Review on performance of geosynthetic liners in municipal solid waste landfills

B.M. Sunil

Assistant Professor, Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, Srinivasnagar, Mangalore -575025, Karnataka, India.

ABSTRACT

Considerable development has taken place in the area of geosynthetics and their applications since their first use in 1980s in the construction of safe containment of hazardous wastes. Geosynthetic clay liner (GCL) and High density polyethylene (HDPE) geomembrane (GM) liners are widely used in municipal solid waste landfills as a barrier system on the base of the landfill. Satisfactory performance of geosynthetic materials when buried under soil depends on several factors. Geosynthetic liners are subjected to degradation by variation in temperatures or settling of landfills or they will be disintegrated by leachate. Several studies on monitored landfills have shown that geosynthetic liners in municipal solid waste landfills have performed extremely well at controlling leakage in field applications for a couple of decades. However, there have also been some problems reported on the very long term performance these materials. To ensure that long-term contamination does not occur, it is important that the durability of GCL and GM is maintained over the contaminating lifespan of the landfill. Some of the factors that influence very long term performance of GCL/GM/composite liners are particle size, strength and initial water content of subgrade soil, desiccation, the effect of daily thermal cycles etc. This paper examines some of these factors and the mechanisms of performance of geosynthetic liners were reviewed in order to supply reference to the study in this field.

Keywords: Compacted clay liner, Geosynthetic clay liner, Geomembranes.

1 INTRODUCTION

From the past few decades, liners have been an integral part of the engineered containment systems for both municipal solid waste as well as for hazardous waste landfills. Apart from engineered landfills more recent, applications include in mining industry where liners are becoming an essential component in surface impoundments, storage of industrial fluids etc. In mining, for many years, there has been a recognized need for engineered covers for minimizing impacts due to acid-generating waste rock; however, there is growing need for covers for other mine waste [(e.g., arsenic bearing gold mine tailings) (Rowe, 2013)].

Geosynthetic clay liners (GCLs), high-density polyethylene (HDPE) geomembranes (GMBs), compacted clay liners (CCLs), or the combination of the above mentioned liner systems have been successfully used all over the world in various geoenvironmental projects. For a landfill with a single liner, the barrier system typically involves a gravel leachate drainage layer, a protection layer, and a composite liner comprised of an HDPE geomembrane and either a geosynthetic clay liner (GCL) or a compacted clay liner (CCL) [Rowe and Rimal, 2007].

In the early sanitary landfills, there was always the danger that metals salts and other chemicals might leach from the fill and percolate through the underlying soil and contaminate nearby groundwater. Due to environmental reasons and in 1983 EPA has required that all landfills be built with an impermeable clay or plastic liner to prevent migration of waste water (leachate) emanating from the landfill (Buell and Girard, 1994). Since then, liner systems have been used in plenty of geoenvironmental projects worldwide.

According to Rowe (2013), HDPE-GMBs have been used in landfill liners and covers, and for liners in ponds and heap leach pads for mining applications, but there has also been growing use of linear low-density polyethylene GMB liners in heap leach applications. Geosynthetic clay liners (GCLs) and compacted clay liners (CCLs) have been used alone in covers and in some bottom liners; however, GCLs used in landfill applications are most commonly used with a GMB to form a composite liner.

The satisfactory field performance of liners used in landfills depend on several factors. Given the long
history of the use of liners in landfills and based upon the available data Rowe (2013), describes that well-designed and constructed composite bottom liners have performed very well. However, there have been challenges too. A number of studies have suggested that the low hydraulic conductivity of the clay barriers can be compromised by alternate wet/dry cycling, freeze-thaw cycles, (Zimmie and LaPlante 1992; Melchior 1997; Albright and Benson 2001; Albright et al. 2006).

2 COMPACTED CLAY LINERS

Construction or installation of liners at sanitary landfills and hazardous waste sites has been one of the commonly recommended methods of containment and control. The primary function of a liner is to prevent, or limit the amount of leachate that might ultimately reach the groundwater. For this reason, liners must have appropriate properties to restrict leachate migration so that a chosen landfill site is ideal and provide ultimate containment (US EPA, 1990). Desirable properties of a liner materials include (i) low permeability, (ii) high adsorption capacity and (iii) resistance to chemical, biological and mechanical breakdown. Compacted clay has traditionally been used as a lining material in municipal solid waste landfills (Daniel 1993, Sharma and Reddy 2004, Guney et al. 2008). In recent years, the lack of availability of natural clays with satisfactory engineering properties has prompted researchers to look for alternative approaches for liner design. Nayak et al., 2014, studied the suitability of shedi soil (local name) blended with bentonite clay to use as a compacted clay liner in municipal solid waste landfill. The compaction curve of blended soil investigated in laboratory is shown in Fig. 1.

