Protecting the Environment with Geosynthetics

R. K. Rowe
GeoEngineering Centre at Queen's-RMC, Department of Civil Engineering, Queen's University, Kingston, Canada

ABSTRACT: The use of geosynthetics in both covers and bottom liners for protecting the environment from contamination in applications such as lagoons, landfills, and heap leach pads is discussed. Particular emphasis is placed on the use of geomembranes and geosynthetic clay liners. There are many examples of excellent performance but there are also potential problems unless care is taken in design and construction. The importance of selection of appropriate geosynthetics for a given application is highlighted together with a number of construction related issues that must be considered to ensure long-term performance.

1 INTRODUCTION

Thirty seven years ago (in 1978), US President Carter's declaration of a State-of-Emergency at Love Canal in Niagara Falls, New York highlighted the potential impacts of unsafe disposal of hazardous waste. The local school was closed and eventually over 700 families were relocated (Phillips et al. 2007). A health study of former residents of the area between 1996 and 2004 reported that "rates of congenital malformations were twice that expected compared to the external standard populations, a difference that exceeded the range of rates expected by chance alone. In addition, the internal comparisons revealed that malformations were positively associated with potential exposure as a child." (New York State Department of Health 2008). This problem was a legacy of the disposal of approximately 21,000 tonnes of chemical wastes between 1942 and 1953 followed by the construction shortly thereafter of a school and homes adjacent to the old unlined dump (for a more complete summary see Rowe 2012a). The enactment of the U.S. Resource Conservation and Recovery Act (RCRA) in 1976, represented a significant step forward in governing the disposal of solid waste and hazardous waste. This progress included the banning of the disposal of liquid hazardous waste, and the development of modern landfill technology in the US. However, for many years after 1980, and indeed in some countries today, waste management has not advanced far beyond the bad practices common in the US prior to the late 1970s.

Thirty years after President Carter's State-of-Emergency at Love Canal, the headline in Australia's Melbourne Age newspaper read: "Gas threat forces residents to flee", and the article stated, amongst other things, that: "more than 200 Cranbourne residents were last night told to evacuate their homes because of dangerous levels of methane gas. The residents of Brookland Greens Estate were told by the State Government's Emergency Response Team that there was an unacceptable risk to their safety if they remained in their homes. It is estimated about 400 houses in 20 streets are affected by the gas, which comes from a nearby tip. The meeting was called by Casey Council after methane gas readings of up to 60% were detected in the walls of some homes in the area. A pamphlet distributed to residents earlier said methane gas could explode at levels between 5% and 15%." (Lowe 2008). This dump accepted waste between 1996 and 2005. As with most environmental "problems" there are a number of factors that ultimately resulted in people's lives being impacted (see Rowe 2012a for a more detailed discussion of the many factors), however it is likely that these problems would not have arisen if current regulations had been in force, and been implemented, at the time of waste being placed.

The good news is that many modern landfills constructed over the past 30 years are performing extremely well. Many factors contribute to the good environmental protection offered by these landfills, but one key factor is the presence of a modern barrier system which includes an effective leachate and gas collection system as well as a suitable liner system. Frequently these liner systems include geomembranes and geosynthetic clay liners (GCLs) as discussed herein.

The use of geomembranes and GCLs in landfill applications is supported by more than 20 years of intensive research. More recently, geosynthetics (especially geomembranes) have seen a massive increase in use in the mining industry. While there are many similarities between landfill and mining applications, there are also many differences. These differences particularly relate to differences in the chemistry of the fluid to be retained and to the magnitude of the stresses imposed on the liner.

There have been a very large number of successful applications of geosynthetics; they work extremely well!!! BUT they are engineered materials and need to be treated with the same respect as other engineered materials. Geosynthetics manufacturers provide many options. Different products are intended for different applications but it is the engineer's responsibility to select the appropriate materials for their application. Sadly, far too often engineers, not understanding what they really need, specify the wrong product (often specifying the cheapest) but some reputable suppliers may decide it is in their best interests to avoid failures and hence to supply (at their cost, but without telling the engineer) what was needed, not what you specified, thereby leading to a successful project. However, it is a rather foolish engineer who relies on a supplier to correct their mistakes; the supplier/manufacturer is under no obligation to do so. The manufacturer's obligation is simply to provide what is specified! If an engineer specifies the wrong material they must accept that they might actually get exactly what was specified (and paid for). As long as the product received met the specifications (even if it is the wrong product for this particular application) do not blame the manufacturer; they are not the engineer of record. Good engineering can be relied on; luck is fickle. Poor design can lead to failures. However, it is not sufficient to have a good design and specifications, one must also ensure that the correct materials are delivered, correctly installed, and that the facility is appropriately commissioned. Poor construction combined with poor construction quality assurance can also lead to failures. Remember the adage: "you get what you inspect, not what you expect"!

