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Geomembranes – From Design to Handover and Some Case Histories

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ABSTRACT
Geomembrane (GMB) liners are being used more frequently for the storage or capping of mine waste due to stricter regulatory requirements relating to environmental protection. The longevity of any liner system will be a function of environmental conditions, design (including materials selection), construction and condition monitoring during operations or closure. Based on experience and case studies, this paper presents a review, from design to handover, of some of the smaller and often overlooked details that can have significant impacts on the performance of the GMB and the project overall. The topics covered will include approaches to selecting and testing GMBs to ensure they are suitable. Design considerations to aid installation and quality assurance during construction. Understanding action leakage rates and the consequences of leakage when it creates whales. Construction quality control and assurance procedures, including a brief discussion on non-destructive liner integrity testing.

1. INTRODUCTION

An important question for designers, contractors or an owner is 'which liner (GMB) should I select?'. This can sometimes be a simple question to answer if the project requirements are such that the GMB is not in contact with aggressive (i.e. oxidative) fluids or soils and the design life is short (e.g. less than 20 years). For low risk structures/facilities the liner can be selected by careful consideration of performance properties defined by manufacturers datasheets and prior experience. However, if the liner is in or likely to be in contact with aggressive fluids/soils then immersion testing is recommended to select the best candidate GMB for a given application. This is particularly important when a long service life is required.

1.1 Selecting a GMB

Selection of a suitable GMB for a specific application needs to consider the different resins available on the market (if polyethylene is being considered) as well as combinations of proprietary stabilisation packages (i.e. formulations). Therefore, the end performance properties (especially stress crack resistance and oxidative resistance for polyethylene GMBs) can vary widely from one GMB to the next. There are many GMB products available such as polyethylene (low, linear low and high density variants), bituminous, scrim reinforced chlorosulfonated polyethylene (CSPE) or ethylene propylene diene monomer (EPDM) rubber, to name few. High density polyethylene (HDPE) is the most commonly selected GMB material in practice, due to its low material cost, broad chemical resistance and excellent mechanical properties. Due to the close packing of polymer chains in HDPE, there is very little free volume for chemicals to infiltrate the polymer, hence giving it excellent chemical resistance. Although it is less flexible than other GMBs, it still offers good elongation properties. Bituminous GMBs are becoming more popular in Australia and are a very robust product with most, if not all, their 'strength' provided by the nonwoven polyester geotextile core (the scrim) which is impregnated by elastomeric modified bitumen. Their selection for high temperature and high pH applications needs to be considered carefully due to potential scrim exposure issues. If the scrim is exposed through poor installation or damage, wicking (i.e. transport of liquor along the scrim reinforcement fibers due to capillary action) can lead to deleterious effects such as hydrolysis of the polyester scrim.

The longevity and service life of a HDPE GMB depends primarily on:

- The resin and antioxidant package used in the GMB
- The chemical composition of the fluid/soil with which it is in contact
- Temperature (this is a very important parameter)
- Welds (e.g. dual wedge fusion welds between GMB panels and extrusion welds in tight areas, where more than two GMBs intersect, and for repairs)
- The nature of the materials in contact with the GMB and the strains developed in the GMB.

Some questions and comments that should be considered when selecting a GMB are presented below:

- It is important to consider the technical merits (i.e. performance over maintenance) of your various liner/capping systems and assess them on this basis.
- Which geosynthetic is best suited to the likely chemical interactions and applied loads, and most importantly the service temperature which is a critical parameter that degrades geosynthetics.

- Selection of a GMB from a datasheet is limited to performance properties defined by manufacturers.
- Performance properties are often very conservative and based on limited testing which is unlikely to include the chemical composition of the fluid/soil with which it will be in contact with during its operational life.
- Often a selection is based on what was previously used without consideration of changed site conditions, loads and materials in contact with the GMB.
- Sometimes a GMB is selected based on a phone call to suppliers or installation contractors without due consideration of the design components.
- A geosynthetic such as a HDPE GMB or bituminous GMB, if appropriately selected and covered will last a long time, but testing which has been carried out for sufficient duration is the only way to determine exactly how long this will be.
- If adequate time is not available for immersion testing, then a client or regulator is unlikely to accept your estimate of the service life.
- Immersion tests do not simulate the effect of tensile stresses, which may be applied to the GMB in the field.
- Immersion tests also expose the GMB to fluid on both sides, which is not typically representative of field applications.