2.1 CCL construction and hydraulic conductivity

Soil liners are constructed in lifts that typically have a maximum thickness after compaction of 150 mm. Prior to using for construction, the soil liner material is tested in the laboratory to determine its permeability, swell potential and strength at the required water content. From Fig. 2, it is observed that as the moulding water content increases the corresponding hydraulic conductivity decreases. In order to obtain the required hydraulic conductivity value (i.e. k<10^{-7} cm/s) the minimum degree of saturation required for the study soil is about 85%. The acceptable range of water contents within which the compacted soil will exhibit hydraulic conductivity ≤ 1 × 10^{-7} cm/s, volumetric shrinkage ≤ 4% and unconfined compressive strength ≥ 200 kPa is shown in Fig. 3.

Most crucial is the hydraulic conductivity test and studies (in laboratory) have shown that low hydraulic conductivity is easier to achieve when the soil is compacted wet of optimum water content with proper kneading of soil and compactive energy (Daniel 1993). However studies have also shown that compacted fine grained soils crack due to volumetric strain caused by desiccation (Albright et al. 2006) thereby compromising the integrity of a liner system. The in-situ and laboratory tests conducted by Albright et al. (2006), indicated that the hydraulic conductivity increased approximately three orders of magnitude.
Clay liners are usually compacted near or above the optimum water content to attain maximum density, to minimize swelling, and to attain the lowest possible values of flow (Lambe, 1955). In general, field hydraulic conductivity will be different from the laboratory values and may be regarded as the conductivity at some effective resultant linear porosity. Hydraulic conductivity also varies depending on kind of compaction and initial water content. Cary et al. (1943) and Mitchell et al. (1965) have found that hydraulic conductivity of clay soils compacted just below the optimum could be several orders of magnitude greater than in soils compacted just above the optimum. Therefore understanding the description of a flow regime in field is a tedious task. Further, a compacted clay liner, may react in different ways leading to changes in hydraulic conductivity (Nayak et al. 2007, Sunil et al. 2009, Nayak et al. 2010). Fig. 4 shows the effect of leachate permeation on the hydraulic conductivity of lateritic soil. With increase in leachate concentration the hydraulic conductivity of lateritic soil increases (Nayak et al. 2007). Similar observations were reported on the soils permeated with sodium chloride solution (Nayak et al. 2010).

![Fig.4 Variation of hydraulic conductivity with concentration of leachate added](Nayak et al. 2007).

Based on their studies Nayak et al. (2014) conclude that low hydraulic conductivity, adequate strength, minimal potential to shrinkage, good adsorption characteristics combined with their availability make blended sheds a potential material for use as compacted soil liners in landfills for environmental protection.

3 GEOSYNTHETIC CLAY LINERS

In view of construction quality control, and issues related to short term or long term performance of CCLs the recent trend is to use geosynthetic clay liners in various geoenvironmental applications.

Geosynthetic clay liners (GCLs) are factory manufactured hydraulic barriers consisting of a layer of bentonite clay supported by geotextiles and/or geomembranes, which are mechanically held together by needling, stitching or chemical adhesives (Koerner, 1986). First use in the United States was in 1986 in solid waste containment as a backup to a geomembrane (Koerner, 1986). Since then, GCLs have gained widespread popularity as a substitute for compacted clay liners in cover systems and composite bottom liners. They are also used as environmental protection barriers in transportation facilities or storage tanks, and as single liners for canals, ponds or surface impoundments. As a result, they are being investigated intensively, especially in regard to their hydraulic and diffusion characteristics, chemical compatibility, mechanical behaviour, durability and gas migration (Bouazza, 2002). The superiority of the GCLs over the CCLs provided by different authors referring to different criteria is given in Table 1. It is evident from Table 1, that in most cases the performance of GCLs exceed that of CCL. However, from the considerations of solute flux and breakthrough time, compatibility, and attenuation capacity favour the use of CCLs as liner systems. To account for this HDPE-geomembranes (GMs) have been used in combination with GCLs.