The objective of this paper is to emphasize that there are a great many examples of excellent performance but also to acknowledge that there are also potential problems, many of which can be resolved by paying attention to recent research. The paper will discuss some of the issues that require careful consideration in design and construction to ensure good long-term performance.

2 GEOSYNTHETICS CONSIDERED

2.1 *Geomembranes*

A geomembrane is defined as a planar, relatively impermeable, polymeric sheet used in civil engineering applications (IGS 2009). There are many types of geomembranes but those most commonly encountered by geoenvironmental engineers are those referred to as high density polyethylene (HDPE), linear low density polyethylene (LLDPE) and polyvinyl chloride (PVC). HDPE is most commonly used in bottom liners in environmental applications because of its (generally) better chemical resistance. LLDPE and PVC tend to be more flexible than HDPE and hence are sometimes preferred for applications when this flexibility is more important than chemical resistance (e.g., in some cover applications).

The reference above to three types of geomembrane commonly used in geoenvironmental applications (with HDPE and LLDPE being the most common in landfill and mining applications) does not adequately reflect the wide variety of materials that can be purchased under any of these general categories. Typically more than 96% of a polyethylene (PE) geomembrane is base resin, 0.5-1% additives (e.g., antioxidants, ultraviolet light stabilizers) and 2-3% carbon black (resistance to ultraviolet light). PVC geomembranes typically have 30-40% PVC resin content (although higher in some cases), 25-30% plasticizers (to make it flexible), 20-30% fillers, 5-10% carbon black or pigment, and 2-5% additives (Koerner 2012; Table 1.6); this provides very considerable scope for variability from one manufacturer to another and even with products from a given manufacturer.

There are also a number of other geomembranes that find use in niche markets but are not widely used in geoenvironmental applications. For example, bituminous geomembranes (an asphalt coating on a polyester geotextile) have been successfully used for potable water (e.g., canal liner) applications for more than 20 years. However, some of the consultants who have used them on mining projects will talk about problems arising from excessive softening (some call it melting) of the bitumen coating (e.g., in areas with hot sunny summers). Others report problems getting good sealing of panels and at penetrations (e.g., in areas with cold winters). Unfortunately these consultants with anecdotal reports of problems with bituminous geomembranes have been too busy to document them in the public literature and so the circumstances behind the problems are unknown. Nevertheless, this serves to highlight the paucity of quality independent/objective research reported in the archival literature examining their long-term suitability for geoenvironmental applications. In the writer's opinion, it would be a very brave engineer who recommends them for geoenvironmental applications in the absence of appropriate independent/objective research to support their use. This is in stark contrast to the large body of archival research data on HDPE and, to a lesser extent, LLDPE geomembranes.

Koerner (2012) indicates that PE geomembranes represent about 80% of geomembranes placed and hence the rest of this paper will focus on PE geomembranes. However, even for PE there are a wide range of potential different geomembranes available as discussed below.

PE geomembranes have a base resin with densities ranging from 0.88 to 0.96 g/cm^3 (Scheirs 2009). The difference in resin density is related to the side chains that control the PE chain packing. The HDPE geomembranes used before the mid 1990's usually comprised true HDPE resins with a linear polymer backbone containing few, if any, short branches. They were highly crystalline with a resin density greater than 0.941 g/cm^3 and excellent chemical resistance compared to other polymers. Unfortunately, it also emerged that they also exhibited poor resistance to slow crack growth (Knuuttila et al. 2004; Hsuan 2013). Manufacturers responded by using a medium density PE resin (MDPE) produced using a co-monomer to form short branches and hence reduce the polymer density (Hsuan 2013) but improve the resistance to slow crack growth (Scheirs 2000; Knuuttila et al. 2004). Thus, most of today's so called "HDPE" geomembranes (referred to simply as HDPE in the rest of this paper) actually comprise 96-97.5% MDPE resin (with a resin density usually in the range of 0.932 to 0.940 g/cm^3), about 0.5% antioxidants/stabilizers, and 2-3% carbon black (Hsuan and Koerner 1998). The addition of carbon black raises the total geomembrane density to within the range defined for HDPE by ASTM D 883 (i.e., > 0.941 g/cm^3).

LLDPE resin has a density of between 0.919 to 0.925 g/cm^3. LLDPE geomembranes typically comprise 94-96% LLDPE resin, 2-3% carbon black, and 0.25-3% antioxidants/stabilizers.

