Pinhole view to Geosynthetics for Geoenvironmental Applications

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Abstract—Issues to the use of geomembranes (GMs) and geosynthetic clay liners (GCLs) as part of composite barriers in geoenvironmental applications have long been established. It was however, pertinent to highlight a few challenges and progresses currently in the front lines from the perspective of a tropical region. Some key concerns include the impact of: temperature on desiccation of GCLs and compacted clay liners (CCLs) as well as advection and diffusion; holes in GMs on leakage through composite liners; wrinkles and bond unsealing in GMs on leakage through composite barriers; temperature and leachate exposure on the service life of GMs; wrinkles on strains developed in GMs and the thinning of GCLs; internal erosion on strains developed in GMs and the choice of a protective layer on the strains developed in GMs. The paper posits that GCLs and GMs are advantageous in protecting the environment. Nonetheless, they are susceptible to damages and must be used under proper quality control with consideration geared towards the factors addressed herein. Field reconnaissance has shown that the necessity for site specific design, strict compliance to construction specification and appropriate post construction protection of the geosynthetics cannot be overemphasized. Specifically, the choice of the diverse available GCLs should not be bench on cost alone but also on their various engineering characteristics and required properties.

Keywords—Geoenvironmental, Geomembranes, Geosynthetic Clay Liners, Composite barriers, Leachate leakage

I. INTRODUCTION

Over recent past, a lot have been documented on the merits and demerits of the use of geosynthetics i.e., geosynthetic clay liners (GCLs) and geomembranes (GMs) in containment facilities. The global embrace of geosynthetics has led to a significant increase in its geoenvironmental applications. As recorded by [1] these applications span from conventional uses of GCLs and GMs as composite bottom barriers or cover liners for landfills. Also [2] and [3] reported geosynthetics to be used as blockers for contaminated fluids, as hydraulic barriers to contain spillages and leachate exposure on the service life of GMs; wrinkles on strains developed in GMs and the thinning of GCLs; internal erosion on strains developed in GMs and the choice of a protective layer on the strains developed in GMs. The paper posits that GCLs and GMs are advantageous in protecting the environment. Nonetheless, they are susceptible to damages and must be used under proper quality control with consideration geared towards the factors addressed herein. Field reconnaissance has shown that the necessity for site specific design, strict compliance to construction specification and appropriate post construction protection of the geosynthetics cannot be overemphasized. Specifically, the choice of the diverse available GCLs should not be bench on cost alone but also on their various engineering characteristics and required properties.

II. FACTORS IMPACTING THE USE OF GEOSYNTHETICS

Protection/Cover of Composite Barriers

Barrier liners are often subjected to enormous pressures from the pile of waste built-up over dumping periods. As well as, pressures from heavy machineries compacting waste layers thereby, subjecting the lining systems to damages. Geomembrane protection layers most commonly in use involve a fairly light needle-punched nonwoven geotextile. This is partly because a geotextile with a mass per unit area as low as 270g/m² “fully protects the GM from construction and compaction loading” [7]. A demonstration of linear increase in protection resistance with increasing thickness (mass per unit area) of a protection layer was done by [8] with a proposed methodology for selection of geotextile protection layers that will provide short-term protection against puncture under the loads applied by the overlying waste. Another proposed test methodology to assessing the suitability of a protection layer by [9] involved three steps. Firstly, a full scale test with the actual materials that are being considered for the project (gravel leachate collection layer, protection layer, GM, and subgrade, as appropriate) is done and the system is subjected to loads as close as possible to the field anticipated loads (construction loads, in-service loads). Secondly, the GM from the system is taken and a large diameter (≥0.5m) burst test (hydrostatic test) is conducted. If inflation is impossible, this implies that the GM specimen is defected (which could be invisible) and the GM specimen fails the test. If inflation is
possible, the GM is inflated till failure occurs. If failure is at the apex of the dome, the point of maximum stress, then the GM specimen passes the test. If failure of the GM occurs at a location outside the apex of the dome, then the GM is considered weakened in the field test and thus, fails the test. Thirdly, if the GM failed, the first two steps are repeated with different protection layers until a satisfactory design is achieved.

