Geosynthetic clay liners

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Review Article

Geosynthetic clay liners

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Abstract

Over the past decade, geosynthetic clay liners (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. In this paper, a review of the main findings is presented with the focus on the critical aspects affecting the service life of GCLs. From this work, a general insight is gained on the design implications for systems that incorporate GCLs. © 2002 Published by Elsevier Science Ltd.

Keywords: Bentonite thinning; Chemical compatibility; Equivalency; Gas migration; Geosynthetic clay liners; Hydraulic conductivity; Slope stability

1. Introduction

Over the past decade, design engineers and environmental agencies have shown a growing interest in the use of geosynthetic clay liners (GCLs) as an alternative to compacted clays in cover systems or in some cases bottom lining of waste containment facilities because they often have very low hydraulic conductivity to water ($k_w < 10^{-10}$ m/s) and relatively low cost. Apart from environmental application, e.g. use as a component of liner or cover systems in solid waste containment, GCLs are also used as environmental protection barriers in transportation facilities (roads and railways) and geotechnical applications such as minimizing pollution of

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subsurface strata from accidental spills and seepage of chemicals from road accidents. GCLs are also used as secondary liners for underground storage tanks at fuel stations for groundwater protection, and used as single liners for canals, ponds or surface impoundments. This increased interest stems from two factors:

1. Better knowledge about the material performance, which resulted from a large body of research publications presented, in a rough chronological order, in the following: USEPA Workshop on GCLs (1993), International Symposium on GCLs, Nurnberg, Germany (1994), ASTM symposium on testing and acceptance criteria for GCLs, Atlanta, USA (1996), GeoBento, Paris, France (1998) and the Geotextile and Geomembrane special issue on GCLs (2000). In addition, a large number of papers on the subject of GCLs have also been published in refereed geosynthetic, geotechnical and geoenvironmental journals and conference proceedings.
2. Increased confidence of regulators and designers.

The present paper will summarize some of the main research findings that have occurred over the past decade.

2. Geosynthetic clay liners

GCLs are comprised of a thin layer of sodium or calcium bentonite bonded to a layer or layers of geosynthetic. The geosynthetics are either geotextiles or a geomembrane. Geotextiles-based GCLs are bonded with an adhesive, needlepunching, or stitch-bonding, with the bentonite contained by the geotextiles on both sides. The needlepunching process causes some fibres from the top geotextile to extend through the bentonite and bottom geotextile, bonding the entire structure together (von Maubeuge and Heerten, 1994). The fibres that are punched through the bottom geotextile either rely on natural entanglement and friction to keep the GCL together or are heated causing them to fuse to the bottom geotextile, potentially creating a stronger bond between the two geotextiles and bentonite (in this case they may be referred to as "thermal locked GCLs"). Alternatively, the reinforcement can be carried out by sewing the entire geotextiles–bentonite composite together with parallel rows of stitch-bonded yarns.

For the geomembrane-supported GCL, the bentonite is bonded to the geomembrane using a nonpolluting adhesive and a thin open weave spun-bound geotextile is adhered to the bentonite for protection purposes during installation. Due to the flexibility of production and rapid innovation, the performance of the different types of GCLs may vary significantly. The primary differences between GCLs are the mineralogy and form of bentonite (e.g., powder versus granular, sodium versus calcium, etc.) used in the GCL, the type of geotextile (e.g., woven versus nonwoven geotextiles) or the addition of a geomembrane, and the bonding methods.

The main advantages of the GCL are the limited thickness, the good compliance with differential settlements of underlying soil or waste, easy installation and low cost. On the other hand, the limited thickness of this barrier can produce:

Table 1
Advantages and disadvantages of GCLs (modified from Bouazza, 1997)

Advantages	Disadvantages
Rapid installation/less skilled labour/low cost	Low shear strength of hydrated bentonite (for unreinforced GCLs)
Very low hydraulic conductivity to water if properly installed	GCLs can be punctured during or after installation
Can withstand large differential settlement	Possible loss of bentonite during placement
Excellent self-healing characteristics	Low moisture bentonite permeable to gas
Not dependent on availability of local soils	Potential strength problems at interfaces with other materials
Easy to repair	Smaller leachate attenuation capacity
Resistance to the effects of freeze/thaw cycles	Possible post-peak shear strength loss
More airspace resulting from the smaller thickness	Possible higher long term flux due to a reduction in bentonite thickness under an applied normal stress
Field hydraulic conductivity testing not required	Possible increase of hydraulic conductivity due to compatibility problems with contaminant if not prehydrated with compatible water source
Hydrated GCL is an effective gas barrier	Higher diffusive flux of contaminant in comparison with compacted clay liners
Reduce overburden stress on compressible substratum (MSW)	Prone to ion exchange (for GCLs with sodium bentonite)
	Prone to desiccation if not properly covered (at least 0.6 m of soil)

