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Geomembranes in the United States: A brief discussion

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Introduction

Landfill liner systems, in the United States (US), have evolved significantly over the last fifteen years. As technology has improved and environmental consciousness has increased, landfill liner systems have dramatically improved. While early liners consisted of little more than compacted local soil, some of today's liners consist of double lined, double composite geosynthetic systems. These systems include numerous barrier layers, leachate collection layers, monitoring wells, gas management systems and other protective measures.

The United States Environmental Protection Agency (USEPA) and state regulatory agencies are forcing stricter regulations. These regulations include specific requirements for municipal waste landfills and even stricter requirements for hazardous waste landfills.

Design engineers must prepare specifications which provide maximum environmental protection, meet state and federal requirements and adhere to the cost constraints imposed by the economic restrictions of the individual states.

Environmental companies in the US have extensive experience in the design and use of flexible geomembranes to economically and effectively contain leachate in landfills and landfill covers. The quality of geomembranes has progressed significantly in the past several years.

This paper will discuss the evolution of the landfill liner systems in the US and several case histories are reviewed to illustrate current applications.

History

There is no record of who first used a synthetic material in a lining application, but Staff [1] reported that polyvinyl chloride (PVC) sheeting became available in the early 1930s and began to be used in the late 1930s and early 1940s to line swimming pools. It was acknowledged that types of rubber sheeting may have been used earlier. He (Staff) also states that Union Carbide became interested in the potential use of PVC and polyethylene film in agricultural applications. Further research into the use of polymeric materials as canal reservoir liners was conducted at Utah State University by Dr. C. W. Lauritzen in conjunction with the US Department of Agriculture. As canal and reservoir research increased, the US Bureau of reclamation became involved, and today continues to conduct extensive field research into these areas of application.

While it was important to the development of the geosynthetic industry that liners were studied for appropriateness of use in canals and reservoirs, by far the largest push for the field has come from waste containment. Regulations to encourage the use of geosynthetics in waste containment began in 1965 when the United States Congress passed the Solid Waste Disposal Act. This was the first federal statute to require safeguards and to encourage the use of environmentally sound methods to dispose of waste. This law was amended in 1970 and in 1976 by passage of the Resource Conservation and Recovery Act (RCRA).

In 1982, the USEPA decided that it was more important to focus on the prevention of leachate migration rather than minimization. Research had shown that compacted clay liners could be affected by organic solvents, and this could result in piping through the liner. In order to accomplish this, the regulations were revised to state that prevention of leachate migration through the use of geomembranes produces better environmental results in the case of landfills used to dispose of hazardous wastes [2].

As a result of the need to differentiate the regulations in terms of the potential environmental impact of the waste being contained, regulations focused on hazardous and non-hazardous waste were developed. The hazardous waste containment requirements are contained in US federal regulation 40 CFR 264.221, Subtitle C, 1986. This regulation states that hazardous waste landfills, surface impoundments, and waste piles must have two or more liners and a leachate collection system between such liners. The liners and leachate collection system must protect human health and the environment. The regulation also states that the leachate collection system should be such that the head of leachate will not exceed 30 cm. The entire system must be chemically resistant to the waste to be contained, strong enough to withstand the loading expected in the facility, and resistant to clogging [3].

The non-hazardous waste is covered under US federal regulation 40 CFR Parts 257 and 258, Subtitle D for solid waste disposal. The focus of this regulation is municipal solid waste, but other non-hazardous industrial waste may be covered. For the containment of the non-hazardous waste, the lining system requirements differ slightly. The leachate collection system has basically the same guidelines as for hazardous waste. It should be able to maintain a head in the facility of no more than 30 cm, be resistant to the chemicals involved, and be resistant to clogging. The liner system is only required to be a single composite system. A double liner with leak detection capabilities is not considered necessary in this case. The single composite liner is to be a geomembrane over a compacted clay liner, and the geomembrane must be in direct and uniform contact with the underlying clay layer [3].

While the regulations briefly discussed above are a tremendous improvement in the approach taken to contain waste of all types, it should be noted that they are minimum technology guidelines. The individual States are allowed to write their own rules that exceed the federal regulations as they see fit, and some (such as New York) have done so. It is the above, briefly discussed regulations that have been the cause of the growth in the geosynthetic industry in the past decade, particularly for geomembranes.