3.1 Chemical compatibility of GCLs

Laboratory conductivities to water of different types of GCLs vary between $2 \times 10^{-12}$ and $2 \times 10^{-10}$ m/s, depending on applied confining stress (Bouazza, 2002). However, GCLs are more often used to contain liquids other than water and hence the evaluation of hydraulic conductivity of GCLs when acted upon by chemical solutions is of utmost importance. Rowe and Rimal (2008) described laboratory-accelerated aging experiments conducted to examine the depletion of antioxidant from a geomembrane (GM) underlain by a geosynthetic clay liner (GCL). Based on Arrhenius modeling, Rowe and Rimal (2008), indicated that the time required for depletion of antioxidants at 35°C is estimated to be 65 years for a GM with a GT-GCL protection layer, 50 years for a GT-sand-GT layer, and 40 years for a conventional GT protection layer. These times are all significantly greater than the depletion time for GM immersed in leachate (10 years) for the geomembrane tested. A detailed summary of issues related to GCL chemical compatibility are provided by Rowe (1998) and Shackelford et al. (2000) and Bouazza (2002).

3.2 Effect of moisture variation

Rowe (2013) describes that the performance of a GCL as a barrier to fluids (either liquid or gas) is
intimately linked to the uptake of moisture by the bentonite in the GCL and its resulting degree of saturation. The extent of changes in GCL due to moisture variation which are very crucial in long term performance are dealt in detail and are provided by Beddoe et al., 2010, Beddoe et al., 2011, Rayhani et al. (2011), Anderson et al. (2012), and Rowe (2013).

3.3 Strength of GCL

The internal shear strength of GCLs will be influenced by different components like bentonite clay, needled or stitched fibers that penetrate through the thickness of the GCL and an adhesive used to bond the clay to the geotextiles.

According to Richardson (1997), each of these components are responsible to provide internal shear strength that is affected by the clay's degree of hydration, the normal load acting on the GCL and the shear strain that has occurred across the GCL.

The long-term internal shear strength of a GCL is important for the safe construction, operation and long-term closure of a contemporary landfill. Under low normal loads, this internal shear strength is significantly influenced by the strength and bonding of the needled fibers (Richardson 1997). The GCL internal strength requirements are dealt in detail and are provided by Richardson (1997).

According to McCartney et al. (2009), the interface shear strength was found to be sensitive to the type of GCL internal reinforcement, geomembrane polymer and geomembrane texturing, but not to the geomembrane thickness of manufacturer.

A database of 534 GCL-GM interface shear strength tests was analyzed and are provided by McCartney et al. (2009).

3.4 Performance of GCL

Successful performance of a system is the end objective of any design. Accordingly, site specific design issues, GCL chemical, hydraulic and structural characteristics are relevant to establishing performance criteria of GCLs.

Hydraulic properties can be evaluated in terms of desiccation/rehydration effects, the specific hydraulic conductivity as well as the overall GCL flux efficiency. Hydraulic properties are related to the application of normal load, the effectiveness of polymer or other chemical additives, influences of adhesives, needle-punched fiber density as well as the first fluid of hydration. Structural categories include GCL internal or interface characteristics, the overall dimensional stability of the product, geotextile or geomembrane characteristics, needlepunching or reinforcing structure effectiveness as well as general product durability.

According to Rowe (2013), the well-designed and constructed composite bottom liners have performed very well in landfills. Apart from landfills (municipal or hazardous waste landfills) composite liners are now being used in mining and various other industrial applications. The design parameters in such environments are entirely different. Typical examples include liners for bioreactors, brine ponds, heap leach pads etc. Row (2013), opines that there is a need for research to examine the effect of these temperatures and the exposure to different chemicals on short- and long-term liner performance.

