Resolving some of the outstanding issues in landfill barrier design

R. Kerry Rowe
GeoEngineering Centre at Queen’s-RMC
Department of Civil Engineering
Queen's University, Kingston, Ontario, Canada
kerry@civil.Queensu.ca

ABSTRACT: Geosynthetics play a very important role in modern barrier systems designed to control contaminant migration from waste disposal sites. This presentation discusses a number of instances where appropriate use of geosynthetics can improve landfill performance. It also discusses some of the issues that need to be examined in developing barrier designs that are likely to provide good long term landfill performance. The specific issues addressed are (1) the design of leachate collection systems (LCS) to minimize clogging; (2) the use of rubber tire shreds as an alternative drainage materials for LCS; (3) providing adequate protection to geomembrane liners; (4) the service life of geomembranes; (5) leakage (advective flow) through the liners; (6) diffusion of contaminants through liners; and (7) the use of geosynthetic clay liners (GCL’s) as an alternative to compacted clay liners (CCLs).

1 INTRODUCTION

This paper is not intended to be a primary reference but rather is directed at summarizing the key points to be raised in my oral presentation and to provide direction to the places where those interested in the topics discussed can find more information. The two key references upon which the keynote lecture is based are Rowe (2001) and Rowe et al. (2004), with the latter book providing the most recent summary of the state of the art with respect to barrier system design for landfills. Seven different issues related to the design of barrier systems and the role of geosynthetics with respect to the issues will be discussed. The following sections provide a brief summary with respect to each of these issues.

2 THE DESIGN OF LEACHATE COLLECTION SYSTEMS (LCS) TO MINIMIZE CLOGGING

Detailed field and laboratory studies of the clogging of municipal solid waste landfill leachate collection systems (see Rowe et al. 2004, Chapter 2) have indicted that:
- these systems must be designed recognizing that clogging can occur;
- a collection system has clogged when it no longer controls leachate to the design level in the landfill;
- clogging involves biological, chemical and physical processes; and
- the service life of LCS (i.e, how long they will serve their design function) is highly dependent on how they are designed.

These studies (e.g., Brune et al. 1991, Fleming et al. 1999) have shown that although substrate utilization by active micro-organisms drives the clogging processes in LCS, clogging of these systems is largely the result of biologically induced precipitation of inorganic constituents contained in leachate. Analyses of clog material both in the laboratory and the field provide very consistent results with 65% (or more) of mature clog material being calcium carbonate (CaCO₃).

Clogging of the collection system (typically involving a drop in hydraulic conductivity to about 10⁻⁸ m/s or lower) will give rise to leachate mounding, a consequent increase in the leachate head...
acting on the liner, and an increase in liner temperature (Barone et al. 1997; Rowe et al. 2004, Chapter 2). Systems involving French drains can be particularly problematic. Sand underdrains are also quite prone to clog (Rowe et al. 2004, Chapters 2 and 9). A coarse uniform gravel drainage blanket below the waste provides much better long term performance than a sand blanket, a geonet system or a French drain system. However, as shown by Fleming et al. (1999) the use of a suitable geotextile separator layer between the waste and the main drainage layer can substantially reduce clogging and prolong the service life of the gravel underdrain. Geotextiles do clog (Koerner et al. 1994) and it has been found that the use of geotextiles to wrap pipes or French drains can cause problems when the geotextile clogs. However provided that geotextiles are selected and used appropriately as a separator above a coarse granular drainage blanket (see Rowe et al. 2004, Chapter 2) they can be expected to improve the performance of the system even with clogging of the geotextile to the greatest levels reported in the literature.

3 THE USE OF RUBBER TIRE SHREDS AS AN ALTERNATIVE DRAINAGE MATERIALS FOR LCS

A comparative study of the clogging of tire shreds and gravel has been reported by Rowe and McIsaac (2004) based on tests involving shreds and gravel permeated with landfill leachate for up to two years. Two different types of tire shred (G shred: 100mm x 50mm x 10mm; and P shred: 125mm x 40mm x 10mm with many exposed wires) and a uniformly graded 38mm gravel were examined. The compressibility of the G and P shreds at 150kPa were found to be 48% and 44% respectively while the initial hydraulic conductivities were 0.007 m/s, 0.02 m/s respectively (compared to 0.8 m/s for the gravel). The gravel maintained a hydraulic conductivity greater than $10^{-5}$ m/s for about 3 times longer than a similar thickness of tire shreds. Some metals (e.g., iron and zinc) were found to leach from both the P and G shreds when exposed to typical MSW leachate, however they were then taken up in the clog material and were not detected at elevated levels in the effluent leachate. The highest concentration of metals was found in the P-shed clog and this is attributed to the greater abundance of exposed steel in these shreds. It was inferred that that gravel should continue to be used in critical zones where there is a high leachate mass loading. However the data suggests that an increased thickness of compressed tire shred may be used to give a service life similar to that of a given thickness of gravel in non-critical zones.