There is a complex interaction between resin, antioxidants, GMB thickness, and the chemistry of the exposure fluid/soil that cannot be assessed from manufacturer's datasheets and initial performance properties. This is best assessed by performing immersion tests to select the most appropriate candidate GMB for a given application when a long design life is required.

Design lives of 1000 years (ANCOLD, 2012) are more frequently being specified, which is admirable but unnecessary, since better ways of containment or disposal may be found before 1000 years has passed. Tests (e.g. immersion testing) need to be initiated early in a project since they take time (at least 1 year and often more to obtain useful results – even with accelerated aging). It is also very important that the GMBs being tested have the same resins and HDPE formulation as proposed for use in the lining system. If possible, the materials likely to be in contact with the GMB (e.g. soils or drainage aggregate) should be incorporated into the testing procedure.

1.2 Background relating to GMB durability

Chemical degradation of a GMB is typically accelerated by higher chemical concentrations, higher temperatures, with applied stresses and when any of these factors are cyclic or combined. In general, degradation is worse for longer exposure times.

HDPE is the cheapest (per mm thickness) material commercially available for GMBs, allowing thicker sheets to be manufactured. Therefore, it is generally the first material considered for a GMB application. Some shortcomings of HDPE are high stiffness, high coefficient of thermal expansion, easily scratched/gouged during installation, which are precursors to stress cracking, and the need for field welding which requires great care and quality control.
Figure *1* shows the additive loss mechanisms and pathways, all of which can be experienced by GMBs used to store liquids that are exposed to the elements.

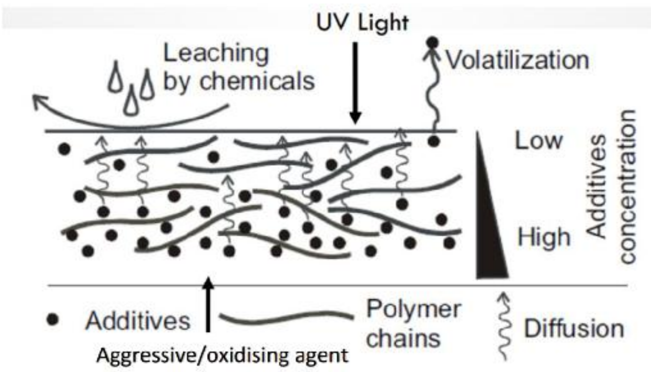

Figure 1. Mechanisms of additive loss (Anon and edited by Author)

1.3 Degradation model for HDPE GMBs

It is important to note that this area of geosynthetic science/engineering is large and complex and it is difficult to distil the available knowledge into a few paragraphs. The degradation of a GMB has been shown to have three distinct stages (Hsuan & Koerner, 1998) and the time to nominal failure of the GMB is taken as the sum of the duration of these three stages. Stage I (1) is the loss of antioxidants due to physical and/or chemical extraction at a rate dependent on the exposure conditions. Oxidative induction time (OIT) tests including standard OIT (Std-OIT) and high pressure OIT (HP-OIT) are used to assess the antioxidant depletion stage.

Stage II (2) begins after antioxidants are depleted to a residual value, yet there are still no measurable changes in the mechanical properties. Stage III (3) begins at the onset of degradation in mechanical properties. Polymer properties monitored to assess degradation are melt index, tensile properties, and single-point notched constant tensile load stress crack resistance (NCTL-SCR) tests. The end of Stage III (3) [time to nominal failure] is usually considered to have been reached when a selected property degrades to 50% of the initial value, or to 50% of the specified value by GRI-GM13 or project specific criteria.

1.4 Immersion testing lessons learnt

Immersion testing involves the incubation of GMB samples in synthetic or actual field liquids at different temperatures to accelerate their ageing. The data can be used to establish a time-temperature superposition model, namely an Arrhenius model (Hsuan & Koerner, 1998) to extrapolate a selected property at a site specific or range of temperatures. In general, the greater the number of specimens tested and the longer they are incubated, the better the accuracy of the Arrhenius model and hence the prediction that can be obtained.