Types of Geomembrane in Use

In addition to the polyvinyl chloride liners mentioned earlier there were liners made from butyl rubber, a thermoset polymer. Today, the majority of geomembranes are made from thermoplastic polymers that include the following;

- High-Density Polyethylene (HDPE),
- Linear Low-Density Polyethylene (LLDPE),
- Polypropylene (PP),
- Polyvinyl Chloride (PVC), and
- Chlorosulfonated Polyethylene (CSPE).

This list is not meant to be all-inclusive, but to represent some of the more popular polymers in use today.

The HDPE and LLDPE geomembranes in use are based on the ethylene monomer and may include a comonomer. The resin for these materials is combined with a stabilizer package that typically includes carbon black and other antioxidants. These stabilizers provide protection during processing and from the effects of aging in the field. The resin package is then formed into a sheet through the extrusion process. This can take one of two forms. Either the polymer is extruded through a flat die, or through a circular die.

If the flat die is used, the solid material is introduced into the machine where heat and pressure are applied as a screw forces the polymer down the length of the barrel. The molten polymer enters a die at the opposite end, and exits as a flat sheet onto a stack of chill and finishing rollers. From there, the sheet proceeds to the wind-up section where it is wound on a core into continuous rolls. National Seal Company currently has the widest flat sheet extrusion process in the world for polyethylene geomembranes at a width of 9.3 m.

If a circular die is used, the process is nearly identical until the end step. The polymer enters the circular die through the center via a number of radial feed ports. These ports feed a circular chamber which forms a tube of molten polymer. The tube exits the die as a ring assisted by a set of rolls, and is then inflated to a pressure that will fix the circumference. The exit direction of the tube is usually upward in a tower. At the top, the tube is slit and opened into a flat sheet that is then wound onto a roll [4].

Polypropylene geomembrane resin is produced by a process that incorporates an amorphous, rubber comonomer. It is the addition of this material to the polypropylene that gives the final geomembrane its flexibility. The resin is compounded with additives meant to provide protection to the rigors of processing, and to prevent deterioration in the field, just as is found in the polyethylene geomembranes [5]. Polypropylene geomembranes can be manufactured by using the blown film method outlined above.

Chlorosulfonated polyethylene is also known by the trade name of Hypalon®, and is similar in chemical structure to polyethylene. In addition to the base polymer, this formulation can contain fillers, antidegradants, process aids, and metal oxides. It is reported that the total polymer content of this compound will be on the order of 30% to 40% by weight. These fillers can include carbon black, titanium dioxide, clay, and calcium carbonate as well as other antioxidant stabilizers. An interesting additive to this product is a metal oxide, often magnesium oxide, that participates in a curing reaction. The curing reaction has the effect of rendering the geomembrane into something like a thermoset polymer over time. The production of the CSPE geomembrane is typically done on a calendering line. In this process, the molten polymer is dropped into a nip opening between rollers. As the melt is pulled through this opening by the rollers, it is shaped into the desired sheet dimensions. Finishing is provided by other rollers further down the roll stack. All CSPE geomembranes are scrim reinforced that include top and bottom layers of the CSPE material encasing the reinforcing scrim. The number of plies can be from three to five, and the most commonly used scrim is a 10 count by 10 count by 1000 denier polyester fiber. The purpose of the scrim is to provide dimensional stability necessary for the handling present in the manufacturing process as well as the installation [6].

PVC geomembranes are also manufactured using a calendering process. The resin is polymerized from the vinyl chloride monomer, and the final product also contains a large amount of fillers and plasticizers that give the geomembrane its final properties. These other ingredients can amount to as much as 40% of the resin by weight [7].

Slope stability is a design concern for many applications, particularly in the many areas of the US that have the potential for seismic activity. Past failures have illustrated the limits of using a smooth HDPE geomembrane with a relatively low coefficient of friction on side slopes. It is also an economic concern in landfill applications, since there is a great deal to be gained in the way of airspace if steeper sideslopes can be used. In response to this the polyethylene geomembrane manufacturers have developed a number of ways to modify the material so that the interface coefficient of friction is increased.