4 PROVIDING ADEQUATE PROTECTION OF GEOMEMBRANE LINERS

In addition to the obvious mechanisms of damage due to puncturing or tearing during construction, geomembranes can develop holes due to stresses that do not initially cause a hole but which act to cause stress cracking over time. Both forms of damage can be minimized by providing adequate protection. Protection layers may comprise sand, geotextiles or other geosynthetics (i.e., rubber geomats) or geocomposites (Rowe et al. 2004, Chapter 13).

Reddy et al. (1996) evaluated the damage to a 1.5 mm HDPE geomembrane due to construction loads and concluded that "a geotextile as light as 270 g/m²...completely protects the geomembrane from construction loading". While investigations such as this are useful for establishing the level of protection needed to minimize damage during construction, they do not consider the long term effects of stresses arising when the overburden stresses are in place. Narejo et al. (1996) go some way towards addressing this concern and have proposed empirical equations and a design methodology for selecting the mass per unit area (g/m²) of a nonwoven needle-punched geotextile required to prevent puncture in a 1.5 mm thick HDPE geomembrane under field stress conditions. This approach appears to provided levels of protection that will avoid puncture; however it was not developed to address the issue of long term stress cracking. To minimize the risk of stress cracking, Brummermann et al. (1995), Saathoff and Sehrbrock (1995), Bishop (1996) and Seeger and Müller
(1996) have recommend minimizing the geomembrane strain under long term loading condition to a very low (~0.25%) strain level.

Large scale laboratory tests conducted to assess the effectiveness of different protection layers have been reported by Zanzinger (1999) and Tognon et al. (2000). The results of Zanzinger (1999) likely underestimate the strains in the geomembrane since arch elongation was used to calculate strains from the measured deflections. The tests of Tognon et al. (2000) examined a range of protection materials for vertical pressures between 250 to 900 kPa. The smallest strains were obtained with the sand-filled cushion and a grid-reinforced rubber protection layer. The maximum strains of 13% calculated for 1200 g/m² geotextile protection at a vertical pressure of 900 kPa were very close to the short term yield strain. These tests highlight the need for protection over and above that commonly adopted and certainly support Narejo et al. (1996) recommendation of adopting a high factor of safety (3 or greater) when using their design methodology.

5 THE SERVICE LIFE OF GEOMEMBRANES

As discussed in detail by Rowe et al. (2004, Chapter 13), the service life of an HDPE geomembrane depends on the type and formulation of the polymer (e.g., crystallinity, stress crack resistance, and antioxidants), and the exposure conditions including: temperature, surrounding medium, chemical concentration, and long-term tensile stresses. Oxidative degradation is the principal mechanism of chemical ageing for HDPE geomembranes in landfills. The rate of oxidation is controlled by the amount of antioxidant in the geomembrane and the rate of antioxidant consumption and/or removal from the geomembrane. Geomembranes should have a specified minimum oxidative induction time (OIT).

The use of laboratory-accelerated ageing tests to examine the depletion of antioxidants from high density polyethylene (HDPE) geomembranes as a result of their exposure to various environments is discussed (Hsuan and Koerner 1998; Rowe and Sangam 2002; Sangam and Rowe 2003; Rowe et al. 2004, Chapter 13). The results indicated that the antioxidants are depleted at rates 1.6 to 2.4 times faster for samples in water than for air-exposed samples. For samples in leachate, the depletion is about 4 times faster than in air and 1.6 to 3.2 times faster than in water. Tests examining antioxidant depletion rates from accelerated ageing tests at elevated temperatures can be used to obtain lower bound estimates of geomembrane service life. Based on presently available data, a primary HDPE geomembrane liner with minimum specified properties (OIT, stress crack resistance etc; see GRI-GM13), has a service life greater than 200 years provided that the temperature is not higher than 15°C, whereas the service life is estimated to be reduced to 70 years if the temperature at the base of the landfill is at 33°C. These findings highlight the importance of controlling temperature on the liner.

6 LEAKAGE (ADVECTIVE FLOW) THROUGH THE LINERS

An intact geomembrane (i.e., one that is free of holes or tears) is essentially impermeable to water. However geomembranes will have some holes and the fluid that flows through these holes is referred to as “leakage”. The quantity of leakage depends on: the number and size of holes in the geomembrane, the hydraulic head acting above and below the composite liner, the hydraulic conductivity and thickness of any underlying soil, and the nature of the interface between the geomembrane and underlying material. Techniques for calculating the leakage through composite liners are described in detail by Rowe et al. (2004, Chapter 5). In this lecture issues such as the number of holes that might be expected, the effect of the number of holes on leakage, and the difference between leakage observed for composite liners involving compacted clay and GCL are discussed from both a theoretical perspective and from the perspective of observed field behaviour (Bonaparte et al. 1996; Othman et al. 1996). A detailed discussion of these issues is provided by Rowe et al. (2004, Chapter 13).
7 DIFFUSION OF CONTAMINANTS THROUGH LINERS