The Arrhenius model provides a simple expression to quantify the three stages of HDPE degradation. There is however a paucity of industry experience in obtaining the necessary parameters for stages two and three; only stage one is commonly quantified. Modern GMBs are packed with antioxidant stabilisers which can take years to age sufficiently to gain insight to the duration of stages two and three, a fact which is often neglected during the GMB selection process.
If a long service life is critical for the project, then sufficient time needs to be included very early in the project design phase, such that selected GMB samples can be tested for sufficiently long periods. It is also important to start dialogue with manufacturers early as they often change resin suppliers and sometimes stabiliser formulations. Additionally, they may be about to release new products that should be considered as part of any testing program. Immersion tests do not consider the effect of tensile stresses in the GMB during ageing and expose the GMB to the immersion fluid from both sides. Typically, neither of these conditions are representative of field applications. Thus, the time to nominal failure inferred from immersion testing does not represent the real service life of the GMB. However, immersion tests do provide insight regarding the ageing of GMBs and allow a comparison of the relative ageing of different GMBs.

The author was involved in a study where six commercially available GMB products were immersed in supernatant liquor obtained from a tailings storage facility in Australia and incubated at temperatures of 55, 75 and 95 °C. Various parameters were evaluated bimonthly to compare the relative aging of each GMB. The Arrhenius model was demonstrated by extrapolating the antioxidant depletion times for a temperature of 35 °C, and the results ranged from 30 to 700 years. It was shown that four months of accelerated aging is not sufficient to age modern GMBs beyond the first stage of degradation, hence quantification of stages two and three was not possible. To enable an estimate to be made for total service life, Stage 2 and 3 aging data generated by (Rowe, Rimal, and Sangam, 2009) was used. This approach was based on several key assumptions associated with the integration of the two datasets.

2. DESIGN CONSIDERATIONS TO AID INSTALLATION AND QUALITY ASSURANCE DURING CONSTRUCTION.

While 1000 years (ANCOLD, 2012) might seem to be an admirable target, how many infrastructure elements are we using today that are 1000 years old? Within that time new technologies will be developed to better handle waste containment if, in fact, it is still considered to be waste. However, there is no need to be complacent and every effort should be made to achieve the longest possible lifetime.

Another reason to be cautious is that the lifetime of a waste containment system depends not only on the performance of the material itself but also on the following:

- Good design and specification.
- Ensuring specification compliant materials are delivered to site.
- The quality of the welding.
- The quality of the subgrade preparation.

- The quality of liner deployment.
- The quality of the construction quality assurance (CQA).
- The facility is appropriately commissioned.

If any of the above are not considered in appropriate detail, then this could compromise the best performing GMB material.

2.1 Applications for GMB liners

There are a wide range of applications for GMB liners in the mining industry and with recent advancement in material properties their use is spreading to a wider range of assets. Some of the applications include:

- Ponds/Dams for aggressive (i.e. highly oxidative) mine fluids (e.g. brines, process water waste streams).
- Liners for heap leach pads.
- Liners for tailings storage facilities.
- Covers for mine waste (e.g. capping of tailings storage facilities as part of closure).

One of the fundamental objectives of a GMB is to limit the migration (i.e. leakage) of stored liquids or reduce the infiltration of water through capped material (e.g. tailings). This function is primarily to provide additional protection to the receiving environment. The design intent should always be to construct a facility which can achieve zero leakage; however, experience has shown that GMBs should not be relied on to be totally impermeable, and that some leakage must be accepted or considered unavoidable. Hence, a Leakage Detection System (LDS) should be incorporated into the design to safely return or store liquid migrating through the lining system to the storage compartment (i.e. sump or collection drainage). Leakage that is not monitored and controlled can lead to increased leakage and potential failure of the liner system, both of which potentially impact the receiving environment. Selected design considerations related to the above leakage issues are discussed in the following sections. A lesson learnt as a result of not managing leakage in a timely manner is also presented.

2.2 Connection of GMBs to ancillary structures

GMB connections to ancillary structures (e.g. pipe penetrations or outlet structures) below operating levels (i.e. subjected to hydraulic head) are critical and are typically where leakage will occur. Sometimes leakage will be realised immediately (e.g. during commissioning) or in the longer term as result of cyclic stresses on the welds or under poorly constructed bolted connections typically referred to as batten bars. When considering what type of connection is the most suitable, the first question that should be asked is 'can I remove the ancillary structure?' such that there is no penetration through the liner system, particularly under a hydraulic head. The author's experience based on successful installations, is to use a liner embedment strip (LES). This is an extruded HDPE concrete embedment strip for GMB attachment to concrete. The embedment of anchor fingers provides a high strength mechanical anchor to the concrete. Figure *2* provides details of a LES.

