorly bonded seam. A wedge separation test would be better than a peel separation test.

Non-destructive Testing

Air pressure testing of dual track seams is performed according to the ASTM D5820-95 standard. The air channel is pressurized to the required pressure dependent upon the thickness of the geomembrane (1 mm/185 kPa, 1.5 mm/195 kPa, 2.0 mm/205 kPa) and should be allowed to stabilize for two minutes. Only when the stabilization period has been reached should the five-minute pressure-loss testing period commence. Maximum allowable pressure drops for the above thicknesses are 28, 21, and 14 kPa respectively. This takes into account the deformation of the geomembrane at the test pressure. However, pressures do change as the geomembrane temperatures change in the sun or the shade. This takes into account the reduction in pressure as the geomembrane deforms at the test pressure. However, pressure changes also occur as the geomembrane temperature varies in the open sunshine or under cloud cover. In practice it is found that seams will either hold the pressure, or cannot be pressurized. Rarely do they have slow leaks. When a pressure test has been completed the pressure should be released from the end opposite to that at which the air was inserted, to ensure that the full length of seam was tested.

The results of vacuum box testing (ASTM D5641-94) is somewhat similar – the box will either hold a vacuum or it will not. Bubbles are shown immediately if a leak is present. Only occasionally does a fine froth develop at very small leaks. The pressure in the box is reduced to 35 kPa and the seam observed for ten seconds. When it is necessary to perform a vacuum box test on a dual track seam the free flap at the edge of the seam must be removed to prevent air from entering the ends of the box. The more flexible geomembranes can be more difficult to test with a vacuum box because they are sucked up into the box. Modifying the box with a stiff screen may reduce this effect. Soap solutions are used to generate bubbles during vacuum box testing. Some soaps can cause environmental stress cracking in HDPE geomembranes. Extruded seams are more susceptible to stress cracking than fusion seams. In arid locations, where exposed seams are not washed by rainwater, soap may cause more stress cracking than elsewhere.

In air lance testing a 4.5 mm diameter jet of air at a pressure of 350 kPa is directed at the edge of chemical or single-track fusion seams by a handheld wand held approximately 50 mm from the edge of the seam. Lifting of the edge of the seam and whistling, or a flapping of the edge of the seam, occurs at unbonded sections. While this works quite well with an experienced operator it is seen to be very sensitive to the direction in which the lance is pointed, and there are no means of quantifying the results.

When extrusion seams cannot be tested by a vacuum box, such as on curved surfaces, at boots around pipe penetrations, when the geomembrane is welded to cast-in strips in concrete, or at butt welds between cast-in sheets, a copper wire can be placed at the back of the seam for AC or DC spark testing. Then, the extruded bead is placed so it just touches the wire and holds it in place. In the DC technique, the wire is grounded. A brass brush, a round tip probe, or a conductive squeegee, charged to an electric potential between 25 and 55kV (depending on the leak path length of interest) is passed over the seam. The negative electrode is grounded and therefore connected to the copper wire. The low resistance in an air channel (leak) through the seam results in an audible and visible discharge from the search probe to the wire. Because no signal signifies an acceptable seam it is necessary to calibrate the equipment to ensure that the voltage is high enough to give a positive signal if there is a leak. ASTM D6365-99 describes the technique and how to determine the voltage required. It should be noted that the dielectric constant of HDPE is about 24 kV/mm so a discharge will occur, and cause a hole, through a thickness of geomembrane equal to (Applied Volts)/24,000 mm. However, in practice, most spark testing is performed using an alternating current method, in which the wire is not grounded.

A new installation may be spark tested prior to filling, and all holes repaired, yet it may still leak when filled. On emptying and performing another spark test, additional holes may be indicated. These will be longer leak paths that are now more conductive since they are filled with moisture, and holes generated as the liner has been stressed during filling. They do not necessarily indicate that a poor spark test was performed the first time.