Table 1. Potential equivalency between geosynthetic clay liners (GCLs) and compacted clay liners (CCLs) [Bouazza, 2002]

| Category               | Criterion for evaluation                        | Equivalency of GCL to CCL |
|------------------------|-------------------------------------------------|---------------------------|
|                        |                                                  | GCL probably Superior     |
|                        |                                                  | GCL probably equivalent   |
|                        |                                                  | GCL probably equivalent   |
|                        |                                                  | Site or product dependent |
| Construction issues    | Ease of placement                               | X                         |
|                        | Material availability                           | X                         |
|                        | Puncture resistance                             | X                         |
|                        | Quality assurance                               | X                         |
|                        | Speed of construction                           | X                         |
|                        | Subgrade condition                              | X                         |
|                        | Water requirements                              | X                         |
|                        | Weather constraints                             | X                         |
| Contaminant transport  | Attenuation capacity                            | X^a                       |
|                        | Gas permeability                                | X                         |
|                        | Solute flux and Breakthrough time               | X                         |
| Hydraulics issues      | Compatibility                                   | X^b                       |
|                        | Consolidation water                             | X                         |
|                        | Steady flux of water                            | X^c                       |
|                        | Water breakthrough time                         | X                         |
| Physical/ mechanical   | Bearing capacity                                | X^d                       |
|                        | Erosion                                        | X                         |
|                        | Freeze-thaw                                    | X                         |
|                        | Settlement-total                                | X                         |
|                        | Settlement-diffential                           | X                         |
|                        | Slope stability                                 | X                         |
|                        | Wet-dry                                        | X                         |

4 SUMMARY AND CONCLUSIONS

In considering the field performance of compacted clay liners (CCLs), construction quality control play a very important role to achieve the desired low hydraulic conductivity (k = 1x10^{-7} cm/s) as recommended by the standards. Otherwise, field performance of CCLs will be pathetic leading to serious health and environmental concerns. Substandard quality of CCLs mainly result due to lack of proper knowledge of materials and their interaction, poor construction practices and not
anticipating the future performance of the material put to use. Studies from different authors indicated that in field CCLs having $k = 1 \times 10^{-7}$ cm/s can be constructed with a broad variety of clayey soils. Adding right amount of moisture content (wet of the line of optimums), maintaining the same (i.e. at wet of the line of optimums) after proper compaction with appropriate type of equipment(s) are crucial to have a good lining system for containment facilities. However, maintaining right amount of moisture in the clay liner is a challenging task due to various reasons. Studies have shown that thicker clay liners tend to have lower field hydraulic conductivity and more emphasis should not be placed on the concept of percent compaction.

With the first use of GCLs in 1986 and their widespread popularity made GCLs a good substitute for CCLs in bottom liners and in covers systems of municipal or hazardous waste landfills. As reported by researchers the added advantage of GCLs or geomembranes is that they have very low hydraulic conductivity to water and they can maintain their hydraulic integrity over the long term. More recently, GCLs/geomembranes or composites are successfully being applied in mining and other industrial application where the anticipated conditions on the liner system are entirely different. This has opened up a new area and scope for research work in geoenvironmental engineering.

REFERENCES

1) Albrecht, B. and Benson, C. (2001): Effect of desiccation on compacted natural clays, _J. of Geotech. and GeoEngr.,_ 127(1),67-76.

2) Albright, W., Benson, C., Gee, G., Abichou, T., Tyler, S., and Rock, S., (2006): Field performance of a compacted clay landfill final cover at a humid site, _J. of Geotech. and GeoEngr.,_ 132(11),1393-1403.

3) Anderson R., Rayhani, M.T. and Rowe R.K., (2012): Laboratory investigation of GCL hydration from clayey sand subsoil, _Geotechnics and Geomembrane_, 31, 31-38.

4) Beddoes R.R., Take W.A., and Rowe R.K. (2010): Development of suction measurement techniques to quantify the water retention behaviour of GCLs. _Geosynthetics International_ 17(5), 301-312.

5) Beddoes R.R., Take W.A., and Rowe R.K. (2011): Water retention behaviour of geosynthetic clay liners, _J. of Geotech. and GeoEngr.,_ 134(7),906-916. _Geosynthetics International_ 137(11), 1028-1038.

6) Benson, C.H., Daniel, D.E. and Boutwell, G.P., (1999): Field performance of compacted clay liners, _J. of Geotech. and GeoEngr._ 125(3), 390-403.

7) Benson, C.H., Zhai, H., and Wang X. (1994): Estimating hydraulic conductivity of compacted clay liners, _J. Geotech. Engrg._ 120(2), 366-387.