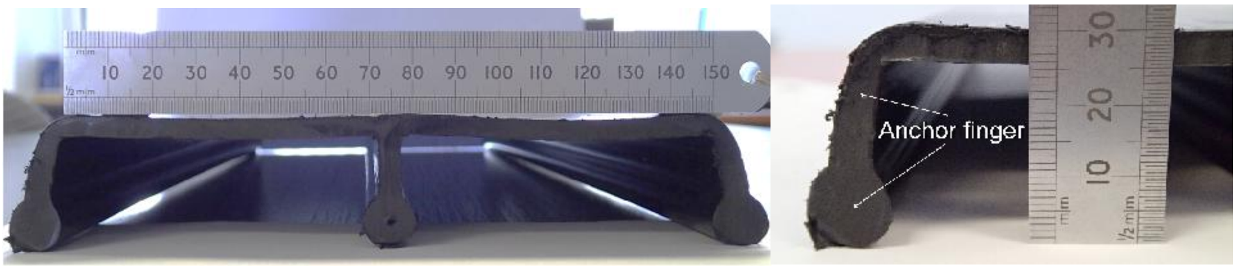

Figure 2. Cross sections of a liner embedment strip

When considering a GMB connection to concrete subjected to a hydraulic head, the detailing and installation of the LES is the most critical component to reduce leakage to acceptable limits. These limits are determined as part of the Action Leakage Rate (ALR) calculated for the liner system. While the LES provides a strong mechanical termination (via extrusion welding), if installed by a lining contractor with prior experience, the connection should also be designed to be as stress free as possible. To assist with mitigating expansion and contraction stresses on the extrusion weld (due to cyclic loading), ballast is required around or alongside the structures, see Figure *3*. If the structures will be permanently submerged then ballast may not be required, however, this should be determined specifically for each project.

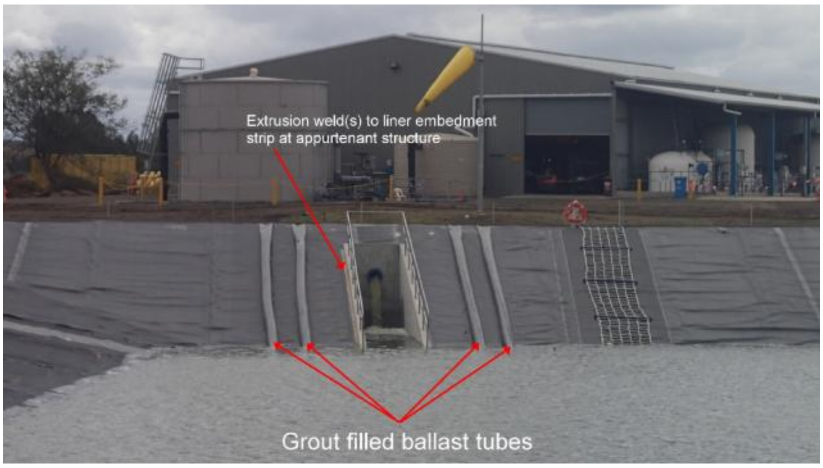

Figure 3. Grout filled ballast tubes assisting with minimising stress on extrusion welds to LES

The author recommends appropriately detailed and scaled onsite trials prior to the installation of a LES frame. As a minimum this should include the designers, lining contractor, formwork, reinforcement and concrete teams, as it is important that all parties understand the complexity around proper installation. Typically, if the trial is appropriately specified and managed, the final installation is successful. Figure 4 provides details of a suitable trial and the required actions to assess its' success (e.g. the lack of concrete voids in the cross section suggesting that concrete compaction techniques adopted were good). Remedial works to correct poor installation are not simple and impacts schedule, budget and increases the likelihood of leakage.