The current techniques all involve manufacturing a textured surface of some type onto the geomembrane. These methods include blown coextrusion, embossing, extrusion coating, and sprayed coatings [8]. In blown coextrusion, a blowing agent and a nucleating agent are combined with the outer layers of a three layer coextruded polymer on a blown film manufacturing line. As the polymer progresses to the opening of the die, the pressure decrease allows the gas to migrate to the surface and form a foam. Shearing forces then break the bubbles in the foam which forms the textured surface on the geomembrane. The spray coating process is secondary in nature in that it is done after the manufacture of the geomembrane. In this method, the molten polymer is pumped to a high pressure and then droplets are sprayed onto the geomembrane as it passes beneath the spray nozzles. The embossing technique is accomplished with engraved rollers in the first and second nips of a flat sheet extrusion line. This technique allows the pattern to dictate the level of interface friction desired for each side of a geomembrane. Different patterns can be applied to the top and bottom of the sheet. The extrusion coating method is another secondary process applied to already manufactured geomembrane. A flat sheet die is used to extrude a foamed coating onto the surface of the geomembrane as it passes underneath. As in the blown coextrusion process, the shearing action of the flow through the die and the movement of the sheet beneath the foam break the bubbles to produce the desired textured coating on the surface of the geomembrane. The texturing can make a dramatic difference in the interface friction properties as measured in a direct shear device. For example, in direct shear interface tests conducted at National Seal Company [9] under relatively low normal stresses (20 Kpa to 62 Kpa) a peak angle of 9° was found for a smooth HDPE vs. a nonwoven needle-punched geotextile under dry conditions. A test under the same conditions with a textured HDPE geomembrane vs. a nonwoven needle-punched geotextile generated a peak friction angle of 35°. The texturing in this case was applied with the extrusion coating method.

Another concern with applications involving geomembranes is their seams. The main idea in seaming a polymeric geomembrane is to use either a chemical or heat energy to soften the material so that the two pieces can bond into essentially one piece. Techniques involving the use of chemicals include solvent seams, bodied solvent seams, solvent adhesive seams, and contact adhesive seams [3]. Solvent seams utilize a liquid placed between the two geomembrane sheets that softens their surface. After this softening, the pieces are pressed together to bond the sheets. This technique can only be used for geomembranes that can be dissolved by the applied solvent. A bodied solvent seam is similar to the solvent seam except that some portion of the same type of resin as used in the geomembrane is dissolved in the solvent first. The addition of the resin is meant to increase the viscosity of the solvent, usually for slope work. Pressure is then applied to complete the bond. For solvent and contact adhesives, a separate compound forms the bond and becomes an additional part of the seam.

Techniques involving the transfer of heat energy include extrusion welding and thermal fusion welding [3]. In extrusion welding (typically found with HDPE applications), a fillet of molten polymer is extruded over the area to be bonded together. The heat from this fillet melts a portion of the underlying geomembrane and the entire mass becomes bonded as it cools. This method is usually used in detail work such as polyethylene patches, around pipes, sump bottoms, or very short seam lengths. Extrusion flat seaming can also be conducted where the molten bead is placed between two sheets to be bonded.

The thermal fusion methods involve melting portions of the two sheets to be bonded and then using pressure to fix them together where they cool into a single unit. One method involves passing the sheets of geomembrane over an electrically heated wedge. The surfaces of the geomembrane melt as they pass over the wedge and are pressed together using pressure wheels. The wedge may be constructed to form either a single bonded area, or two bonded areas side by side that have an air channel between them. The devices that do this are self propelled and have the ability to control wedge temperature, bonding wheel pressure, and speed of travel. Extensive research has been conducted by geomembrane manufacturers into the variables that control this process, and the reader is directed to the literature for further detail [10] [11]. In a similar manner, hot air can also be used to transfer heat to the geomembrane to be seamed prior to applying the pressure to fix the bond.

One of the issues concerning seams in the US is their quality. In an ideal case, one might expect that the seam of a geomembrane should have the same mechanical properties (specifically tensile) as the parent material from which it was made. However, due to factors such as seam geometry and stress concentrations this is not the case. At this point, the strength of the seam must be defined in some manner. Nondestructive and destructive methods are employed to determine the integrity of a seam. Among the nondestructive methods are creating a vacuum over a portion of the seam and monitoring for air leaks (used with extrusion and single track fusion welds), air lance testing in which the air channel of a double track fusion weld is pressurized and monitored for pressure loss, and a variety of electrical techniques [3]. An advantage of the air lance and electrical techniques is the ability to evaluate large sections of seam quickly. The destructive testing techniques involve cutting samples and testing the seam for peel and shear strength in a tension testing device. It is desirable to do this as little as possible to minimize the amount of patching needed. The USEPA has offered guidance in the area of defining the seam strength for polymeric geomembranes [12]. The suggestions are based on an efficiency value defined as the strength parameter of the seam (peel or shear) divided by the tensile strength of the unseamed sheet. The suggestions for the seam shear strength of geomembranes are 95% of the minimum yield strength for HDPE, and 80% of the tensile strength for PVC and CSPE (3-ply reinforced). The suggestions for the peel strength of seamed geomembranes are 62% of the minimum tensile yield strength for HDPE, and 1.75 kN/m for PVC and CSPE (3-ply reinforced). The peel test is the more rigorous of the two and is often the focus of specifications concerning seam integrity. Similar recommendations have yet to be defined for LLDPE and PP geomembranes.