8) Bouazza, A. (2002): Review Article Geosynthetic clay liners, _Geotextiles and Geomembranes_, 20, 3-17.

9) Buell, P., and Girard J. (1994): Chemistry An Environmental Perspective, _Prentice-Hall Inc._ New Jersey.

10) Cary, A.S., Walter, B.H., and Harstad, H.T., (1943): Permeability of mud mountain core material, ASCE, 108,(719-737).

11) Daniel, D.E. (1984): Predicting hydraulic conductivity of clay liners, _J. Geotech. Engrg._ 110, 285-300.

12) Daniel, D.E. (1993): Case histories of compacted clay liners and covers for waste disposal facilities, _Proceedings of the 3rd International Conference on Case Histories in Geotechnical Engineering_, St. Louis, Missouri, USA, 1407-1425.

13) Guney, Y., Koparal, S., and Aydilek, A.H. (2008): Sepiolite as an alternative liner material in municipal solid waste landfills, 134(8),1166-1180.

14) Korner, R. M., (1994): Designing with geosynthetics, _Prentice-Hall Inc._ New Jersey.

15) Lambe, T.W., (1955): The permeability of fine-grained soils, Symposium on Permeability of Soils, ASTM STP 163, Am Soc of Testing and Materials 240, Ilg.

16) McCartney J., Zomberg J., and swan R. (2009): Analysis of a large database of GCL-Geomembrane interface shear strength results, _J. of Geotech. and GeoEngr._ 135,209-223.

17) Melchior, S. (1997): Insitu studies on the performance of landfill caps, _Proceedings of International Containment Technology Conference_, St. Petersburg, FL, 365-373.

18) Mitchell, J.K., Hooper, D.R., and Campanella, R.G (1965): Permeability of Compacted clays, ASCE: J. Soil Mechanics and Found Div, 91(SM4), 41-65.

19) Nayak S., Sunil B. M., and Allamprabhu K. (2014): Assessment of blended lithomargic clay as landfill liner material, _J. Current Advances in Civil Engineering_, 2(4), 102-107.

20) Nayak S., Sunil B.M., and Shrihari S. (2007): Hydraulic and compaction characteristics of leachate contaminated lateritic soil, _J. Engineering Geology_, 94(3–4), pp.137-144.

21) Nayak S., Sunil B.M., Shrihari S. and Sivapullaiah, P.V. (2010): Interactions between soils and laboratory simulated electrolyte solution contaminated lateritic soil, _J. Geotech Geol.,_ 94(3-4), 137-144.

22) Richardson G. (1997): Geotechnical Fabrics Report, 20-25.

23) Rowe, R.K. (1998): Geosynthetics and the Minimization of Contaminant Migration through Barrier Systems Beneath Solid Waste. _Proceedings of the Sixth International Conference on Geosynthetics_, Vol. 1, Atlanta, 27–102.

24) Rowe, R.K. (2010): Short-and lon- term leakage through composite liners. The 7th Arthur Casagrande Lecture, _Can. Geotech. J._, 49, 141-169.

25) Rowe, R.K. (2013): Performance of GCLs in liners for landfill and mining applications, _Environmental Geotechnics, 1(EG1),_ 3-21.

26) Rowe, R.K., and Rimal, S. (2008): Aging of HDPE geomembrane in three composite landfill liner configurations, _J. of Geotech. and GeoEngr._, 1342(7),906-916.

27) Shakesford, C.D., Benson, C.H., Katsumi, T., Edil, T.B., Lin, L., (2000): Evaluating the hydraulic conductivity of GCLs permeated with nonstandard liquids. Geotextiles and Geomembranes 18 (2–4), 133–161.

28) Sharma, H. D., and Reddy K. R., (2004): Geoenvironmental Engineering- Site Remediation, Waste Containment and Emerging Waste Management Technologies, _John Wiley & Sons Inc._ New Jersey.

29) Sunil, B.M., Shrihari S., and Nayak S. (2009): Shear strength characteristics and chemical characteristics of leachate contaminated lateritic soil, _J. Engineering Geology_, 106(1), pp.20-25.

30) Zimmie, T.F., and LaPlante, C.M. (1992): The effects of freeze-thaw cycles on the permeability of a fine-grained soil, _Proceedings of the 22nd Mid-Atlantic Industrial Waste Conference_, Philadelpiu, 580-593.