For well designed and constructed barrier systems the leakage through holes is very small and the primary mechanism for contaminant transport is molecular diffusion. Diffusion has been well documented over thousands of years from natural sources and over periods of up to 14 years from landfill sites (see Rowe et al. 2004, Chapter 9). Diffusion can occur through thick compacted clay liners (Rowe et al. 2003), GCLs (Lake and Rowe 2000, 2004) and geomembranes (Sangam and Rowe 2001b). HDPE geomembranes act as an excellent diffusion barrier to water and hydrated ions such as chloride with negligible migration being observed in tests that have been running for over a decade (Rowe et al. 2004, Chapter 13). However, for certain low solubility organic contaminants, diffusive migration may be quite significant for a well constructed liner (i.e., one with only a few holes), and should be considered if one is to ensure a safe design. While there can be diffusion through geomembranes, the combination of geomembrane, clay liner and, as needed, an attenuation layer can control the migration of these organic contaminants and provide negligible impact on groundwater (Sangam and Rowe 2001a; Rowe et al. 2004, Chapter 16).

8 GEOSYNTHETIC CLAY LINERS (GCL’S) AS AN ALTERNATIVE TO COMPACTED CLAY LINERS (CCLS)

Any assessment of the “equivalency” of GCLs and CCLs must consider the total design performance rather than individual properties. Rowe (1998), Shackelford et al. (2000), Manassero et al. (2000) and Rowe and Lake (2000) have discussed properties of a GCL important to an assessment of equivalency. Any assessment of the environmental protection afforded by the two systems should involve calculations that include consideration of the: (1) hydraulic conductivity of GCLs permeated with the leachate of interest (Petrov and Rowe 1997, Petrov et al. 1997a,1997b), (2) the effect of high gradients and potential for internal erosion (Rowe and Orsini 2003), (3) diffusion and sorption (Lake and Rowe 2000, 2004), (4) interface contact with any overlying geomembrane (Harpur et al. 1993), and (4) the thickness of the entire barrier system (Rowe and Brachman 2004). A qualitative comparison of GCLs and CCLs is given in Rowe et al. (2004, Chapter 12). For many criteria, the performance of a GCL is either equivalent to or better than that of a CCL. However, in terms of liner applications, both the liner itself and the underlying attenuation layer must be considered when examining contaminant transport and equivalency in terms of potential contaminant impact over the contaminating lifespan of the facility. This is discussed by Rowe et al. (2004, Chapter 16) and it is shown that provided the total thickness of liner and attenuation layer between the contaminant source and the receptor aquifer are similar, a liner system involving a geomembrane and GCL is comparable to (or better than) the system involving compacted clay from a contaminant transport perspective.

9 CONCLUSION

This presentation shows that considerable advances have been made in recent years with respect to the development and use of geosynthetics in landfill barrier applications. It has been shown that:

1) Leachate collection systems (LCS) can be designed of to minimize clogging and that appropriate use of geotextiles can results in an extended service life of these systems.

2) Subject to field verification of laboratory studies, rubber tire shreds may potentially be used as alternative drainage materials in non critical areas of LCS provided that the thickness of material is increases to make allowance for the difference in compressibility and porosity under compression. However conventional uniform coarse gravel should continue to be used in critical areas.
(3) More attention needs to be paid to providing adequate protection of geomembrane liners (GM) in order to achieve long service lifetimes for these liners.

(4) The service life of geomembranes is very sensitive to temperature. Based on current studies it appears that a suitable 1.5mm HDPE geomembrane that meets specified criteria (GRI-GM13), and is adequately installed and protected may have a service life greater than 200 years provided that the temperature is not higher than 15ºC, whereas the service life is estimated to be reduced to 70 years if the temperature at the base of the landfill is at 33ºC.

(5) Leakage (advective flow) through composite liners is highly dependant on the number of holes, the presence of wrinkles, and the nature of the interface between the geomembrane and clay liner. However the evidence also suggests that for well designed and constructed landfills, the leakage is very small throughout the service life of the leachate collection systems and the geomembrane. Under these conditions diffusion is likely the primary contaminant transport mechanism.

(6) Diffusion of contaminants through liners can be well predicted and assessed in design. By appropriate design of liner materials and attenuation layer, diffusion can be controlled to negligible levels at the receptor aquifer.

(7) With appropriate design and construction, geosynthetic clay liners (GCL’s) represent a viable alternative to compacted clay liners (CCLs).

ACKNOWLEDGEMENTS

This presentation has been made possible by research supported by the Ontario Centre for Research in Earth and Space Technology, Terrafix Geosynthetics Inc., Naue Fasertechnik GmbH & Co., and the Natural Sciences and Engineering Research Council of Canada

PRIMARY REFERENCES


OTHER REFERENCES CITED