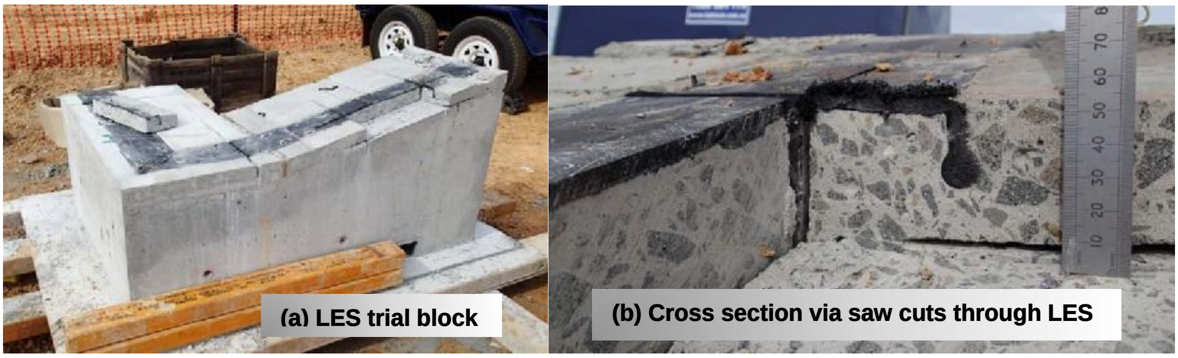

Figure 4. LES trial (a) appropriate detail and scale (b) Cross sectioning to assess for concrete voids

2.3 Action leakage rates

The purpose of ALRs is to provide a benchmark for evaluating the performance of the installed liner system in terms of leakage rate, and to define triggers which require actions to be taken if the performance goal is not met (i.e. measured leakage rate exceeds the design leakage rate). This leads to the following question; 'what is an acceptable rate of leakage? The purpose of ALRs is to define this rate.

ALRs are used as a trigger value to ensure leakage rates are not allowed to become excessive, thereby protecting the liner system and environment from potential damage or harm. Figure *5* provides example data and shows the importance of leakage rates being monitored during operations. The liner system comprised a HDPE geomembrane (2.0mm thick) overlying a herringbone arrangement of geocomposite drainage strips placed on a clayey subgrade.

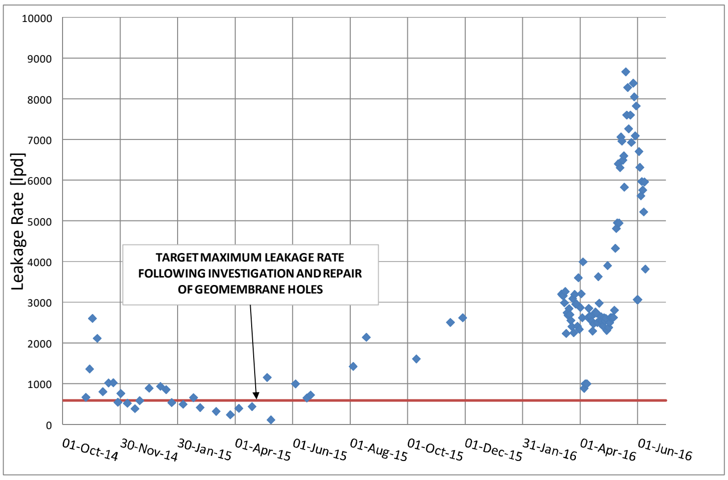

Figure 5. Plot of leakage rate versus time and an example of measured leakage rate exceeding design leakage rate

The ALRs provide criteria for asset operators to evaluate the performance of the installed liner system and triggers corresponding action plans if performance goals are not met. It is recommended that the asset owner is involved with the assessment of ALRs as it becomes their responsibility to monitor leakage and undertake appropriate actions if trigger levels are exceeded. The technical understanding of ALRs and the identification of the causes of excessive leakage form the essential background to cost-effective measures to reduce the risk of failures. While physical or intrusive investigations have an important role, regular inspections and monitoring of instrumentation with the knowledge of how to respond (i.e. having a trigger action response plan in place) can provide an essential component in developing this understanding. During the condition assessment of a leaking liner system, the performance history of the liner system is one of the most useful and important elements in identifying potential issues at an early stage and making an accurate diagnosis of the problem.

2.4 GMB whales and a case study

GMB ‘whales’ are not entirely uncommon, and the incidence of whales has been seen in many different types of GMB containment systems across the world.