A large-scale physical testing of a number of different protection layers performed by [10] revealed that the protection layer between the GM and the overlying drainage material has a critical effect on the tensile strains induced in the GM. As gathered from landfill reconnaissance in Johannesburg, it became clearer that the best protection for the underlying GM was provided by a sand filled geocushion or a special rubber geomat, which limited strains induced by coarse (40-50mm) angular gravel to 0.9% at 900kPa and 1.2% at 600kPa respectively. Although in reality, considering the heights and depths of the dumps from the visited landfill sites, the waste loads were measured to be in a range of 150kPa-200kPa as shown in Fig. 1. From related works however, the worst protection was provided by the lowest mass (435g/m²) nonwoven geotextile which allowed 350 indentations/m² and a maximum strain of 8% at an applied pressure of 250kPa and 1200g/m² of geotextile which permitted about 340 gravel indentations/m² in the GM and a peak strain (13%) close to the yield strain at 900kPa. In either case, if only 0.001% of the indentations eventually resulted in a pin hole defect, this would correspond to over 30holes/ha. The two rubber geomats examined in literature were identical except for the presence of a polyester grid reinforcement bonded to the second geomat.

![Fig. 1 Pictorial view of visited sites with waste loads up to 200kPa](image)

The large difference in maximum strains (7.5% and 1.2% respectively at a pressure of 600kPa) observed for these two geomats suggested that the tensile stiffness provided by the polyester grid played a significant role in reducing lateral deformation of the rubber and hence, reduced indentation and strains in the GM. Therefore the tensile stiffness of the protection layers may be a critical factor in minimizing strains in GMs. It is however, noted that the tests conducted by [10] were relatively short-term (200-720min) and at room temperature (24±1°C). Thus, the peak strain may not represent the maximum localized strain that could develop in longer term tests. As such, additional laboratory and field investigations are recommended to clarify the time dependent effects of strains induced by gravel particles. Nonetheless, it is clear that sand protection layer provides the best behaviour over a long-term.

**Effect of Temperature/Ultraviolet Rays on Lining Systems**

The GCL and CCL barrier lining systems are known to be vulnerable to shrinkage and desiccative cracking, mainly when underlain a GM in a composite lining system. Geomembrane temperature has been discovered to be very sensitive to ultraviolet (UV) radiation and can reach temperatures of about 80°C [11]. An increase in GM temperature can cause evaporation of water from the underlying GCL into any air space between the GCL and the GM and subsequent transfer of this moisture down-slope upon cooling of the GM. The temperature gradient beneath the GM can also cause movement of fluid from the GCL into the subsoil. Field instances have been recorded by [12] to involve desiccation of CCLs and shrinkage of GCLs from temperature increase caused by UV radiation mostly associated tropical regions. Laboratory studies have also suggested that some GCLs are more liable to shrinkage than others with [13] providing review of works relating to the desiccation of CCLs and GCLs from thermal gradients generated by the dumped waste. Considering the numerical studies by [14] and the experimental data by [15], the following tentative conclusions were reached; the potential desiccation of composite barrier systems (both GM/GCL and GM/CCL) is controlled by the temperature gradient which affects the surface of the liner. This may be a function of landfill operation and the likely temperatures to be experienced by the barrier system need to be considered in landfill design.

For single composite barriers with a GCL, it was suggested that: (1) The unsaturated soil characteristics and initial water content of the foundation layer beneath the GCL can greatly influence the potential for desiccation. (2) The higher the overburden pressures at the time of GCL hydration, the lower the risk of desiccation. Thus, as suggested by landfill operators in Johannesburg, both the potential for short term (e.g., solar induced) and long term (biodegradation temperature induced) desiccation can be reduced by immediately placing the waste over the composite barrier after construction is concluded. These findings have considerable implications on the manner in which landfills within and outside South Africa should be designed and constructed. (3) Increasing distance to the underlying water table increased the risk of desiccation for aquifer depths up to about 5m below the GCL, but relatively little change was predicted for increased depths beyond 5m due to the offsetting effects of reduced water content and temperature gradient. However, for single composite barriers having a CCL, it was suggested that: (a) the unsaturated soil characteristics of the barrier significantly affects the distribution of moisture and stress. (b) The effect of overburden pressure was not as significant as for a GCL, although it reduces the risk of desiccation. Hence, the need for more investigations into the potential for long-term desiccation of clay barriers making up part of a composite system, with respect to the scarcity of relevant soil parameters is emphasized. Current findings suggest that there is real potential for desiccative impacts which can be avoided by appropriate design and construction.

