SYNTHETIC LINER INSTALLATION

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Geomembrane liners entered the Civil Engineering market in the 1950's as a means of limiting water loss from water storage and conveyance facilities. In such applications, the impact of minor penetrations in the geomembrane was inconsequential to the overall improvement in seepage loss. Typical geomembrane liners in these early applications were PVC with a thickness range of 10 to 20 mils. The past decade has seen an explosion of environmental applications of synthetic liners such as the lining of hazardous and non-hazardous solid waste landfills, surface impoundments, waste piles, and enclosure caps eventually placed over filled landfills or contaminated sites. This paper will focus on the more rigorous selection, design, and installation requirements of the environmental applications.

1 - Composite Liners: Clay versus Synthetic

After a landfill site has been chosen and a basin has been excavated, the basin is lined with one or more layers of water-retaining material (liners) that form a "leachate bathtub." The contained leachate is pumped out through a network of pipes and collector layers. EPA's minimum technology guidance for hazardous waste landfills and many state regulations for solid waste landfills rely on a composite liner that utilizes advantages obtained from combining both liner systems.

Understanding the basic hydraulic mechanisms for synthetic liners and clay liners is very important in appreciating the advantages of a composite liner. Clay liners are controlled by Darcy's law ($Q = kiA$). In clay liners, the factors that most influence liner performance are **hydraulic head** and **soil permeability**. Clay liners have a larger hydraulic conductivity and thickness than do synthetic liners. Additionally, leachate leaking through a clay liner will undergo chemical reactions that reduce the concentration of contaminants in the leachate.

Leakage through a synthetic liner is controlled by Fick's first law, which applies to the process of liquid diffusion through the liner membrane. The diffusion process is similar to flow governed by Darcy's law except it is driven by concentration gradients and not hydraulic head. Diffusion rates in membranes are very low in comparison to hydraulic flow rates even in clays. In synthetic liners, therefore, the factor that most influences liner performance is **penetrations**.

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synthetic liners may have imperfect seams or pinholes, which can greatly increase the amount of leachate that leaks out of the landfill.

Clay liners, synthetic liners, or combinations of both are required in landfills. Figure 1 depicts the synthetic/composite double liner system that appears in EPA's minimum technology guidance. The system has two synthetic flexible membrane liners (FMLs): the **primary FML**, which lies between two leachate collection and removal systems (LCRS), and the **secondary FML**, which overlies a compacted lay liner to form a composite secondary liner. The advantage of the composite liner design is that by putting a fine grain material beneath the membrane, the impact of given penetrations can be reduced by many orders of magnitude (Figure 2). In the figure, Q_g is the inflow rate with gravel and Q_c is the inflow rate with clay.

2 - Synthetic Liner Selection

Synthetics are made up of polymers-natural or synthetic compounds of high molecular weight. Different polymeric materials may be used in the constructions of FMLs:

- Thermoplastics-polyvinyl chloride (PVC)
- Crystalline thermoplastics-high density polyethylene (HDPE), linear low density polyethylene (LLDPE)
- Thermoplastic elastomers-chlorinated (CPE), chlorylsulfonated polyethylene (CSPE)
- Elastomers-neoprene, ethylene propylene diene monomer (EPDM)

Typical compositions of polymeric geomembranes are depicted in Table 1. As the table shows, the membranes contain various admixtures such as oils and fillers that are added to aid manufacturing of the FML but may affect future performance. In addition, many polymer FMLs will cure once installed, and the strength and elongation characteristics of certain FMLs will change with time. It is important therefore to select polymers for FML construction with care. Chemical compatibility, manufacturing considerations, stress-strain characteristics, survivability, and permeability are some of the key issues that must be considered.

2.1 Chemical Compatibility

Chemical compatibility tests using EPA Method 9090 should be performed for all liners used on hazardous waste sites and some municipal landfill sites. Past studies by EPA have found no evidence of synthetic liner deterioration due to leachate from municipal refuse. Recent leachate quality studies have, however, found organic chemical constituents in the leachate that could damage certain synthetic liners. As a result of this, EPA is suggesting a chemical compatibility test even for municipal waste proposal sites.

EPA's Method 9090 can be used to evaluate all geosynthetic materials used in liner and leachate collection and removal systems currently being designed. Method 9090 is used to predict the effects of leachate under field conditions and has been verified with limited field data. The test is performed by immersing a geosynthetic in a chemical environment for 120 days at two different temperatures, room and elevated. Every 30 days, samples are removed and evaluated for changes in physical properties. Tests performed on FMLs are listed in Table 2. The results of any test should be cross-referenced to a second, corollary test to avoid errors due to the test itself or to the laboratory personnel.

It is important that the leachate being tested is representative of the leachate in the landfill. Leachate sampled directly from a sump is usually representative, but care must be taken not to mix it during removal. This will disturb the sample's homogeneity and may result in components separating out. Another problem is that municipal solid waste landfill leachate will start to oxidize as soon as it leaves the sump and probably should be sampled under an inert atmosphere.