Typically, a whale contains gas above the water/liquor line and water/liquor beneath the GMB if the GMB is leaking due to defects (e.g. small holes, defective welds). Typically, the GMB will have a lower density than the stored liquor, so it will float. This will lift the GMB off the subgrade (or underlying geosynthetic layer), breaking the intimate contact, resulting in an increased leakage rate. The stressed GMB forms a bubble-shaped feature which is termed a ’whale’ as it looks like the back of a whale above water level, as shown in Figure *6*. GMBs with many defects are more susceptible to developing whales.

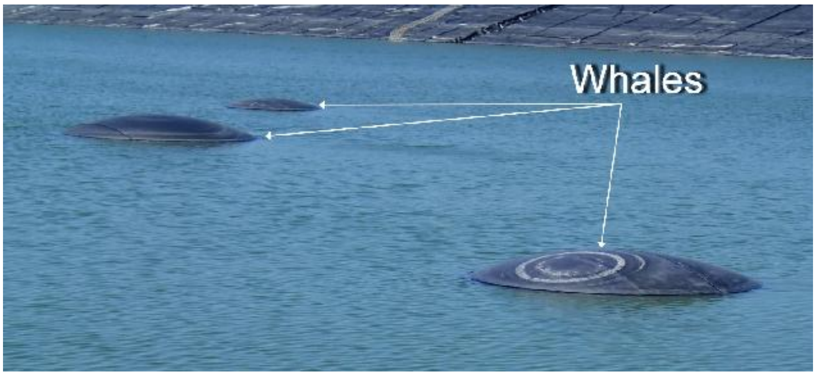

Figure 6. Examples of whales with trapped gas and liquid beneath the GMB

Once initial GMB deformation occurs or loss of intimate contact, gas tends to concentrate at localised areas, causing the GMB to rise to the liquid surface, and even above it. The level of water below the GMB is the same as that above the GMB, as shown in Figure *7*.

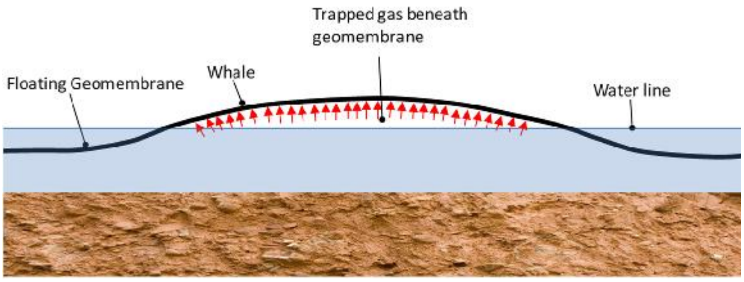

Figure 7. Indicative diagram of a GMB whale

The solution to avoid the incidence of whales is to incorporate a pressure relief system that allows the venting of gas and removal of leakage. This is achieved by installing an underlying permeable material (such as geocomposite drains on a sloping subgrade) which have the coverage and capacity to enable trapped gas to escape via vents in the liner system, constructed above the maximum operating liquor level. Similarly, a leakage detection and recovery system should be installed to mitigate build-up of leakage and subsequent uplift (i.e. loss of intimate contact) on the underside of the GMB. In addition to having an adequate venting system, the best practice during first filling (i.e. commissioning) is to carefully 'walk-out' (e.g. manually remove trapped air with personnel in the dam) any developing whales at the advancing front of the liquor. This is typically only necessary on the floor, not on the slopes.

2.5 Failure analysis of HDPE GMB liner system with whales – case study

The objective of this study was to determine the root cause and mechanism of whale failures in the HDPE GMB that formed part of a temporary liner system (refer to Figure *6*.) There were at least four known whales where the GMB had ruptured based on evidence provided by the client and inspection/retrieval of the failed GMB samples from the dam. Visual inspection suggested that the failure mode was by 'necking' (i.e. multiaxial tensile deformation associated with large strains and thinning of the material) until holes/tears appeared, allowing the gas to escape. These holes/tears increased the leakage rate.

It is possible that rupture occurred at pre-existing surface defects (e.g. scratches or gouges) in the GMB. However, the author's scope was to assess the hypothesis that gas, rather than just trapped air, created the additional tension in the whales and subsequent failure of the GMB. The hypothesis resulted from observations during inspection (and subsequent retrieval of samples) that anaerobic digestion of algae beneath the GMB introduced additional gas. Evidence of what appeared to be algae was found in the gravel toe drains and desiccation cracks in the compacted clay liner, as well as other unknown sludges on top of the GMB. It is not known whether algae could survive in the liquid stored in dam, however, anaerobic digestion does have the ability to generate biogas.