All of these tests are only performed on seams, which constitute perhaps only 0.3% of the area of the liner. However, 79% of leaks are caused as the liner is covered. Such leaks can occur anywhere in the liner. Electrical methods, initially introduced circa 1985 for liquid impoundment liners, have been developed for exposed liners, and soil and waste covered liners. The success of these techniques requires a reasonably homogeneous electrically conductive medium above the liner and a conductive medium immediately below the liner. The medium above is positively charged and the medium below is negatively charged such that a current of between about 5 and 100 mA flows through the leaks in the liner. The media above and below the liner should be electrically isolated from each other such that current only flows through the leaks, not through pipe penetrations, batten bar bolts, concrete pads, or soils located at the edge of the cell being tested. Such extraneous current flow will reduce the sensitivity of the technique, particularly adjacent to these areas, often the locations of liner leaks.

With the potential applied across the geomembrane, a pair of survey electrodes is used to measure the potential gradient throughout the liquid or soil above the liner. The potential gradient is quite uniform at most locations except near a leak where the high current density at the hole generates a high potential gradient. The point of highest gradient is at the hole. In shallow, “safe” liquids the search probe can be handheld as the operator wades through the liquid. In deep or hazardous liquids a remote probe can be dragged over the liner from one side of the pond to the other. When wading, leaks of about 0.5 to 1 mm can be pinpointed. Remote surveys can identify the same size of leak but location accuracy is reduced to about 500 mm.

On soil layers the potential gradient is measured at the nodes of an orthogonal grid with a spacing, depending on sensitivity required and depth of cover, of between about 500 mm and 3 m. A potential contour map is developed that shows peaks at leak locations. Underneath 1 m of sand cover a 5 mm diameter leak can be located to within about 150 mm to 1m, depending on the profile of the liner (pipe trench, toe of slope) and adjacent pipes etc.

Successful tests have been performed on liners under 5 m of MSW and up to 18 m of industrial waste. Successful tests have been performed to find a 25 mm diameter hole in a liner under 5.5m of select ore in a heap leach pad (McEuen 1996) and to find two leaks (of unknown size) under 5m of municipal solid waste (Peggs 2001). In the latter case, although the overlying waste was not excavated, leakage stopped when the leachate level was maintained below the maximum elevation of the indicated leaks (McEuen 1996).

A survey on a covered liner should be performed when about 500 to 750 mm of soil have been placed on the liner. It is then unlikely that additional damage will be incurred by the liner, yet a leak is still relatively easy to repair.

When the liner is used in an exposed application, a small amount of positively charged water in the sump can be pumped through a hose to a “water lance” or “water puddle” that directs a solid stream of water onto the liner. When the water penetrates a hole and contacts the negatively charged subgrade, current flows and is recorded. Holes of less than 1 mm diameter can be located to within about 15 mm. This technique is valuable when water is difficult to obtain or when the time taken to fill a facility with water for testing will be excessive. However, it is not possible to survey the primary liner of a double geomembrane system with only a geonet or geocomposite between them using the water lance or water puddle (or any other electrical method), since there is no guaranteed conductive medium directly under the geomembrane. Relying on the leaking liquid to provide a pathway is not practical. The leak detection layer must be backfilled with water or another conductive layer must be placed under the primary geomembrane. Portable leak survey methods are capable of covering up to approximately 2 acres of liner per day.

Alternatively, an orthogonal grid of electrodes can be placed under the liner as it is being installed. Such items enable the continuous monitoring of the liner and identify the location of leak anywhere in the liner as soon as it occurs. Location accuracy is a function of the grid spacing.

Typically, it is not possible to locate a leak in a secondary liner but the placement of multiple electrodes around the periphery of a cell and another in the leak detection system may provide a means of doing this (Binley et al 1997). To the authors’ knowledge, this has not yet been done commercially.

Depending on the size of the cell being measured, electrical surveys show a leak frequency of between about 2 (large cells) and 12 (small cells) per 10,000 m^2 of liner, even though independent CQA monitoring has been performed. Because of these statistics an increasing number of design engineers are specifying electrical integrity surveys as the last stage of the CQA for lining systems (Rollin et al 1999).