**Leakage through Composite Lining Systems-Tears/Holes**

Where no tears/holes are present, a GM is effectively impermeable to water and hence, any leakage (advective transport) through GMs must be through holes in the GM as shown in Fig. 2. Based on 205 results as recorded by [1] from four published leak detection surveys it was found that: (i) no
holes were detected for 30% of the cases; and (ii) less than 5 holes/ha were detected for half of the surveys. After installation and placement of drainage layer, 3 holes/ha and 12 holes/ha were recorded by [16] respectively. This implies that defects in GM are inevitable either before or after installation. Since the leak detection surveys used to establish the number and size of holes stated above were conducted soon after construction of the barrier system, it is uncertain how many holes may develop under combined overburden pressures, elevated temperatures and chemical exposure years after construction and placement of the waste.

These holes may arise from: (a) indentations at gravel contacts following placement of the waste; (b) stress cracking at points of high tensile strain in wrinkles; and (c) sub-standard seams subjected to tensile stresses. Extensive works of leakage through composite lining systems based on both theoretical considerations and observed field behaviour have been recorded by [15] with just a brief summary presented herein. Leakage through composite barriers is mostly calculated using equations by [18]-[20]. The results obtained from these equations can be compared with the observed leakage through the primary barrier at a large number of landfills with double liner systems as reported by [21]. This comparison was done by [15] and was concluded that one cannot explain the typical observed leakage using the traditional equations as a reasonable number of holes/ha could be present yet unseen. The monitoring of flows in the leak detection system can provide pointers of when damage to the barrier has occurred. This may be mainly vital when the composite liner is composed of a GM and GCL. It has been shown that this combination generally gives a less leakage as compared to GM and CCL. Nevertheless, if not protected by a satisfactory cover layer or reliable system, it remains vulnerable to defects. Even if a landfill is well constructed, UV degradation and subsequent landfill activity such as waste transfer can cause holes through the entire GM/GCL primary barrier system. This in turn, can lead to flow in the leak detection system. The advantage of a double lined system is that it allows the detection of these accidents and their repair before too much waste has been placed over the site.

In the case of a single lined system, it is improbable that such a failure would be detected until the waste has all been dumped and becomes impracticable to fix. Hence, the need to place an appropriate protection layer above the composite liner to minimize the risk of such accidental damage is clear. This also points to the need to strictly monitor not only the construction of the liner but also any waste placement or other work that could potentially cause damage to the liner since a leak detection system does not form part of the barrier lining systems in some of the waste sites around Johannesburg.

**Internal Wash Offs/Erosion-Thinning of Barrier Systems**

GCLs are commonly utilized in applications where there may be several meters of fluid over the GCL (e.g. ponds, lagoons and landfills when leachate pools build up). Since GCLs are comparatively thin, these applications can give rise to high gradients and the potential for internal wash offs/erosion. This is particularly true when the GCL is placed over gravel or a geonet (e.g. in double lined facilities- as in the case of most landfills in Johannesburg). An analysis by [22] gave the implications of bentonite thinning/loss from GCLs used above geonet drainage layers and concluded that a bentonite loss in excess of about 100g/m² (i.e. about 2.5% of the initial bentonite mass) would negatively impact the permeability of the GCL. From the analysis, it was concluded that 10g/m² (i.e. about 0.25%) could be used as bench mark for allowable bentonite wash off. Failures have been recorded due to internal wash offs of barrier systems such as a field case reported by [23] where a GCL was used to line a lake. Investigations revealed “patchy” bentonite piping from the core of the GCL through the lightweight nonwoven geotextile resting on the coarse sand subgrade.