2.2 - <u>Manufacturing Considerations</u>

Geomembrane sheets are produced in various ways:

- Extrusion-HPDE
- Calendaring-PVC
- Spraying-Urethane

In general, manufacturers are producing high quality polyethylene sheets. However, the compatibility of extrusion welding rods and high density polyethylene sheets can be a problem. Some manufacturing processes can cause high density polyethylene to crease. When this material creases, stress fractures will result. If the material is taken into the field to be placed, abrasion damage will occur on the creases. Manufacturers have been working to resolve this problem and, for the most part, sheets of acceptable quality are now being produced.

In general, the quality of installation is improved as the quantity of field seaming is reduced. Thus geomembranes available in wider sheets offer an advantage in installation. For rigid FML's such as HDPE sheets are commonly available in widths to 22-feet.

Flexible FML's such as PVC may be factory fabricated into panels of even greater widths. The limiting factor is the increase weight and difficulty in placing of very wide FML's.

2.3 - Stress-Strain Characteristics

Typical mechanical properties of HDPE, CPE, and PVC are shown on Table 3. Tensile strength is a fundamental design consideration and Figure 3 shows the uniaxial and biaxial stress-strain characteristics of the three FML polymers. As 600, 800, 1,100, and 1,300 percent uniaxial strain is developed, the samples fail. when biaxial tension is applied to HDPE, the material fails at strains less than 20 percent. In fact, HDPE can fail at strains much less than other flexible membranes when subjected to biaxial tensions common in the field.

Another stress-strain consideration is that high density polyethylene, a material used frequently at hazardous waste facilities, has a degree of thermal coefficient of expansion -three to four times that of other flexible membranes. This means that during the course of a day (particularly in the summer when 100 °F variations in the temperature of the sheeting are routinely measured) a 600-foot long panel would grow 6 feet during a day.

2.4 - Survivability

Various tests may be used to determine the survivability of unexposed polymeric geomembranes. Puncture tests (ASTM D4833) frequently are used to estimate the survivability of FMLs in the field. During a puncture test, a 5/16 steel rod with rounded edges is pushed down through the membrane. A very flexible membrane that has a high strain capacity under biaxial tension may allow that rod to penetrate almost to the bottom of the chamber rupture. Such a membrane has a very low penetration force but a very high survivability in the field. High density polyethylenes will give a very high penetration force, but have very high brittle failure. Thus puncture data may not properly predict field survivability.

2.5 - Permeability

Permeability of a FML is evaluated using the Water Vapor Transmission test (ASTM E96). A sample of the membrane is placed on top of a small aluminum cup containing a small amount of water. The cup is then placed in a controlled humidity and temperature chamber. The humidity in the chamber is typically 20 percent relative humidity, while the humidity in the cup is 100 percent. Thus, a concentration gradient is set up across the membrane. Moisture diffuses through the membrane and with time the liquid level in the cup is reduced. The rate at which moisture is moving through the membrane is measured. From that rate, the permeability of the membrane is calculated with the simple diffusion equation (Fick's first law). It is important to remember that even if a liner is installed correctly with no holes, penetrations, punctures, or defects, liquid will still diffuse through the membrane.

3 - Design of Synthetic Liner

A number of design elements must be considered in the construction of flexible membrane liners: (1) minimum technology guidance, (2) stress considerations, (3) structural details, and (4) panel fabrication.

3.1 - Minimum Technology Guidance

EPA has set minimum technology guidance for the design of hazardous waste landfill and surface impoundment liners to achieve de minimis leakage. De minimis leakage is 1 gallon per acre per day. Flexible membrane liners must be a minimum of 30 mils thick, or 45 mils thick if exposed for more than 30 days. There may, however, be local variations in the requirement of minimum thickness, and these variations can have an impact on costs. For example, membranes cost approximately $.01 per mil per square foot, so that increasing the required thickness of the FML from 30 mils to 60 mils, will increase the price $.30 cents per square foot or $12,000 per acre.

Similar minimum technology guidance has been established by States for municipal solid waste landfills. New York for instance requires a minimum 60-mil geomembrane in each of two required composite liners.

3.2 - Stress

Stress considerations must be considered for side slopes and the bottom of a landfill. For side slopes, self-weight (the weight of the membrane itself) and waste settlement must be considered; for the bottom of the facility, localized settlement and normal compression must be considered.

The primary FML must be able to support its own weight on the side slopes. In order to calculate self-weight; the FML specific gravity, friction angle, FML thickness, and FML yield stress must be known.

Waste settlement is another consideration. As waste settles in the landfill, a downward force will act on the primary FML. A low friction component between the FML and underlying material prevents that force from being transferred to the underlying material, putting tension on the primary FML. A 12-inch direct shear test is used to measure the friction angle between the FML and underlying material.

An example of the effects of waste settlement can be illustrated by a recent incident at The Kettlemen Hill hazardous waste landfill facility in California. At this facility, waste settlement led to sliding of the waste, causing the standpipes (used to monitor secondary leachate collection sumps) to move 60 to 90 feet downslope in 1 day. Because there was a very low coefficient of friction between the primary liner and the geonet, the waste (which was deposited in a canyon) slid down the canyon. There was also a failure zone between the secondary liner and the clay. A two-dimensional slope stability analysis at the site indicated a factor of safety greater than one. A three-dimensional slope stability analysis, however, showed the safety factor had dropped below one. Three-dimensional slope stability analyses should therefore be considered with canyon and trench landfills.