There are also co-extruded geomembranes with: (i) white and/or conductive coatings, (ii) with thin "HDPE" outer layers and an LLDPE core (to try and take advantage of the strengths of both materials), or (iii) with a LLDPE or HDPE outer layers and a thin ethylene vinyl alcohol (EVOH) core to resist volatile hydrocarbon diffusion.

The long-term performance of a PE geomembrane depends on many factors relating to the geomembrane itself (including the resin, the antioxidants/stabilizers, and the type of carbon black used) as well as external factors that are application specific and discussed later. Even with exactly the same resin, antioxidants/stabilizers, and carbon black, the manufacturing process can have an effect on the initial geomembrane properties which is not generally well recognized (Ewais and Rowe 2014a) but may affect the interpretation of aging of the geomembrane; especially in terms of changes in its stress crack resistance (Ewais and Rowe 2014b; Ewais et al. 2014b; Ewais and Rowe 2014c).

De-facto specifications for HDPE (e.g., GRI-GM13) and LLDPE (e.g., GRI-GM17) set minimum physical, mechanical and chemical properties that must be met, or exceeded, by a PE geomembrane. These specifications are extremely useful in setting a minimum expectation for geomembranes to be used for non-critical applications such as clean water retention at modest temperatures and pressures where the implications of failure are not substantial and the required service life is a few decades or less. However, these defacto specifications were not developed considering the wide range of geoenvironmental applications that may include high pressures (several MPa in some applications), elevated temperatures (especially those greater than 40^{o}C), and aggressive fluids (e.g., high salt concentrations, high or low pH, etc.). This does not mean that geomembranes may not be suitable for these applications but, rather, that special care is needed with the selection of the geomembrane and the associated design. For example, manufacturers responded to the increase in the range of applications by developing specialty geomembranes with different resins and/or antioxidant/stabilizer packages that improve the geomembranes performance in challenging applications.

Most of the research over the past 15 years into the long-term performance of geomembranes has been for HDPE with particular reference to landfill applications. Some recent examples include the effect on the durability of HDPE geomembranes of: geomembrane thickness (Rowe et al. 2010; Rowe et al., 2014a; Rowe and Ewais 2014a), leachate chemical composition (Abdelaal et al. 2014), elevated temperatures (Abdelaal and Rowe 2014a), and geomembrane resin (Ewais et al. 2014b; Abdelaal and Rowe 2015a).

The studies just cited in the paragraph above are all for geomembranes immersed in a fluid of interest. In real applications, the geomembrane will be installed with material above and below it, and contact with the contaminated fluid of interest is usually only from one side (i.e., immersion tests are conservative in this regards) but there may be significant local strains developed in the geomembrane due to the contact materials and applied pressure. These situations can be examined in specially designed geosynthetic liner longevity simulators (GLLS) developed by Brachman et al. (2008). A number of GLLS studies have been conducted that not only provided new insight into the depletion of antioxidants and geomembrane aging in realistic settings, but also highlighted the effect that decisions made by designers regarding the materials near the geomembrane can have on the geomembrane service-life in the field (Rowe et al. 2013, Abdelaal et al., 2014b; Ewais et al. 2014a).

Recently there have been new insights regarding (i) the performance of exposed geomembranes, and (ii) some challenging mining applications. These studies have targeted geomembranes in different climatological conditions (e.g., Rowe and Ewais 2014b) and mining applications for LLDPE geomembranes (e.g., Abdelaal et al. 2012; Abdelaal and Rowe 2014b) and HDPE geomembranes (e.g., Abdelaal et al. 2011; 2015b; Abdelaal and Rowe 2013) in extremely high or low pH solutions.

For the applications considered in this paper the geomembrane is invariably≥ 1 mm -thick and in cases involving a bottom liner it generally will be 1.5-2.5 mm thick. One important characteristic of HDPE and, to a lesser extent, LLDPE geomembranes is that, after being placed, heating by solar radiation can induce wrinkles (Fig. 1) in both black and white geomembranes (although the effect is the most pronounced for black geomembranes). The implications of this will be discussed later.

Fig. 1 HDPE geomembrane with a wrinkle

2.2 *Geosynthetic clay liners (GCLs)*

A GCL is a manufactured product comprised of relatively low permeability clay (usually bentonite) and one or more geosynthetics. They are delivered to site on rolls (Fig. 2) that are laid down with adjacent panels overlapped to provide a continuous layer of GCL.

The GCLs most commonly used in geoenvironmental engineering comprise a lower “carrier” geotextile, a layer of bentonite, and an upper “cover” geotextile that are all held together by needle-punching the upper cover geotextile fibers through the bentonite and into the carrier geotextile. There are a vast number of GCLs meeting this broad description (over 50 from one manufacturer alone). This wide range of different products provides the engineer with GCLs having different characteristics suitable to different design/site conditions.