Applications and Case Study Survey of Geomembrane Usage in the US

The main purpose of polymeric geomembranes is that of separation, or in other words, to form a barrier that prevents the transport of liquids. The specifics of the materials to use and the necessary properties of those geomembranes depends upon the application at hand. Those applications can include, but are not limited to, the following;

- Canal liners for water conveyance,
- Pond liners for aquaculture or water storage (potable, agricultural, and stormwater runoff),
- Industrial waste/raw material pond liners,
- Secondary containment of storage tanks,
- Barrier walls,
- Landfill closures (caps), liners, and "piggyback" expansions
- Heap leach mining pads,
- Waterproofing tunnels,
- Floating pond covers,

and on and on. New applications are continually being developed, and more complete lists can be found in the literature [3]. The relative impermeability of these materials makes their use attractive anywhere a liquid or vapor needs to be conveyed or contained. One example of this is the case where geomembranes compete with compacted clay liners for containment of waste. A compacted clay liner typically has a targeted hydraulic conductivity (permeability) of 10^{-9} m/s. The equivalent diffusion permeability of a typical thermoplastic geomembrane is in the range of 10^{-13} to 10^{-15} m/s.

The brief list of possible applications above also serves to make one aware that every application is probably not best served by any single geomembrane. Each have their advantages and disadvantages in any given situation. Where the geomembrane is expected to contain a leachate or other waste, the material must be chemically resistant. In this regard overall resistance can be related to the density of the geomembrane, and HDPE with its semicrystalline structure and relatively high density compared to other materials is generally considered the most resistant available. What follows are examples of recent successful applications with geomembranes in the US that have been reported in the literature.

Landfills

Feeney and Maxson [13] reported on the field performance of double-liner systems in landfills. They presented field data on leachate flows for 49 landfill units (that included 8 damaged units) at 8 different facilities. The units were not all monitored for the same length of time. The shortest monitoring period was four months and the longest monitoring period was 60 months. The landfill units were constructed to exceed the USEPA minimum technology guidance requirements. All of the liner systems consisted of at least two 1.5 mm HDPE geomembranes, and all but two of the landfill units had a composite geomembrane/compacted clay liner on the landfill base. The systems were described as the waste being underlain by a primary leachate collection and removal system, then a geomembrane/compacted clay composite liner, then a secondary leachate collection and removal system, and finally another geomembrane/compacted clay liner. The compacted clay was nominally 0.46 m thick, and was compacted to achieve a hydraulic conductivity that does not exceed 1×10^{-9} m/sec. The other two units had a primary liner underlain by a geosynthetic clay liner. The height of the waste in the landfill units ranged from 15 meters to 45 meters.

After examining the flow data, the authors concluded that all of the units were functioning as designed. Even those designated as having been damaged were performing as expected after repairs had been made. It is important to note that the "damage" in those units was as a result of placement of the waste by heavy equipment and not any part of the installation of the liner system. The data presented indicated that liquids and flow will be present in the secondary collection systems of well designed, constructed, and operated landfills. The average weekly flow rates in the secondary collections systems monitored were less than 0.56 m^3/ha/d. It was estimated in the paper that approximately 98% of all the liquid removed from the monitored landfill units came from the primary leachate collection layer. The authors could not correlate the flow in the secondary collection systems of intact units with the flow in the primary collection systems. They concluded that this indicated the integrity of the primary system. The data indicated that the consolidation of the clay component of the primary liner system can contribute significant quantities of liquid to the flow measured in the secondary collection system. The authors state that during the early stages of landfill operation, the contribution of liquid due to consolidation may even dominate the observed flow rate. The authors finish by stating that the results presented are consistent with previously reported field data, but are a little higher than theoretical calculation might predict. No reason for the difference was known when the paper was published.

Another paper discusses the use of geomembranes in creating a vertical expansion in an existing landfill [14]. An existing landfill in the State of Massachusetts was to have a liner system including geomembrane, leachate collection system, and gas collection system over 25 m of municipal solid waste. The existing waste was relatively compressible which caused concern over the expected magnitude of future settlements. The site had started as a municipal dump in 1954, was named a sanitary landfill in the late 1960s, and filling ceased in the early 1980s. The total expansion was to be 8 hectares in area and contain lime stabilized sludge. In order to answer concerns about slope stability and differential settlement, a textured LLDPE geomembrane was selected for the liner in this project.