3.3 - Structural Details

Synthetic liner systems are prone to defects in the structural details (anchorage, access ramps, collection standpipes, and penetrations.) Anchor trenches can cause FMLs to fail in one of two ways: by ripping or by pulling out. The pullout mode is easier to correct. It is possible to calculate pullout capacity for FMLs placed in various anchorage configurations. (see EPA/600/52-87/087).

Most facilities have access ramps which are used by trucks during construction and by trucks bringing waste into the facility. Because ramps can fail due to traffic-induced sliding, roadway considerations, and drainage, these three factors must be considered during the design and construction of access ramps.

Pipe penetration through the liners below the waste elevations is not permitted in hazardous waste landfills, but is very common in municipal solid waste landfills. There are two methods of making these penetrations: rigid or flexible (Figure 4). In the rigid penetrations, concrete anchor blocks are set behind the pipe with the membranes anchored to the concrete. Flexible penetrations are preferred since these allow the pipe to move without damaging the liner. In either case, the pipe must not be attached to the liner in such a manner that movement of the pipe would damage the liner.

3.4 - FML liner Panel Fabrication

The final design aspect to consider is the FML panel layout of the facility. Three factors should be considered when designing a FML panel layout: (1) seams should run up and down on the slope, not horizontally: (2) the field seam length should be minimized whenever possible: and (3) there should be no penetration of a FML below the top of the waste (hazardous waste only).

Panels must be properly identified to know where they fit in the facility. A panel-seam identification scheme should be used for this purpose. This numbering scheme also assures a high quality installation, since seam numbers are used to inventory all samples cut from the FML panel during installation. The samples cut from the panels are tested to ensure the installation is of high quality. Quality assurance and the panel-seam identification scheme are discussed in more detail in the next section.

4 - Construction of Synthetic Liners

The engineer is responsible for establishing an inspection program that ensures that the installed synthetic liner meets the design specifications. Under EPA's construction quality assurance program (CQA) this inspection program has five key elements: (1) responsibility, (2) CQA personnel qualifications, (3) inspection activities, (4) sampling strategies, and (5) documentation. This chapter discusses each of these elements.

4.1 - Responsibility and Authority

A FML may be manufactured by one company, fabricated by a second company, and installed by a third company. The FML also may be manufactured, fabricated, and installed by the same company. Depending on how the FML is constructed, various individuals will have responsibilities within the construction process. These individuals may include engineers, manufacturers, contractors, and owners. In general, **engineers** design the components and prepare specifications, **manufacturers** fabricate the FML and **contractors** perform the installation.

Any company that installs a FML should have had past experience with at least 10 million square feet of a similar FML material. Supervisors should have been responsible for installing at least 2 million square feet of the FML material being installed at the facility. Caution should be exercised in selecting firms to install FMLs since many companies have experienced dramatic growth in the last several years and do not have a sufficient number of experienced senior supervisors.

A qualified CQA **auditor** should be employed to review two key documents: (1) a checklist of requirements for facilities, which will help ensure that all facility requirements are met; and (2) a CQA plan, which will be used during construction to guide observation, inspection, and testing.

Designers are responsible for drawing up general design specifications. These specifications indicate the type of raw polymer and manufactured sheet to be used, as well as the limitations on delivery, storage, installation, and sampling. Some specific high density polyethylene (HDPE) raw polymer and manufactured sheet specifications are:

Raw Polymer Specifications

- Density (ASTM D1505)
- Melt index (ASTM D1238)
- Carbon black (ASTM D1603)

Manufactured Sheet Specifications

- Thickness (ASTM D1593)
- Tensile properties (ASTM D638)
- Tear resistance (ASTM D1004)
- Carbon black content (ASTM D1603)
- Carbon black disp. (ASTM D3015)
- Dimensional stability (ASTM D1204)
- Stress crack resistance (ASTM D1693)

Both the design specifications and the CQA plan are reviewed during a preconstruction CQA meeting between the CQA auditor, the synthetic liner installer, and the general contractor.

The preconstruction meeting also is the time to define criteria for "seam acceptance." Seams are the most difficult aspect of field construction. What constitutes an acceptable seam should be defined before the installation gets under way. One technique is to define seam acceptance and verify the qualifications of the personnel installing the seams at the same time. The installer's seamers produce samples of welds during the preconstruction CQA meeting that are then tested to determine seam acceptability. Samples of "acceptable" seams are retained by both the owner and the installer in case of disputes later on. Agreement on the most appropriate repair method also should be made during the preconstruction CQA meeting. Various repair methods may be used, including capstripping or grinding and rewelding.

4.2 - <u>CQA Personnel Qualifications</u>

EPA requires that the CQA officer be a professional engineer (PE), or the equivalent, with sufficient practical, technical, and managerial experience. Beyond these basic criteria, the CQA officer must understand the assumptions made in the design of the facility and the installation requirements of the geosynthetics.