Samples of the GMB from the whales, which were yielded and thinned in parts were extracted and sent to a specialist polymer-testing laboratory. Figure *8* provides an example of these samples. Unaffected GMB reference liner samples were also supplied.

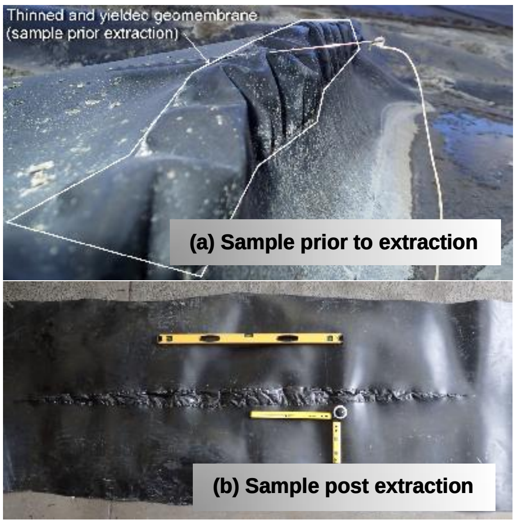

Figure 8. Samples of failed GMB (a) prior to (b) post extraction from the dam

The experimental method included the following testing which was performed on both the yielded and reference GMB:

- 'Thermal Desorption Cooled Injection System Gas Chromatography Mass Spectrometry' (TDU-CIS-GC-MS).

The results indicated that there were specific aldehydes and mercaptan that were detected only in the thinned liner, which are by-products of decomposition of organic matter, such as biomass, and are produced along with methane.
Based on the results this provided strong evidence that the additional tension in the whales was formed by methane which was formed by anaerobic decomposition of algae. It is likely that the whales formed via a 3-step process:

1. During installation and initial filling, air entrapped (as a result of the temporary liner system design) in wrinkles become localised to form a pocket of accumulated air under the liner.
2. Leakage in the form of algae-laden water penetrated under the liner through defects and collected at the site of accumulated air.
3. The absence of sunlight and heating of the exposed whales, led to the algae decaying and generating methane via anaerobic decomposition leading to the observed tensioned whale formation.

Case study findings:

- The failed section of HDPE GMB contained sorbed hydrocarbons namely, aldehydes as well as a mercaptan. These compounds are well known to be very odorous and collectively have a 'rotting manure' smell descriptor.
- The specific aldehydes and mercaptan were not detected in the reference samples of HDPE GMB.
- The specific aldehydes and mercaptan sorbed into the failed areas of GMB are the by-products of decomposition of organic matter such as biomass and are produced along with methane during anaerobic decomposition.
- Another compound of significance, which was associated only with the failed areas of GMB liner is 2-Furanmethanol also known as furfuryl alcohol which is formed by decomposition of polysaccharides/cellulose.

3. CONSTRUCTION QUALITY ASSURANCE AND LINER INTEGRITY TESTING

The most common approach to improve the liner system installation quality and in particular, to find holes, is by implementing a construction quality assurance plan. In the case of GMB liners, construction quality assurance typically consists of inspections and measures taken by a team that should be independent from the GMB installer during installation of the GMB and associated materials, including overlying materials. Frequently, damage to GMB liners is caused by the placement of materials (e.g. soil layers or permanent ballast) on top of the GMB. Additionally, further damage can result from the installation of ancillary items (e.g. pipework) after construction (i.e. during operations), when potentially, a new contractor or the asset owner are not cognisant of the importance regarding protection of the installed liner system.
Typical construction quality assurance activities aimed at finding holes in the GMB include:

- Nondestructive tests (e.g. air pressure testing) on seams to find gaps or poorly welded seams.
- Visual inspection of the entire GMB liner to find:
  - punctures, tears or deep scratches (e.g. gouges) in the GMB.
  - gaps in attachments of GMB to appurtenant structures.
  - Bridging (or trampolining).
  - Excessive wrinkles and wrinkle height.
- Destructive tests (e.g. weld specimens tested in peel and shear modes), if warranted, weld specimens can also be sectioned for visual examination. A thin microtomed section can be examined by transmitted light microscopy for the uniformity of the weld zone and squeeze-out beads, and using crossed polarising filters, the presence of residual stresses.