Fig. 2 GCL being unrolled on site as it is installed

GCLs perform extremely well in many different applications, but there have also been problems when the wrong GCL has been selected for a given application or when the GCL was not installed as per manufacturers’ recommendations. The many factors that can affect the performance of a GCL include (Rowe 2014): (a) the type of bentonite, (b) whether or not there is a polymer in the bentonite, (c) the mass per unit area of bentonite, (d) the type and mass per unit area of the geotextiles used, (e) the amount of needle-punching, (f) whether or not the needle-punched fibers are thermally fused to the carrier geotextile, (g) the presence or absence of a geofilm bonded to the GCL, the nature of the geofilm, and how the geofilm is bonded to the carrier geotextile, (h) the characteristics of the GCL panel overlap, (i) whether or not the GCL is part of a composite liner, (j) the physical and hydraulic characteristic of the interface between the GCL and the adjacent geomembrane or other materials, (k) the presence of wrinkles in the geomembrane, (l) the initial water content and particle size distribution of the soil above and/or below the GCL, (m) geochemical interactions between the bentonite and the pore water in the soil adjacent to the GCL, (n) chemical interaction of the bentonite with the fluid to be retained, (o) the amount of cover soil over the GCL, (p) the level of exposure to thermal cycles, (q) sustained thermal gradients, and (r) the stress on the GCL.

The effect of many of these factors on GCL performance has been discussed by Petrov and Rowe (1997), Lake and Rowe (2000), Rowe and Orsini (2003), Southen and Rowe (2005), Rayhani et al. (2011), Rowe (2014), Brachman et al (2014), Rowe et al. (2014), and Take et al. (2014).

2.3 *Composite liners*

Geomembranes and GCLs may be used alone in some applications but most commonly are used together as a composite liner (Fig. 3). As discussed by Rowe (2012b), a well designed and constructed composite liner can substantially reduce leakage through a composite liner (i.e., with substantially less leakage for a composite liner than for a geomembrane or GCL alone).

Fig. 3 Typical barrier with gravel drainage layer, geotextile protection layer, HDPE geomembrane, and GCL

3 APPLICATIONS

There is a very wide range of geoenvironmental applications for geosynthetic (geomembrane and GCL) liners and the list is growing yearly. Applications include: (a) covers for MSW waste landfills, (b) lagoons for landfill leachate, (c) landfill bottom liners, (d) covers for mine waste, (e) liners for heap leach pads, (f) ponds for mine fluids (e.g., brines), (g) liners for tailings storage facilities, and (h) secondary containment of hydrocarbon spills, amongst many. A number of examples are discussed in the following paragraphs.

There is extensive literature on the use of GCLs in landfill covers where there are low stresses and potential for climatic affects to cause desiccation of the GCL if there is not an adequate design (e.g., Benson et al. 2007, 2010; Meer and Benson 2007; Scalia and Benson 2010; Bradshaw et al. 2013). There are some similar issues for GCLs used in covers for mine waste as illustrated by Hosney and Rowe (2010; 2013; 2014a) who reported on the field performance of GCLs for covering arsenic-contaminated gold mine tailings.

In addition to being used alone, or with a geomembrane as a composite liner, GCLs have also been used as a liner below concrete-lined sewage treatment tanks. Rowe and Hosney (2015) have examined the effect of the hydration of four different types of GCLs with moisture from concrete and the subsequent interaction with synthetic wastewater on the hydraulic conductivity of the GCLs and the concrete/GCLs interface transmissivity after up to 14 months exposure.

GCLs have also been successfully used as part of barrier systems to minimize advective and diffusive transport of hydrocarbon arising as a result of spills (e.g., Rowe et al. 2004, 2005, 2006, 2008; Bathurst et al. 2006; Hosney and Rowe 2011, 2014b; McWatters et al. 2014, 2015; Jones et al. 2015).

4 LEAKAGE

An intact PE geomembrane is essentially impermeable to water. The leakage through a geomembrane will in the first instance depend on the number and size of holes. This, in turn, will depend on the construction quality control and quality assurance that is exercised on a particular project and, in particular, on whether there is a leak detection survey conducted.

For a geomembrane with a highly permeable material above and below (e.g., a single geomembrane pond liner) the leakage through a circular hole is described by Bernoulli's equation (Giroud and Bonaparte 1989a; Rowe 2012b):

$$Q = \pi \ CB\, r_o^2 \sqrt{(2gh)} \quad (1)$$

where Q is the leakage through the hole (m^3/s), CB is a coefficient (-) related to the shape of the edges of the hole with CB = 0.6 for sharp edges, r_o is the radius of the hole (m), g is the acceleration due to gravity (m/s^2), and h is the head loss across the geomembrane liner (m).