Finding personnel with the requisite qualifications and actual field experience can be somewhat difficult. To develop field expertise in landfill CQA, some consulting firms routinely assign an inexperienced engineer to work with trained CQA people on a job site and not bill for the inexperienced engineer receiving training. This enables companies to build up a reservoir of experience in a short period of time.

4.3 - <u>CQA Inspection Activities</u>

Because handling and work in the field can damage the manufactured sheets, care must be taken when shipping, storing, and placing FMLs. At every step, the material should be carefully checked for signs of damage and defects.

<u>Shipping and Storage Considerations</u>...FML panels frequently are fabricated in the factory, rather than on site. The panels must be shipped and stored carefully. High crystalline FML, for example, should not be folded for shipment. White lines, which indicate stress failure, will develop if this material is folded. Flexible membrane liners that can be folded should be placed on pallets when being shipped to the field. All FMLs should be covered during shipment. Each shipping roll should be identified properly with name of manufacturer/fabricator, product type and thickness, manufacturer batch code, date of manufacture, physical dimensions, panel number, and directions for unfolding.

Proper on site storage also must be provided for these materials. All FMLs should be stored in a secure area, away from dirt, dust, water, and extreme heat. In addition, they should be placed where people and animals cannot disturb them. Proper storage prevents heat-induced bonding of the rolled membrane (blocking), and loss of plasticizer or curing of the polymer, which could cause embrittlement of the membrane and subsequent seaming problems.

<u>Bedding Considerations</u>...Before placing the membrane, bedding preparations must be completed. Adequate compaction (90 percent by modified proctor equipment; 95 percent by standard proctor equipment) is a must. The landfill surface must be free of rocks, roots, and water. The subgrades should be rolled smooth and should be free from desiccation cracks. The use of herbicides can also affect bedding. Only chemically compatible herbicides should be used, particularly in surface impoundments. Many herbicides have hydrocarbon carriers that will react with the membranes and destroy them.

FML Panel Placement...Prior to unfolding or unrolling, each panel should be inspected carefully for defects. If no defects are found, the panels may be unrolled. The delivery ticket should describe how to unroll each panel. Starting with the unrolling process, care should be taken to minimize sliding of the panel. A proper overlap for welding should be allowed as each panel is placed. The amount of panel placed should be limited to that which can be seamed in 1 day.

Seaming and Seam Repair...After the panels have been inspected for defects, they must be seamed by a qualified seamer. The membrane must be clean for the seaming process and there must be a firm foundation beneath the seam. Figure 5 shows the configuration of several types of seams.

The most important seam repair criterion is that any defective seam must be bounded by areas that pass fitness structure tests. Everything between such areas must be repaired. The repair method should be determined and agreed upon in advance, and following a repair, a careful visual inspection should be performed to ensure the repair is successful.

Weather and Anchorage Criteria...Weather is an additional consideration when installing a FML. From the seaming standpoint, it is important not to expose the liner materials to rain or dust. Any time the temperature drops below 50°F, the installer should take precautions for temperature. For example, preheaters with the chambers around them may be used in cold weather to keep the FML warm. There also should be no excessive wind, because it is very difficult to weld under windy conditions.

In addition, FML panels should be anchored as soon as possible. The anchor trench may remain open for several days after installation of a panel. However, the anchor trench must be filled when the panel is at its coolest temperature and is, therefore, shortest in length. This will occur early in the morning.

4.4 - CQA Sampling Strategies

In a CQA program, there are three sampling frequency criteria: (1) continuous (100 percent), (2) judgmental, and (3) statistical. Every FML seam should be tested over 100 percent of its length. Any time a seaming operation begins, a sample should be cut for testing. A sample also should be taken any time a seaming operation is significantly modified (by using a new seamer or a new factory extrusion rod, or by making a major adjustment to the equipment).

Continuous (100 Percent) Testing...There are three types of continuous tests: visual, destruct (DT), nondestruct (NDT). **Visual inspection** must be done on all seams, and DT **tests** must be done on all startup seams.

There are several types of **nondestruct** (NDT) seam tests (see Table 4). The actual NDT test depends on the seam type and membrane polymer. An **air lance** (a low pressure blast of air focused on the edge of the seam) can be used on polyvinyl chloride (PVC), chlorinated polyethylene (CPE), and other flexible liner materials. If there is a loose bond, the air lance will pop the seam open.

In a mechanical point stress test, a screwdriver or a pick is pressed into the edge of the seam to detect a weak bond location. In a **vacuum chamber test**, the worker applies soapy water to the seam. The vacuum chamber is then moved over the seam. If there is a hole, the vacuum draws air from beneath the membrane, causing a bubble to occur. The chamber should not be moved too quickly across the seam. To be effective, the vacuum box should remain on each portion of the seam at least 15 seconds before it is moved. Otherwise, it may not detect any leaks.