While researchers have shown that damaged GCLs can self-heal with only a slight increase in permeability, this self-healing process as reported by [24] can be compromised and considerable bentonite can be eroded if the damaged GCLs are placed on a coarse subgrade with large pore sizes. As such, increase in GCL bentonite loss automatically increases its permeability. However failures, characterized by a large increase in permeability of barrier systems, could initially be quite localized and in some cases failure may be associated with relatively little bentonite loss (as little as 1%). This posits that the limit proposed by [22] of about 10g/m² (about 0.25%) may be appropriate as a conservative limit in wash off scenarios. For this reason, it was concluded that designs involving GCLs over a gravel or geonet subgrade need to be carefully examined since internal erosion at water heads as low as 8m can cause an increase in the permeability to order of magnitude [25]. The works of [25] revealed that the choice of GCL carrier geotextile could appreciably impact the performance of GCL. Hence, this highlights the importance to carefully consider the choice of GCL in the context of the expected gradient and erosion conditions.

**Wrinkling and Debonding in Geomembranes**

Wrinkles and unsealing of bonds in a GM predominantly arise from thermal expansion when the GM is heated by the sun after placement. A theoretical analysis was performed by [26] that led to the conclusion that HDPE may be expected to exhibit large wrinkles with heights up to 10cm and widths up to 30cm with a case reported by [1] where there were 1200 wrinkles/ha. It was however emphasized at the visited sites in Johannesburg, that high density polyethylene (HDPE) geomembranes was more resistant to ultraviolet (UV) radiation than other geomembranes. Wrinkles are important to note because of the increased potential for contaminant migration through a hole in the GM at or near the wrinkle. There is also increased potential for development of future holes due to stress cracking at points of high tensile stress in the wrinkle. Since fluid entering a hole in a wrinkle can run along the entire interconnected length, the length of a wrinkle...
The presence of wrinkles can significantly increase the leakage through the composite liner. The wrinkles formed during placement of the GM do not necessarily disappear when the GM is covered and the waste is placed. Compression of these wrinkles due to loading can be expected to induce tensile strains in the GM and these may contribute to the formation of holes due to stress cracking. An examined interaction between the granular material and the wrinkle using a specially designed apparatus that allows the simulation of the foundation layer, composite liner with a wrinkle in the GM, the protection layer and the granular drainage layer was done by [27].

Attention have also been focused by [28] on the effect of wrinkle on GCL deformations and the effectiveness of different protection layers to minimize GCL deformations. They found the thickness of the GCL to decrease beside the wrinkle and increase beneath the wrinkle due to lateral extrusion of bentonite into the gap beneath the wrinkle. Without protection layer, the gravel backfill led to bentonite extrusion from beneath gravel contacts to zones in between particles causing large variations in the thickness of the GCL (with a minimum thickness of about 2mm). The sand protection layer redistributes the gravel contact stresses such that the majority of the GCL deformation was caused by consolidation of the bentonite rather than lateral extrusion. It was also recorded that, this is preferable because a relatively uniform reduction in void ratio from consolidation would be accompanied by a reduction in hydraulic conductivity. Nevertheless, while more research is needed, it appears that in order to provide the best performance of both the GM and GCL used in composite liners, a 150mm thick sand protection layer can best a thick nonwoven needle-punched geotextile (2000g/m²) on the base of a typical landfill.