When the geomembrane is in contact with an underlying clay liner (i.e., as part of a composite liner) the leakage is very substantially reduced; especially if the geomembrane is in close and intimate contact with the clay liner as shown on design drawings. There are many methods for calculating leakage for this case (e.g. (e.g., Giroud and Bonaparte 1989b; Giroud 1997). However, as discussed in some detail by Rowe (2005; 2012b), in the majority of practical cases, leakage is likely to be controlled by holes coincident with wrinkles that are present in the geomembrane at the time it is covered. In this case the leakage can be calculated using the Rowe (1998) equation which, in its simplest form, can be written as:

$$Q = 2\, L\, [k\, b + (k D\, \theta)^{0.5}]\, h_d / D \quad (2)$$

where Q is the leakage (m^3/s), L is the length of the connected wrinkle (m); $2b$ is the width of the wrinkle (m); k is the hydraulic conductivity of the clay liner (m/s); θ is the transmissivity of the geomembrane/GCL interface (m^2/s); h_d is the head loss across the composite liner (m); and D is the thickness of the liner (m). The application of this equation is discussed in more detail by Rowe (2012b), including a discussion of hydraulic conductivity, k, interface transmissivity θ, and typical wrinkle width ($2b$) and length (L).

5 CONSTRUCTION CONSIDERATIONS

As noted earlier, good design and appropriate specifications are needed to ensure a successful project; however on their own they are not sufficient. It is also critical to have good construction and appropriate construction quality assurance to ensure that the construction is good. There are many issues that need to be considered in construction and space only permits a few to be discussed. However these few are often sources of problems if they do not receive the required attention.

5.1 *Installers, quality assurance, and training*

Contracts for construction are often awarded based on a competitive bid process. However, most general contractors have little or no experience installing liners and while it may look simple, success will depend on many factors that may not be obvious to the uninitiated. A good starting point for a quality project is to pre-qualify installers that the general contractor may use based on their experience, knowledge, and equipment before the general call for tenders. The next step is to retain an independent, but suitably experienced, company to perform construction quality assurance (CQA). Provided that they have appropriate experience with CQA, ideally this will be the same company who developed the design and specifications since they have the best understanding of the intent of the design and the reason for the specification of certain materials.

While it is generally a good idea, it is especially critical on large and/or sensitive projects (e.g., where a large leakage through the liner could have significant environmental or health and safety implications) to conduct compulsory on-site briefings/training prior to the start of liner installation. The objective is to allow the workforce to understand the project and what will require special attention to ensure a successful project. The briefings would be different for two different groups:

(i) Installers and contractors. Since the design, materials, site conditions and people change between projects, even experienced installers and contactors will benefit from knowing what is required for quality installation on this particular project. This briefing should discuss some common problems that may arise at this site and how to avoid/manage them (e.g., as noted in following sub-sections).

(ii) Those not directly involved with liner installation but whose work may interface with the liner before, during, or after placement need to understand the importance of maintaining the integrity of the liner.

It is important that anyone who will be on site be aware that the greatest mistake in a lining project is burying a problem; all problems/errors (and there will always be some) need to be identified and rectified as soon as possible. Thus, if they notice any anomaly or are aware of anything unusual that has, or may have, occurred that could possibly damage the liner then they should mark the location and be sure to notify the supervising engineer as soon as possible.

5.2 *Installing GCLs and geomembranes*

GCL and geomembrane panels are rolled out with an overlap to the adjacent panel to allow seaming. This is simple enough. However the foundation should be smooth (no protruding stone, rocks or other objects, and no rutting) and firm (unyielding). A geomembrane can be damaged by isolated angular gravel in the foundation layer both during construction (Fig. 4) and subsequently (Brachman and Sabir 2010). The performance of both a GCL and geomembrane can be badly affected if they are placed on a badly rutted surface (Fig. 5)

Fig. 4 Geomembrane damaged by stones in an unsuitable foundation (Photo: courtesy of R. Thiel)

Fig. 5 GCL installed on an irregular/rutted (poor) foundation and not covered before heavy rainfall

Problems can arise during installation even if the foundation was initially satisfactory but is damaged by rainfall events making it wet, soft or eroding it where liner material has not yet been placed (Fig. 6). In these situations, the foundation needs to be adequately dried and repaired to be smooth and firm before more geosynthetics are placed. If the foundation for a geomembrane is a compacted clay liner, considerable care is required to avoid liner desiccation before the geomembrane is placed. For a GCL, the foundation also needs to be without sharp changes in grade and the GCL should be covered quickly so that the GCL is not exposed to heavy rainfall (i.e., avoid situations as shown in Fig. 5). Placing a geomembrane on a poor underlying foundation or liner (e.g., as shown in Figs 4-6) can substantially increase both short and long-term leakage.