The **pressurized dual seam test** checks air retention under pressure. This test is used with double hot air or wedge seams that have two parallel welds with an air space between them, so that air pressure can be applied between the welds. Approximately 30 psi is applied for 5 minutes with a successful seam losing no more than 1 psi in that time. This seam cannot be used in sumps or areas in which there is limited space for the equipment to operate.

Judgment Testing...Judgmental testing involves a reasonable assessment of seam strength by a trained operator or CQA inspector. Judgmental testing is required when a visual inspection detects factors such as apparent dirt, debris, grinding, or moisture that may affect seam quality.

Statistical Testing...True statistical testing is not used in evaluating seams; however, a minimum of one DT every 500 feet of seam, with a minimum of one test per seam, is required. Sumps or ramps, however, may have seams that are very short, and samples should not be cut from these seams unless they appear defective. In addition, a minimum of one DT test should be done per shift.

There are no outlier criteria for statistical testing of seams. In other words, no failure is acceptable. Typically two tests, a shear test and a peel test, are performed on a DT sample (Figure 6). The shear test measures the continuity of tensile strength in a membrane. It is not, however, a good indicator of seam quality. The peel test provides a good indication of the quality of a weld because it works on one face of a weld. A poor quality weld will fail very quickly in a peel test.

In a shear test, pulling occurs in the plane of the weld. This is comparable to grabbing onto the formica on a desk top and trying to pull the formica off horizontally. The bond is being sheared. The peel test, on the other hand, is a true test of bond quality. This test is comparable to getting beneath the formica at one corner of a desk top and peeling up.

4.5 - Documentation

Documentation is a very important part of CQA process. Documents must be maintained throughout FML placement, inspection, and testing. A FML panel placement log, which details the panel identity, subgrade conditions, panel conditions, and seam details, should be kept for every panel that is placed. This form is filled out on site and typically carries three signatures: the engineer's, the installer's and the regulatory agency's on site coordinator's (if appropriate).

In addition, all inspection documents (e.g., information on repairs, test sites, etc.) must be carefully maintained. Every repair must be logged. Permits should be issued to a facility whose records do not clearly document all repairs.

During testing, samples must be identified by seam number and location along the seam. This log indicates the seam number and length, the test methods performed, the location and the date of the test, and the person who performed the test.

At the completion of a FML construction, an as-built record of the landfill construction should be produced that provides reviewers with an idea of the quality of work performed in the construction, as well as where problems occurred. This record should contain true panel dimensions, location of repairs, and location of penetrations.

5 - Summary

The rigorous CQA program required for installation of synthetic liner on environmental applications has produced numerous documents of significant aid to the engineer. In particular EPA has recently published a Technical Guidance Document on the Fabrication of Polyethylene FML Field Seams and is currently preparing a similar document for Low Crystallinity FML field seams. Engineers serious about improving the skills related to synthetic liners should also obtain and review the additional references listed at the end of this paper.

ADDITIONAL REFERENCES

- International Conference on Geomembranes, IFAI, Denver, Colorado, June, 1984
- U.S.E.P.A., Seminar Publication - Requirements for Hazardous Waste Landfill Design, Construction, and Closure, EPA/625/4-89/022, August 1989
- U.S.E.P.A. Geosynthetic Design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments, EPA/600/S2-87/097, February 1988
- U.S.E.P.A., Technical Guidance Document: The Fabrication of Polyethylene FML Field Seams, EPA/530/SW-89/069, September 1989
- U.S.E.P.A., Lining of Waste Containment and Other Impoundment Facilities, EPA/600/2-88-052, September 1988.

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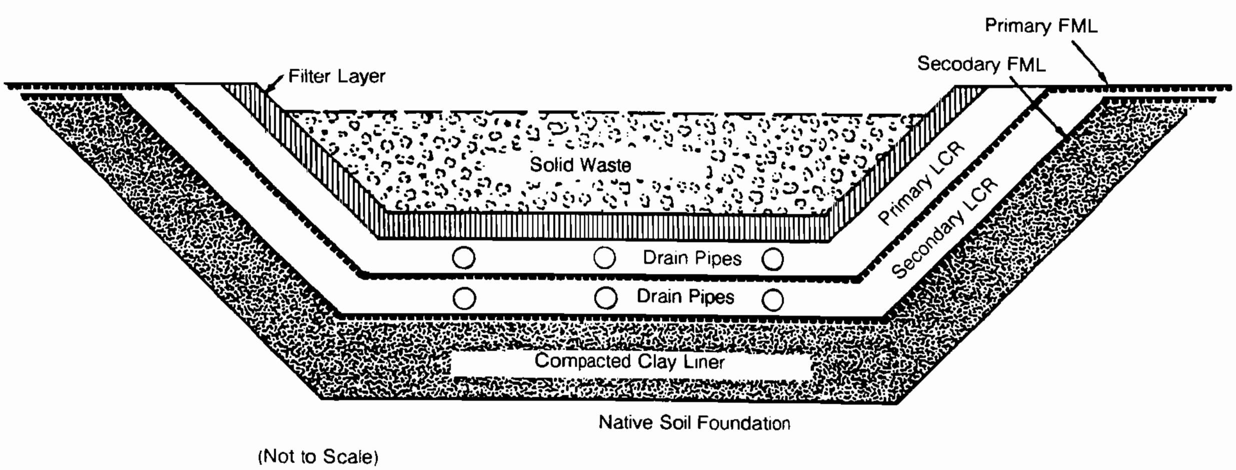

Figure 1 Synthetic/composite double liner system.