**Geomembrane Service Life**

It has been recorded that even with typical wrinkles and holes in wrinkles, provided there is appropriate construction quality control and construction quality assurance (CQC/CQA), the leakage through composite barriers can be controlled to a large extent that percolation becomes not much of a threat but diffusion becomes the controlling transport mechanism. However, Geomembranes are also excellent diffusion barriers to ions (like chloride and heavy metals) and while volatile organic compounds can readily diffuse through the GM they can be controlled by design of the barrier system with an adequate attenuation layer [1] and [25]. This is under the condition that the GM is performing optimally. Nonetheless, GMs are susceptible to damage with a finite service life and their long-term performance will depend on their properties (e.g. stress crack resistance, crystallinity and oxidative induction time), the tensile strains, wrinkles (as earlier stated) and temperature. Degradation caused by UV radiation was a major issue peculiar to all the visited landfills. It is generally noted that UV degradation is a mitigating factor shortening the life span of GMs as well as chemical ageing. However, landfill experts on the visited sites noted that additives such as carbon black were used to improve UV resistance thereby, extending the service life of exposed GMs. The HDPEGM chemical ageing process is known for three distinct stages as recorded by [29] which are: (i) depletion time of antioxidants; (ii) induction time to the onset of polymer degradation; and (iii) degradation of the polymer to decrease some property (or properties) to an arbitrary level (e.g. to 50% of the original value). It has been reported that the consumption of antioxidants and subsequent oxidation reaction in polyethylene can be increased in the presence of transition metals (e.g. Co, Mn, Cu, Pd and Fe) present in landfill leachate [29]. Since it is impracticable to establish the service life under actual field conditions with immediate results, accelerated ageing tests are most often conducted at elevated temperatures and the results are then used to calculate the expected service life at the temperatures expected at the base of a landfill [29]. In most cases the testing to assess chemical ageing of GMs involves submerging samples in a fluid of interest and then, after different periods of submergence, samples are removed and tested to obtain the oxidative induction time (OIT).

It is vital to note that exposure conditions and temperature have a profound effect on the time to antioxidant depletion. In particular it is noted that there is a significant difference between immersion in water and leachate. As was demonstrated by [30] the primary factor affecting this difference is the presence of surfactant in the leachate. Volatile fatty acids and ions typically found in leachate (e.g. Na, Cl etc) have no major effect on the time to antioxidant depletion. It has been proven that for temperatures around 20°C, service lives reach the order of 565-900 years and hence a service life of 600 years (or more) could be anticipated at a temperature of 20°C (or less). For liners at a temperature of 35°C, the service life is of the order of 130-190 years. Finally at elevated temperatures of 50-60°C, the service lives are very short (15-50 years). In light of the pointer to the impact of temperature on barriers, it is noted that for an area where the background temperature is 15°C and assuming the primary GM temperature increases to 35°C (i.e. by 20°C), the secondary GM might be expected to be at about 30°C (assuming a primary composite liner with a GM, 0.75m compacted clay and an 0.3m thick gravel leak detection system). Under these circumstances it is suggested that the service life of the primary and secondary GMs would be of the order of 130-190 years and 205-315 years respectively. This offers a general idea of the order of magnitude of the GM service-life and highlights the importance of barrier temperature. While these numbers represent the best currently available information, they should be used with care since most results are not entirely based on actual tests on GMs typically utilized in landfill applications. This also reveals that while operational features such as operating a landfill as a bioreactor may shorten the period of high temperatures on the
lining system, the increase in temperature associated with this mode of operation can essentially decrease the overall service life. Hence, this emphasizes the importance of considering the mode of landfill operation when developing a barrier design.

CONCLUSIONS

Over the past decade, there have been immense advances and challenges in knowledge pertaining factors potentially impacting the utilization and performance of GCLs and GMs in a span of geoenvironmental applications. This paper highlighted a few of these issues based on site reconnaissance and related literature and the following conclusions were drawn based on relevant specific notes:

- Different GCLs have significantly different susceptibilities to internal erosion that can occur at high or low hydraulic gradients.
- Both GCLs and CCLs are vulnerable to shrinkage and desiccation when used as part of a composite barrier.
- Typical construction practice will result in GMs having a considerable number of wrinkles before covering.
- Under typical loads, wrinkles remain in the GM as gaps remain between the GM wrinkle and a GCL.
- Leakage for composite liners with CCLs and GCLs can be explained by holes for a number of holes/ha and combinations of numerical parameters.
- It is clear that a sand protection layer between the gravel and the GM (perhaps combined with a traditional nonwoven geotextile) provides the best potential long-term performance.
- The long-term service life of a GM will depend on the GM properties, the tensile strains in the GM, the exposure to chemicals in the leachate, and temperature.
- That GCLs and GMs can play a beneficial role in environmental protection.

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REFERENCES