Fig. 6 Eroded foundation layer due to heavy rainfall

Once the geomembrane has been laid it must be adequately ballasted against wind up-lift or what seemed like a heavy geomembrane soon becomes a very large and expensive waste ball of plastic (Fig. 7) with risks of damage to people and/or equipment.

Before welding, the surfaces to be welded need to be dry (a fog can provide sufficient moisture to be a problem), clean (no dust or mud), and at an appropriate temperature for welding.

Fig. 7 Geomembrane panel picked up by wind (Photo: courtesy of R. Thiel)

While a rare problem these days due to the relatively high stress-crack resistance of modern HDPE geomembranes (with MDPE resin), short-term (within weeks to months after welding) stress cracking can still occur (Peggs et al. 2014). For example, there appears to be a potential problem for liners either installed in areas with a high ambient temperature (e.g., ~ 40^{o}C) and solar radiation or in areas with a very low ambient temperature (e.g., ~ -40^{o}C) when welding is done on a sunny day.

If a geomembrane is welded on a hot sunny day, the geomembrane temperature at the time of welding could be ≥ 80^{o}C. This has the potential to cause problems by creating (i) a poor weld, and (ii) tensions in the geomembrane when it cools from a high as-seamed temperature (it is the change in temperature from the as-welded temperature that controls rather actual temperature).

Construction in cold regions can be complicated by the fact that the geomembrane can be at very different temperatures depending on the level of solar exposure/heating. For example, on a day with a cold ambient temperature and snow on parts of the geomembrane, the geomembrane may be hot enough where exposed to direct sun (e.g., a south facing slope in a Canadian winter) to have significant wrinkles (Fig. 8). Thus, as discussed by Rowe et al. (2014b), there is potential for evaporation of moisture and down-slope erosion even on chilly spring days such as that on which Fig. 8 was taken.

Fig. 8 Geomembrane partially covered by snow but with significant wrinkles in snow free areas on south facing slope

While successful techniques have been developed for welding geomembranes in very cold ambient conditions (e.g., Canadian Arctic), care is still needed to consider differential temperatures that may occur – especially when the sun emerges. Despite the cold ambient temperature, on a sunny day a panel welded with full sun exposure may be substantially warmer than the air temperature and hence welding a geomembrane locking in the expanded length can result in high tensions (and potentially seam failure/stress cracking) when the geomembrane temperature decreases to a very cold ambient temperature at night.

Care is needed to have sufficient slack in the geomembrane to accommodate reasonable contraction but not so much as to leave excessive wrinkling. In challenging applications, a geomembrane with an initial stress crack resistance higher than 1000-2000 hours may be required (Peggs et al. 2014).

Testing of seams (e.g., air channel testing of duel wedge welded seams) is useful for detecting and correcting some problems with seams but it will not detect all problems. For example, the defect apparent in Fig. 9 is on the underside of a white faced geomembrane adjacent to the weld and visually hidden by the geomembrane above. This was not detected by air channel testing, and would not have been detected by a visual inspection unless one looked between the two welded geomembranes. It should be detectable by a suitable leak detection survey, provided the design allows reasonable detection sensitivity (e.g. see ASTM 7007; § 6).

Fig. 9 Defect on underside of a geomembrane weld that would not be detected by an air channel test or casual visual inspection from the top of the geomembrane

5.3 *Leaving liners exposed*

Because polyethylene geomembranes have a relatively high coefficient of thermal expansion, when left exposed (i.e., not covered by an appropriately thick layer of soil cover - often 0.3 m is sufficient), they can expand and contract substantially due to daily and seasonal thermal cycles. In addition to issues that arise during construction, as discussed above, prolonged exposure can give rise to unexpected impacts on long-term performance that may not be evident when the liner is covered unless appropriate measures have been taken to mitigate these potential impacts as discussed below.

When exposed to solar radiation a black geomembrane can heat to 40°C (or more in some cases) above ambient temperature. This causes wrinkling of the geomembrane (Fig. 1), as discussed earlier. On a hot day these wrinkles can represent a third of the lined area and have connected lengths (L in Eq. 2) of up to 5000 to 10000 m/ha (Chappel et al. 2012a,b; Rowe et al. 2012). Thus, it is essential that the geomembrane be covered at a time of day when there are relatively few wrinkles (e.g., less than 5% of area) and that leakage calculations have taken account of some wrinkles at the time of covering (e.g., using Eq. 2; see Rowe 2012b).