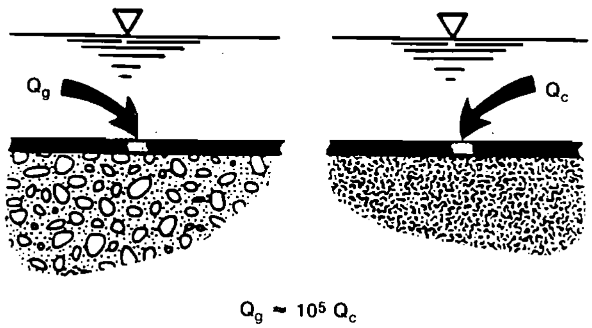

Figure 2 Advantage of composite liner.

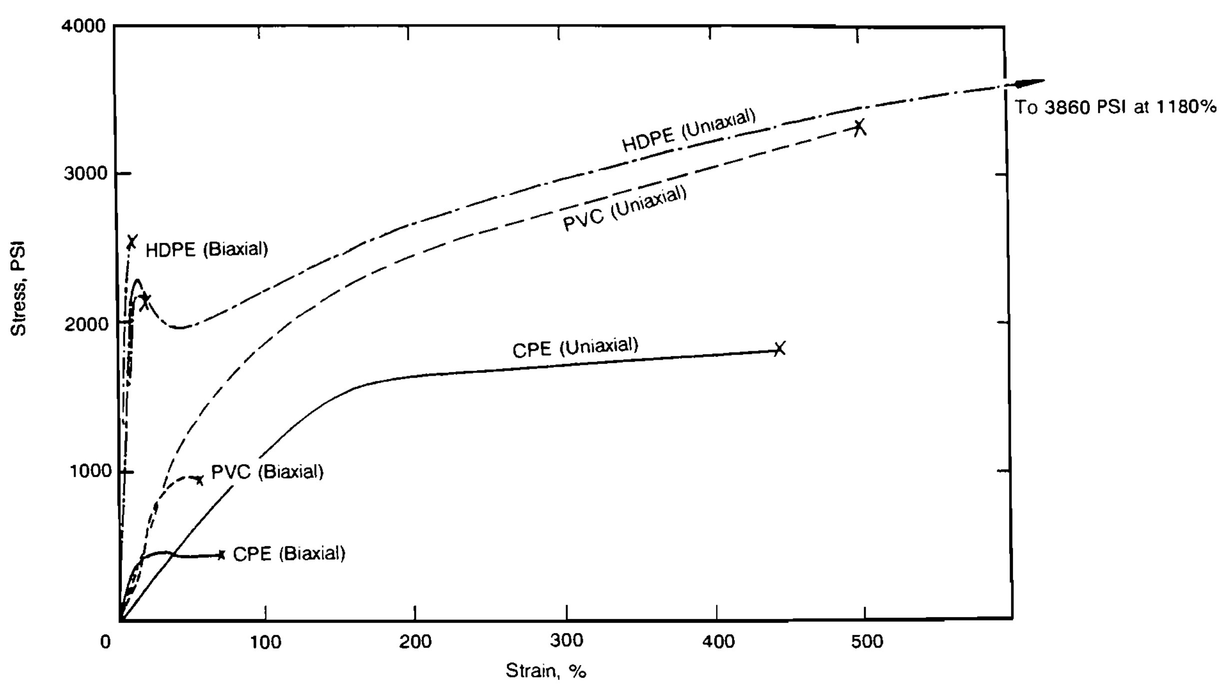

Figure 3 FML stress-strain performance (uniaxial – Koerner, Richardson; biaxial – Steffen).