(1) vulnerability to mechanical accidents, (2) limited sorption capacity, and (3) an expected significant increase of diffusive transport if an underlying attenuation mineral layer is not provided. Moreover, when hydrated with some types of leachates instead of pure water, bentonite will show a minor swelling that will result in reduced efficiency of the hydraulic barrier. Advantages and disadvantages of GCLs are summarized in Table 1.

As the use of the GCLs broadens, they are being investigated intensively, especially in regard to their hydraulic and diffusion characteristics, chemical compatibility, mechanical behaviour, durability and gas migration (Bouazza et al, 1996; Petrov et al. 1997a, b; Fox et al., 1998a, b; Daniel et al., 1998; Lake and Rowe, 2000; Shackelford et al., 2000; Mazzieri and Pasqualini, 2000; Vangpaisal and Bouazza, 2001, amongst many others).

3. Hydraulic conductivity, chemical compatibility and diffusion

The hydraulic performance of GCLs depends in most cases on the hydraulic conductivity of the bentonite. The only exceptions are GCLs containing a geomembrane where the geomembrane is seamed during construction (e.g., with a cap strip). In general, laboratory hydraulic conductivities to water of different types of geotextile-supported GCLs vary approximately between 2×10^{-12} and

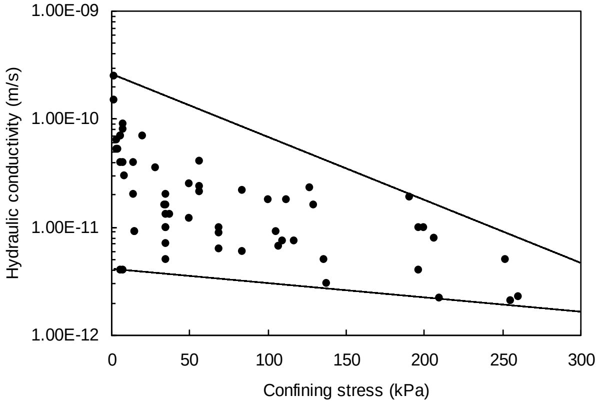

Fig. 1. Variation of hydraulic conductivity versus confining stress (results compiled from various sources).

2×10^{-10} m/s, depending on applied confining stress (Fig. 1). Petrov et al. (1997a) attributed the reduction in GCL hydraulic conductivity to lower bulk void ratios resulting from higher confining stresses. More importantly, they showed that there is a strong correlation between the bulk void ratio and the hydraulic conductivity, k, for a given permeant.

GCLs are often used to contain liquids other than water, in this case the evaluation of hydraulic conductivity of GCLs when acted upon by chemical solutions is of a paramount importance. Hydraulic conductivity to the actual permeant liquid is usually assessed by a "compatibility test" where the specimen is permeated with the liquid to be contained or a liquid simulating the anticipated liquid. GCL compatibility with various permeants has been studied by a number of researchers and evaluated for numerous projects (Shan and Daniel, 1991; Rad et al., 1994; Ruhl and Daniel, 1997; Petrov et al., 1997a, b; Petrov and Rowe, 1997; Rowe, 1998; Shackelford et al., 2000; Mazzieri et al., 2000; Jo et al., 2001). The GCL features, which influence their hydraulic conductivity with liquids other than water are: aggregate size, content of montmorillonite, thickness of adsorbed layer, prehydration and void ratio of the mineral component. On the other hand, the main factors related to the permeant that influence the hydraulic conductivity are: concentration of monovalent and divalent cations. When performing these tests, it is important to monitor the chemical composition in permeant influent and effluent and that sufficient pore volumes of the permeant has passed through the sample to ensure that chemical equilibrium has been reached. Furthermore, it is recommended that the height of the GCL be constant before terminating these types of tests. A detailed summary of issues related to GCL chemical compatibility is provided by Rowe (1998) and Shackelford et al. (2000).