The new New Source Performance Standards (NSPS) (EPA 1999) require the periodic surface monitoring of landfill caps for methane concentrations exceeding 500 ppm. This has led to the development of compact infrared (IR) spectrometry (IRS) equipment that, in conjunction with GPS equipment, is capable of locating very small leaks in landfill caps, both geomembrane and clay. The equipment measures the concentrations of methane, carbon dioxide, and non-methane hydrocarbons simultaneously, to less than 1ppm every second, at rates upwards of about 6 ha/day. Such techniques, like electrical surveys, can be used to locate leaks in caps via gas concentration contour plots. However, recent work has shown that the peaks in gas concentrations may be some distance from the actual leak through the geomembrane on slopes, at culverts, and near access roads (Peggs and McLaren 2002). Similar techniques are contemplated for basal liners, particularly large area liners, that would require the spreading of an activating agent prior to placement of the geomembrane. The activating agent generates a gas that, like methane, can be monitored above the geomembrane, whether the liner is exposed or covered by a permeable soil layer.

All of these testing methods only locate leaks in liners – they do not identify flaws that may not be leaks at the time of testing (poor bonding, voids) that might initiate cracks that will propagate into leaks under and develop into leaks under operational stresses.

Ultrasonic thickness measuring techniques were used many years ago to assess weld interface quality but were discontinued due to their inability to assess extrusion welds. The rough surface of an extruded weld bead made it impossible to transmit the ultrasonic signal from the transducer into the material and back. This technique was used to identify an unwelded interface by the sound reflected from such an inhomogeneity. The technique has recently been revived but this time to measure the thickness of a fusion weld every 8 m. This follows the German model (Luders 2000) that the thickness of a weld should be twice the thickness of the geomembrane less 0.3 to 0.8 mm. However, without the close control (certification) of HDPE resins, welding machines, and installation conditions that occur in Germany inadequate welds could fall in this range. Clearly, the same weld thickness could be achieved by welding at high wedge temperatures and low nip roll pressures or at low wedge temperatures and high roll pressures. However, it is unlikely that both welds would have the same performance characteristics. A better ultrasonic method is the shadow technique presented in GRI GM1 (1986) in which the acoustic energy is induced in the geomembrane at one side of the weld, passes across the weld interface, and is recovered from the geomembrane on the other side of the seam. The loss of acoustic energy reflects the quality of the weld interface. Clearly, most of these types of flaws occur in and adjacent to seams. Ultrasonic techniques have been investigated that pass the signal across the seam interface.

The most promising approach is infrared thermography (IRT) (Peggs et al. 1994), in which the surface is heated through about 10ºC and the temperature distribution on the surface monitored with an IR camera a few seconds later. At homogeneous well-bonded seams the surface temperature decreases rapidly while at defects and poorly bonded regions the thermal energy cannot diffuse through the liner thickness, therefore keeping the surface at higher temperatures. IRT shows the differences between the two tracks of double track seams, shows the effects of minor adjustments in welding machine speed, shows the presence of soil particles, and may even show the effects of temperature cycling of the wedges. None of these effects are evident in conventional seam peel and shear testing. Thus, IRT is capable of nondestructively assessing seam bond strength. Such a technology will require the definition of critical flaw sizes in seams such that Artificial Intelligence (AI) can be used to interpret IRT signals. The AI will then be able to determine in real time whether or not defects are critical. It is estimated that IRT surveys could be made at the rate of 10 km/hr. They could mark the location of each type of defect on the liner with a different colored spot of paint. Ultimately the equipment will be attached to a welding machine for immediate interrogation of the weld for feedback control of the welding machine. After a ten year hiatus, work on IRT has been revived as of this writing.

Conclusions

There are many aspects of geomembrane lining technology for which significant performance experience has been gained but for which the next phase of technical development has not yet been defined. This paper identifies sectors where questions related to testing have been raised and where further development or research is needed to realize improved performance and longer term assured performance of geosynthetic lining systems.

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