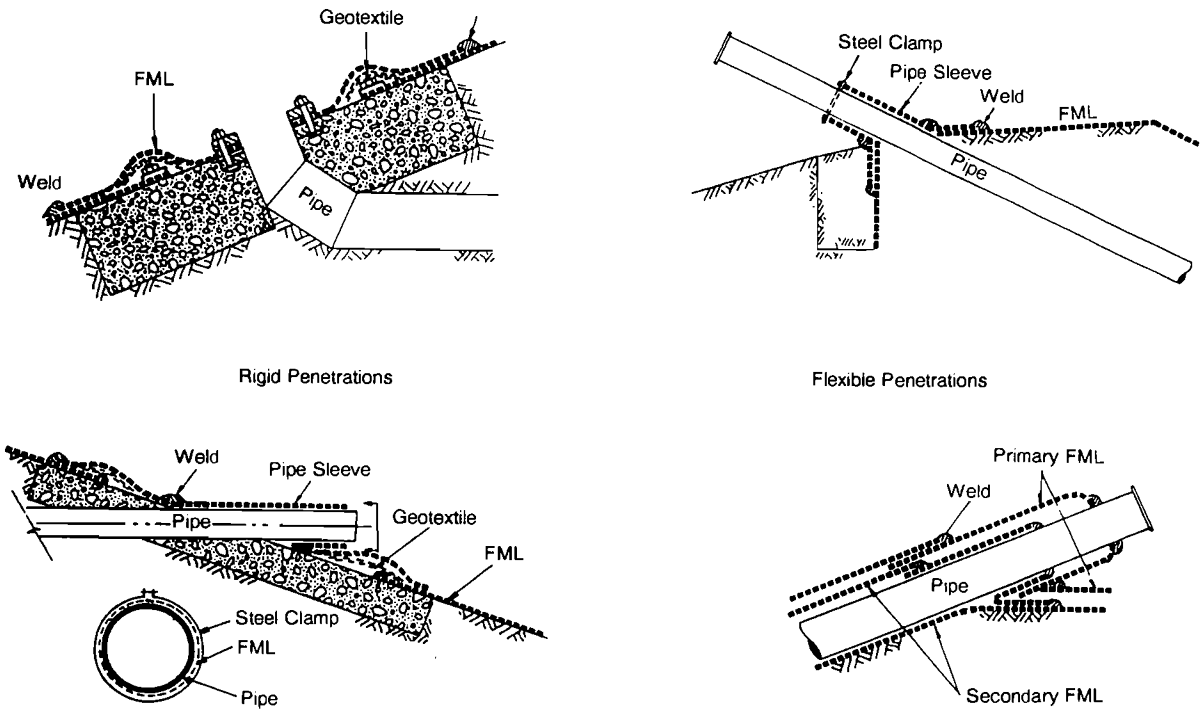

Figure 4 Details of rigid and flexible penetrations.

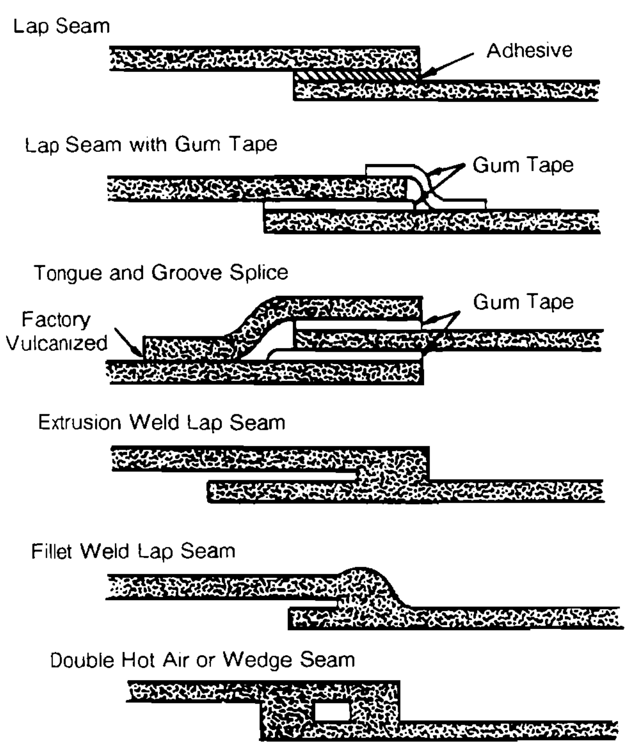

Figure 5 Configurations of field geomembrane seams.

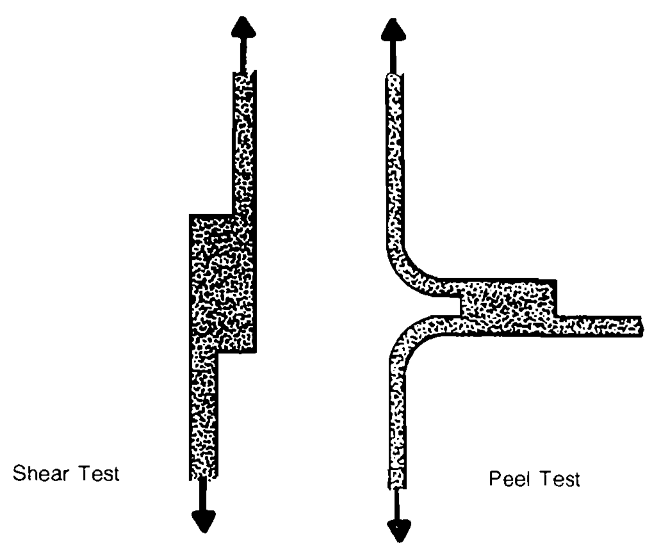

Figure 6 Seam strength tests.

Table 1 Basic Composition of Polymeric Geomembrane

Component	Composition of Compound Type (parts by weight)		
	Crosslinked	Thermoplastic	Semicrystalline
Polymer or alloy	100	100	100
Oil or plasticizer	5-40	5-55	0-10
Fillers:	5-40	5-40	2-5
Carbon Black	5-40	5-40	--
Inorganics			
Antidegradants	1-2	1-2	1
Crosslinking system:			
Inorganic system	5-9	--	--
Sulfur system	5-9	--	--

Source: Haxo, H. E. 1986. Quality Assurance of Geomembranes Used as Linings for Hazardous Waste Containment. In: Geotextiles and Geomembranes, Vol. 3, No. 4. London, England.