Diffusion is a chemical process involving contaminant migration from areas of higher concentration to areas of lower concentration even when there is no flow of water. The diffusive behaviour of inorganic contaminants through a GCL has been reported recently by Rowe (1998) and Lake and Rowe (2000). Their main findings can be summarized as follows: (1) void ratio and related confining stress have a strong influence on diffusion coefficient, (2) the solute concentration level can give significant variation in the diffusion coefficients due to the modification of the microstructure of the sensitive mineral component (in particular sodium bentonite). On the other hand, GCL manufacture process was found to not significantly affect the diffusion coefficient.

4. Punctures, bentonite thinning, internal erosion, ion exchange

GCLs are susceptible to accidental punctures, which might occur during handling and installation. In this respect, their hydraulic performance can be compromised depending on the level of damage incurred. It has been shown that small penetrations or defects can be effectively sealed by the sodium bentonite in the GCL, with a minor increase in the hydraulic conductivity of the damaged specimen compared to intact specimens (Shan and Daniel, 1991; Bouazza et al., 1996; Mazzieri and Pasqualini, 2000). Furthermore, the healing kinetics of open holes up to 30 mm diameter show that only a short time (15 days) is necessary to totally heal the defect (Didier et al., 2000b). More importantly, Didier et al. (2000b) found that the stability of the self-healing area depended on the hydraulic head, it was observed that failure of the self-healed area occurred when the hydraulic head was >1 m (under a 10 kPa confinement). Although it is established that the self-healing capacity of sodium bentonite GCLs is high, experimental evidence published recently show that this capacity can be impeded if the self-healing process is coupled with ion exchange (Lin and Benson, 2000; Mazzieri and Pasqualini, 2000).

A number of case histories related to GCL in situ defects have been reported in the literature. Mazzieri and Pasqualini (1997) reported on a case where an adhesive bonded GCL was punctured by plant roots, resulting in an increase in the hydraulic conductivity. However, Daniel (2000) pointed out that the source of high hydraulic conductivity was likely to be the root itself, not the seal between the bentonite and the perimeter of the root. This was further confirmed by Didier et al. (2000b) who showed that a very good seal can be obtained around objects inserted in GCLs. Peggs and Olsta (1998) describe a case study where a GCL was severely punctured by the subgrade stones and compromised its hydraulic performance, but this was more a design issue rather than a performance issue.

The hydraulic performance of geotextile-supported GCLs depends also on the distribution of bentonite mass/area within the material. Once hydrated, the bentonite has a very low shear strength, it is possible in this case that stress concentration activities and permanent structural loads may cause the bentonite to squeeze laterally and lead to a local reduction in thickness which in its turn can cause a higher liquid flux at these locations (Koerner and Narejo, 1995; Fox et al., 1996). To avoid local bentonite displacement, and consequent possible impact on the hydraulic performance of a GCL, a cover soil of suitable thickness and particle size should be placed over a GCL before it hydrates and before it is subjected to concentrated surface loads. The presence of coarse-grained material, such as gravel, overlying a GCL can also be another cause of bentonite migration due to stress concentration. However, it was found that the effect on hydraulic conductivity is insignificant even at high confining stress (Fox et al., 1998b, 2000). Another potential source of stress concentration is the presence of wrinkles in an overlying geomembrane, these may create a void or area of reduced stress into which bentonite in an underlying GCL could migrate (Stark, 1998). The choice of subgrade is another important consideration for the installation of GCLs. Like the cover soil, the subgrade on which the GCL is installed should be suitable with respect to particle size. Daniel (2000) discusses steps that can be taken to minimize bentonite thinning in GCLs.