These typical construction quality assurance activities may be sufficient for low risk projects (i.e. low risk of environmental harm if leakage occurs), however, most projects requiring the installation of GMB have a higher risk level. As a result, it is recommended that liner integrity testing (LIT) is performed in addition to the implementation of construction quality assurance. LIT is common referred to as a 'leak location survey', however, it is important to note that LIT methods detect holes or defects rather than actual leaks.

The principle of LIT is simple. Most GMBs are electrical insulators, therefore, electric current will pass if there is a hole in the GMB or a gap in an attachment of the GMB to an appurtenant structure. The LIT requires a conductive layer immediately beneath the GMB. Therefore, the LIT is not as effective if the GMB is not in intimate contact with the underlying soil unless a conductive-backed GMB is used (i.e. a GMB with a thin high carbon content layer across its bottom side). In particular, with ordinary GMBs (i.e. GMBs with no conductive layer), the LIT is not effective or not possible at locations where the GMB exhibits wrinkles or on multi-layered liner systems.

Figure *9* depicts a wrinkle formed in white on black, conductive, 2 mm thick HDPE GMB. The photo was taken around 3:40pm and the ambient temperature was approx. 36ºC (location is Western Queensland, Australia). The wrinkle height was approximately 300 mm and the underlying geocomposite drain wasn't exacerbating the wrinkle height. Despite the wrinkle LIT was still possible because the GMB was a conductive liner.

Figure 9. Wrinkle in white conductive GMB

In the past two decades, LIT technology has advanced significantly. Today, LIT can be performed on a bare GMB, on a GMB under water, or on a layer of soil overlying a GMB. The latter is still very dependent on there being intimate contact, hence why conductive backed GMBs should be used if LIT is critical. The LIT equipment can be modified such as that shown in Figure *10* to increase its performance and reduce the physical stress on the operators. This modification assists with articulation over wrinkles, ridges and extrusion welds facilitating a better outcome through strict quality control.

Figure 10. Modified LIT equipment

Following on from good design, the liner system must be installed by suitably qualified and experienced lining contractors. They should be able to demonstrate successful installation of similar liner systems. It is important from a liner system durability perspective that it is installed with the least amount of stress. That is, no folds, wrinkles, and waves that coincide with the welds. The latter is typically where failures have occurred.

4. CONCLUSIONS

The author has been involved with many successful geosynthetics liner system designs and construction oversight for storage dams and cover systems. The factors affecting the performance of GMBs have been discussed together with some of the issues that need to be considered in design and construction to minimise problems and provide acceptable leakage rates or environmental protection.

There are many geomembranes available and they are intended for different applications and it is the design engineer's responsibility to select the appropriate materials for their application. Exposure conditions relate to chemical exposure and temperature. Both of these can be captured in traditional laboratory immersion testing programs. The immersion test is useful for assessing the relative performance of the different geomembranes, the effect of geomembrane-chemical interactions, and temperature.

Penetrations through a liner system represent one of the most likely sources of a leak. Designer's should minimise and, where possible, totally avoid penetrations through the liner system. Where penetrations cannot be avoided, attention is required to the design and construction of penetrations to minimise both short and long term leakage. Several factors relating to liner embedment strips that need to be considered to avoid common problems have been discussed.

The author has developed a rational and quantitative approach for calculating ALRs, through review of published literature and consultation with leading industry experts. The method provides values for two ALRs; ALR1 and ALR2. ALRs provide criteria for operators to evaluate the performance of the installed liner system and triggers corresponding action plans if performance goals are not met.

Lack of monitoring liner systems during commissioning and uncontrolled leakage can lead to the development of whales. Whales can create failures in the liner system under surprising circumstances. Methane biogas generated from anaerobic decomposition was investigated and presented as a case study. Whales formed when algae-laden water leaked through the liner and biogas continued to be generated but could not be vented. Designs must incorporate a means of removing leaked water very quickly and an effective venting system to remove any biogas generated under the liner.

Poor design and/or poor construction combined with poor construction quality assurance can lead to failures. Visual inspection and testing of welded seams is useful for detecting and correcting some problems, but it will not detect all problems. For high risk projects where the risk of failure potentially leads to loss of containment, liner integrity testing should be undertaken.

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