Table 3 Typical Mechanical Properties

	HDPE	CPE	PVC
Density, gm/cm^3	>.935	1.3 - 1.37	1.24 - 1.3
Thermal coefficient of expansion	12.5 x 10^{-5}	4 x 10^{-5}	3 x 10^{-5}
Tensile strength, psi	4800	1800	2200
Puncture, lb/mil	2.8	1.2	2.2

Table 4 Overview of Nondestructive Geomembrane Seam Tests

Nondestructive Test Method	Primary User			General Comments					
	Contractor	Design Engr. Insp.	Third Party Inspector	Cost of Equipment ($)	Speed of Tests	Cost of Tests	Type of Result	Recording Method	Operator Dependency
1. Air lance	Yes	--	--	200	Fast	Nil	Yes-No	Manual	V. high
2. Mechanical point (pick) stress	Yes	--	--	Nil	Fast	Nil	Yes-No	Manual	V. high
3. Vacuum chamber (negative pressure)	Yes	Yes	--	1000	Slow	V. high	Yes-No	Manual	High
4. Dual seam (positive pressure)	Yes	Yes	--	200	Fast	Mod.	Yes-No	Manual	Low
5. Ultrasonic pulse echo	--	Yes	Yes	5000	Mod.	High	Yes-No	Automatic	Moderate
6. Ultrasonic impedance	--	Yes	Yes	7000	Mod.	High	Qualitative	Automatic	Unknown
7. Ultrasonic shadow	--	Yes	Yes	5000	Mod.	High	Qualitative	Automatic	Low

Source: Koerner, R. M. and G. N. Richardson. 1987. Design of geosynthetic systems for waste disposal. ASCE-GT Specialty Conference, Geotechnical Practices for Waste Disposal, Ann Arbor, Michigan.

Table 2 Test Methods for Polymeric Geomembranes

Property	Membrane Liner Without Fabric Reinforcement: Thermoplastic	Membrane Liner Without Fabric Reinforcement: Crosslinked	Membrane Liner Without Fabric Reinforcement: Semicrystalline	Fabric Reinforced
Analytical Properties				
Volatiles	MTM-1[a]	MTM-1[a]	MTM-1[a]	MTM-1[a] (on selvage and reinforced sheeting)
Extractables	MTM-2[a]	MTM-2[a]	MTM-2[a]	MTM-2[a] (on selvage and reinforced sheeting)
Ash	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34 (on selvage)
Specific gravity	ASTM D792, Method A	ASTM D297, Section 15	ASTM D792, Method A	ASTM D792, Method A (on selvage)
Thermal analysis:				
Differential scanning calorimetry (DSC)	NA	NA	Yes	NA
Thermogravimetry (TGA)	Yes	Yes	Yes	Yes
Physical Properties				
Thickness - total	ASTM D638	ASTM D412	ASTM D638	ASTM D751, Section 6
Coating over fabric	NA	NA	NA	Optical method
Tensile properties	ASTM D882, ASTM D638	ASTM D412	ASTM D638 (modified)	ASTM D751, Method A and B (ASTM D638 on selvage)
Tear resistance	ASTM D1004 (modified)	ASTM D624	ASTM D1004 Die C	ASTM D751, Tongue method (modified)
Modulus of elasticity	NA	NA	ASTM D882, Method A	NA
Hardness	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D	ASTM D2240 Duro A or D	ASTM D2240 Duro A or 0 (selvage only)
Puncture resistance	FTMS 101B, Method 2065	FTMS 101B, Method 2065	FTMS 101B, Method 2065	FTMS 101B, Methods 2031 and 2065
Hydrostatic resistance	NA	NA	ASTM D751, Method A	ASTM D751, Method A
Seam strength:				
In shear	ASTM D882, Method A (modified)	ASTM D882, Method A (modified)	ASTM D882, Method A (modified)	ASTM D751, Method A (modified)
In peel	ASTM D413, Mach Method Type 1 (modified)	ASTM D413, Mach Method Type 1 (modified)	ASTM D413, Mach Method Type 1 (modified)	ASTM D413, Mach Method Type 1 (modified)
Ply adhesion	NA	NA	NA	ASTM D413, Mach Method Type 1 ASTM D751, Sections 39-42
Environmental and Aging Effects				
Ozone cracking	ASTM D1149	ASTM D1149	NA	ASTM D1149
Environmental stress cracking	NA	NA	ASTM D1693	NA
Low temperature testing	ASTM D1790	ASTM D746	ASTM D1790 ASTM D746	ASTM D2136
Tensile properties at elevated temperature	ASTM D638 (modified)	ASTM D412 (modified)	ASTM D638 (modified)	ASTM D751 Method B (modified)
Dimensional stability	ASTM D1204	ASTM D1204	ASTM D1204	ASTM D1204