Canal Liners

The US Bureau of Reclamation has published several research papers and case studies in this area of application. One paper describes the development of concrete covers over geomembranes in canal liner applications [15]. The purposes of a concrete cover include providing a rigid surface for maintenance equipment, and protecting the geomembrane from UV degradation, vandalism, and animal damage. Several conclusions were drawn in this paper. First, the adhesion between the concrete and the geosynthetic is critical until the concrete develops enough strength to hold itself in place. Second, moisture has an adverse affect on the adhesion. Third, adhesion can be improved by the use of either a textured geomembrane, or the use of a geotextile bonded to the geomembrane in some manner.

Another paper reviews the Bureau's recent experiences with canal remediation using geomembranes [16]. Projects in several states were involved that included a buried PP geomembrane, an exposed HDPE geomembrane, and an exposed very low density polyethylene (VLDPE) geomembrane. It should be noted that the VLDPE geomembrane is not available at the present time in the United States. The authors report that after 3 years of service, the PP geomembrane still has adequate properties for the application. The geomembranes were placed in exposed applications as a result of concerns about the economics of finding and placing a soil cover, and concerns over slope stability of such a cover due to the need for steeper sideslopes in some areas. One of the exposed sites used an HDPE geomembrane that was covered with soil on the bottom and left exposed along the sides. After 12 years of exposure, the geomembrane still appears to be in satisfactory condition. This is also evidenced by evaluations of coupons removed from the test section. The only problem that has occurred in this application is a number of small punctures that are consistent with local deer crossing the canal. This animal damage is being repaired as necessary. A third site reported on utilized a VLDPE geomembrane. This site was covered on the bottom with the side slopes exposed. Again, there has been no degradation of the geomembrane to report after 4 years of operation other than animal damage like that seen with the previously mentioned HDPE liner. One interesting note on this project involved an occurrence of one winter. Water was left in the canal during the first part of the winter of 1994. The estimated depth of the ice cap that formed in this period was 0.3 m. An examination showed that the ice did not cause damage to the geomembrane, but the ice did do extensive damage to the access ladders that were attached to the side slopes of the canal.

Floating Covers

A successful floating cover with a CSPE geomembrane on a water reservoir in the state of Oregon was inspected after 16 years of use [17]. Samples were taken from four areas of the cover and evaluated by an independent laboratory and the original manufacturer. The tests involved tensile strength, seam strength, tear strength, puncture resistance, hardness and visual evaluation. According to the author, the results of the tests and a physical inspection of the cover give every indication that the cover will meet and probably exceed its 20 year design life.

Another case study describes the use of a coextruded geomembrane as a floating cover for a brine solution storage pond near Detroit, Michigan [18]. Two 2.4 ha ponds were being used to store a brine solution. The solution was being used in the creation of caverns in underground salt formations that were in turn being used to store liquified petroleum gas. It was found that the solution was being diluted during above ground storage by precipitation and the cost of adding salt was becoming detrimental to the operation. The coextruded material was deemed the optimum solution after performance criteria review. The performance criteria included such things as the need for the cover to be installed while the ponds were full, ability of the cover to withstand pond fluctuations of up to 1.5 m, ability of cover to sit on the bottom should the ponds empty, ability to inflate the covers should the liner need repairs, and the material needed to be resistant to UV exposure and exposure to the brine. The ceoextruded material selected for the project consisted of a layer of very low density polyethylene and a layer of high density polyethylene. The combination provided the flexibility needed for the project and the UV resistance of HDPE. The density of the material allowed the installation of the cover by floating the fusion welded geomembrane panels across the ponds. The installation was a success with little, if any, disruption of the customer's business. It is important to note that with the loss of very low density polyethylene from the market, polypropylene geomembranes also nicely fill this application niche.

Future ?

The application examples described above represent only the briefest examination in terms of geomembrane usage in the United States, and the market and range of applications is expected to grow. There is also a vast body of knowledge regarding the physical and chemical properties of concern with geomembranes, parts of which were only briefly examined here. There is simply too much for one paper to cover adequately, and this knowledge is also expected to grow. One other thing is certain about the future of this market. National Seal Company will be there to help it along with innovative research, manufacturing ability, and installation expertise.

Acknowledgments

This paper would not be possible without the work of others. They are listed in the reference section and their work also contains numerous other important references to which the reader can turn for valuable information.

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