The high temperatures that can be reached by an exposed black geomembrane (60-80°C) can cause the evaporation of water from the underlying clay liner (if present). This can have potential detrimental effects on the clay liner as discussed in the following paragraphs.

For an exposed geomembrane over a compacted clay liner, the thermal cycles can cause rapid and serious desiccation of the underlying compacted clay liner to the point where good composite liner action is lost (Rowe 2012b). The compacted clay liner cannot be expected to self-heal when the liner is eventually covered.

A GCL below a geomembrane is less likely to be damaged by exposure than a compacted clay liner and a composite liner can be left exposed without a problem for a limited period of time. However, once the GCL has experienced significant hydration and is then subjected to sufficient thermal cycles there can be both shrinkage of the GCL panels (e.g., Thiel et al. 2006; Rowe 2012b), and a recently discovered phenomena called down-slope erosion which effectively removes the bentonite from the GCL at discrete locations, often in associated with wrinkles and seam/welds (Rowe et al. 2014a,b; Take et al. 2015; Brachman et al. 2015). These problems can be completely avoided by timely covering of the liner as recommended by GCL manufacturers. In the event that this is not possible there are some GCL products much less prone to shrinkage and down-slope erosion (Rowe et al. 2014a,b) that may be used. Irrespective of the product used, it is highly recommended that GCLs covered by a geomembrane be placed with a 0.3m overlap between adjacent panels (more at the end of panels) and with sufficient supplemental bentonite to provide a good reliable and consistent seam below any remaining wrinkles when the geomembrane is covered.

When the geomembrane is much colder than at the time it was welded and if adequate allowance has not been made for contraction from the as-welded dimensions, thermal contraction caused by cooling of the geomembrane causes the geomembrane to rise up (trampoline or bridge) over changes in slope (e.g., at intersection of side slope and base; Fig. 10) and go into tension both here and elsewhere. These tensions can be "locked" in if the geomembrane were covered in this state. This could cause an immediate tear/hole (especially at a change in slope as shown in Fig. 10) but even if not, the tensions may contribute to long term stress cracking in these locations. Just as the geomembrane should not be covered with too many wrinkles, it should not be covered when there is tension in the geomembrane due to thermal contraction.

Another factor to be considered for exposed geomembranes, in addition to the obvious potential for damage from humans, animals, ice, fire, wind etc., is cyclic fatigue of wrinkles. This fatigue is most likely to be a problem if a significant wrinkle is near the water level where wind and wave action cause it to be subjected to physical loading cycles as well as thermal cycles induced by the sun. In these applications a suitable geomembrane with a high (> 1000 or 2000 hours) initial stress crack resistance and an excellent antioxidant package (HP-OIT > 1000 min) may be required (Peggs et al. 2014).

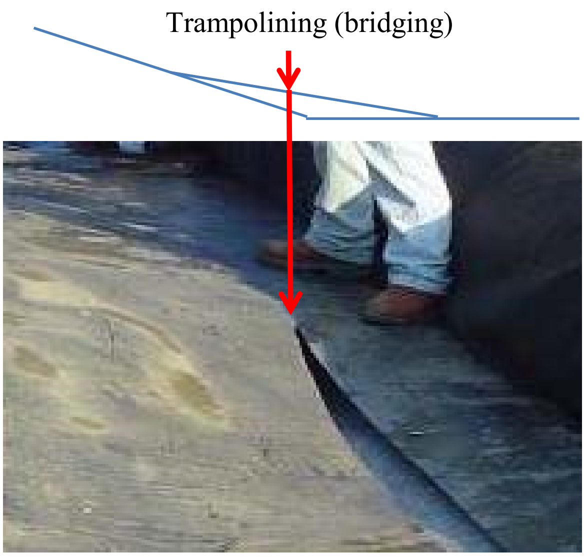

Fig. 10 Geomembrane trampolining (bridging) due to thermal contraction on cooling of the geomembrane if welded at a temperature significantly above the current temperature (Photo: courtesy of R. Thiel)

5.4 Penetrations

Penetrations through a liner, be it a geomembrane, GCL, compacted clay, or composite liner, represent one of the most likely sources of a leak and yet they often get inadequate attention both in design and in construction. Where ever possible a design should avoid, or at least minimize, penetrations through the liner. Where penetrations cannot be avoided, attention is required to the design and construction of penetrations to minimize both short and long-term leakage. Problems can arise from many sources but some factors that need to be considered to avoid common problems include:

- (i) use pipe materials (skirt and sleeve) compatible with the liner being sealed.
- (ii) corrugated PVC or steel should not penetrate an HDPE liner.
- (iii) it is possible, but challenging, to get a good seal on a corrugated HDPE pipe; it is much better to use smooth pipe;
- (iv) use appropriate clamps (this is not the place to save money).
- (v) HDPE weld knuckles must be ground flush so that a good seal can be obtained.
- (vi) the sleeve to skirt weld (at the pipe) is critical and it should be specified that this weld be checked for leaks. The welding should be observed and inspected by the engineer's representative during welding and leak testing.
- (vii) sealing around penetrations through GCLs also requires special attention; carefully follow manufacturers guidelines.
- (viii) attachments to concrete walls and perimeter walls are critical to liner integrity and must be done well. Because batten bar work is tedious and time consuming, it is often assigned to unskilled laborers. However there are many things that can go wrong if this is not done under the supervision of an experienced installer <u>while</u> the work is being done (not after).
- (ix) caulking must be applied patiently and evenly and avoid air bubbles. Hurried caulking at the end of a project is often the cause of problems.
- (x) penetrations are locations of stress concentration. The concentration of stress should be minimized by good design. Also, the designer should avoid penetrations in location that could be subjected to thermal cycles (e.g., solar radiation, freeze-thaw, or wet-dry) or cycling physical stresses (e.g., due to wind/wave action, changing water levels, or ice). A penetration that is sometimes above water level and sometimes partially or fully submerged in a pond is especially prone to problems.

6. CONCLUSIONS

There have been a very large number of successful applications of geosynthetics as bottom liners and covers for fluid storage, landfills and a growing number of mining applications. The factors affecting the performance of geomembranes and GCLs have been discussed together with some of the factors that need to be considered in design and construction to minimize problems and provide acceptable fluid retention. That said, a full discussion would take much more space than is available for this paper which has simply attempted to review, summarize and highlight some of the most important issues with respect to short- to medium-term fluid retention (with many source references cited for the reader interested in more detail). Important issues such as the long-term performance of geomembranes and GCLs, diffusion, and liner stability have not been discussed. A number of key points that are discussed in the paper are summarized below.

1. There are a large number of geomembranes and GCLs available. Different products are intended for different applications and it is the engineer's responsibility to select the appropriate materials for their application.
2. While the hydraulic conductivity of a GCL is important – there are many GCLs that will provide a similar hydraulic conductivity in a short-term index test but behave very differently when deployed in the field. Often those that perform best in the field do so because of features that add to the cost. Selection of a GCL based only on hydraulic conductivity and price is not a wise way to select for many applications.
3. Poor design and/or poor construction combined with poor construction quality assurance can lead to failures.
4. A knowledgeable designer, pre-qualification of installers prior to a call for tenders, and the retention of a suitably experienced company to perform construction quality assurance (CQA) represent a good start to a quality project, as is compulsory on-site briefings/ training prior to the start of liner installation.
5. For liners with geomembranes, leakage is likely to be controlled by holes coincident with wrinkles that are present in the geomembrane at the time it is covered.
6. For good performance, the foundation onto which GCL and geomembrane panels are placed should be relatively smooth and firm.
7. A liner must be adequately ballasted against wind up-lift.
8. Before welding, the surfaces to be welded need to be dry, clean, and at an appropriate temperature for welding
9. While not common, short-term stress cracking can still occur in some unusual situations that have been discussed.
10. HDPE has a high coefficient of thermal expansion that requires consideration in design/construction. Care is needed to have sufficient slack in the geomembrane to accommodate reasonable contraction but not so much as to leave excessive wrinkling.
11. Testing of seams is useful for detecting and correcting some problems with seams but it will not detect all problems. On important projects, a leak detection survey is recommended.
12. Prolonged solar exposure of a composite liner can give rise to unexpected impacts on long-term performance that may not be evident when the liner is covered. These problems can be completely avoided by timely covering of the liner as recommended by GCL manufacturers. In the event that this is not possible there are some GCL products much less prone to problems due to exposure that may be used.
13. Penetrations through a liner represent one of the most likely sources of a leak. Designer's should minimize and, where possible, totally avoid penetrations through the liner. Where penetrations cannot be avoided, attention is required to the design and construction of penetrations to minimize both short and long-term leakage. A number of factors that need to be considered to avoid common problems have been discussed.

While not all important factors have been discussed, consideration of those that are discussed will serve to increase the likelihood of a successful project with geosynthetic liners playing a key role in providing good long-term environmental protection.

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