The process of internal erosion involves the movement of fine particles due to the presence of a high hydraulic gradient (typical in fluid containment facilities). Stam (2000) reported a case where abnormal leakage was observed in a GCL-lined lake. Excavation of the installation revealed areas of "patchy" bentonite piping through the lightweight nonwoven geotextile of the GCL into the coarse sand subgrade to a depth of 15–20 cm. Recent work by Orsini and Rowe (2001) indicated that at a high gradient, there is potential for piping of the GCLs when used in contact with a pea gravel subgrade. Another scenario, which can be considered is a geotextile-supported GCL overlying a leachate collection layer (coarse-grained material or geonet). The possible accumulation of bentonite fines in the drainage layer may have a detrimental effect on the hydraulic transmissivity of the drainage layer and lead eventually to the failure of the leachate collection system. Giroud and Soderman (2000) provide a detailed analysis of the mechanisms and consequences of bentonite migration from a GCL. They proposed a criterion for acceptable bentonite migration. The criterion sets the limit for acceptable bentonite migration, into a geonet drainage layer, at 10 g/m^2. At this limit, the drainage layer is not significantly affected. Another way of avoiding bentonite loss from geotextile-supported GCL is to use an additional geotextile filter between the GCL and the drainage layer (Estornell and Daniel, 1992).

The issue of cation exchange-induced changes in hydraulic conductivity, for GCLs with sodium bentonite, has received a lot of attention recently (Dobras and Elzeas, 1993; James et al., 1997; Melchior, 1997; Lin and Benson, 2000). This attention stems from the fact that an increase in the GCL hydraulic conductivity (one to two orders of magnitude) has been observed when in contact with calcium-rich soils or calcium solutions. These observations are related to GCLs subjected to low compressive pressures (<20 kPa), typical of landfill cover systems. It is expected that at high compressive pressures such as encountered in bottom liners of landfills no detrimental effect would be observed (Daniel, 2000). A detailed summary on ion exchange problems is also given in Egloffstein (2000).

One of the main problems encountered in the post-closure of a landfill is the internal cap distress due to subsidence. Indeed, the heterogeneous waste composition and ageing process (waste biodegradation) can lead to substantial differential settlement of the cover system which in turn may lead to zones of tension cracking. It was shown that GCLs could withstand distortion and distress while maintaining their low hydraulic conductivity (Bouazza et al., 1996; LaGatta et al., 1997).

5. Gas permeability and diffusion

The migration of gas into or from waste containment facilities capping systems has received a lot of attention recently. With GCLs being increasingly used as part of the capping, their gas performance has come under a growing scrutiny. In the context of landfills, the primary driving force for gas migration, especially through cover systems, is pressure differentials due to natural fluctuations in atmospheric pressure (barometric pumping). An elevated leachate/water table and temperature gradient can also give rise to pressure differences and lead to gas migration. Gas movement by diffusion can also occur due to molecular interactions. When a gas is more concentrated in one region of a mixture more than another, it is likely that this gas diffuses into the less concentrated region. Thus, the molecules move in response to a partial pressure gradient or concentration gradient of the gas. This is a key issue (diffusion) in the performance of cover systems for milling wastes and mined rocks where sulphidic minerals should not come into contact with atmospheric oxygen to prevent acidification of leachate. Recent work by Didier et al. (2000a), Bouazza and Vangpaisal (2000) and Vangpaisal and Bouazza (2001) has shown that the manufacturing process, volumetric water content and the presence of an overburden pressure during the hydration phase can affect the gas permeability of geotextile-supported GCLs (Figs. 2 and 3). The diffusive transport of gases in a GCL or in any porous media can occur following two scenarios. (1) The medium is partially saturated, in this case diffusion will occur mostly within the air filled pores; (2) the medium is fully saturated, in this case the diffusion will occur partly in the gaseous phase and partly in the liquid phase. Both mechanisms of transport are reviewed in detail in Aubertin et al. (2000). Furthermore, they illustrated the importance of moisture content variation and the fact that the GCLs need to stay fully saturated in order to mitigate any potential gas migration due to diffusion.

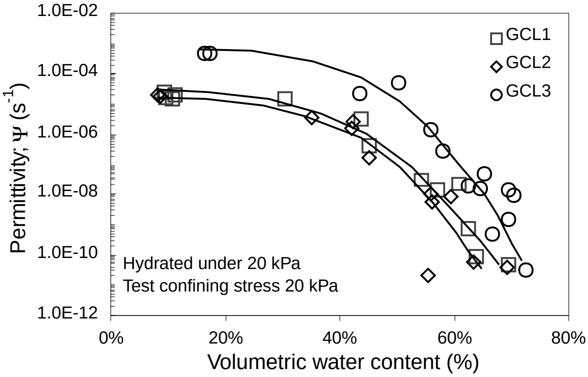

Fig. 2. Variation of gas permittivity with volumetric water content for confined hydration (from Vangpaisal and Bouazza, 2001).

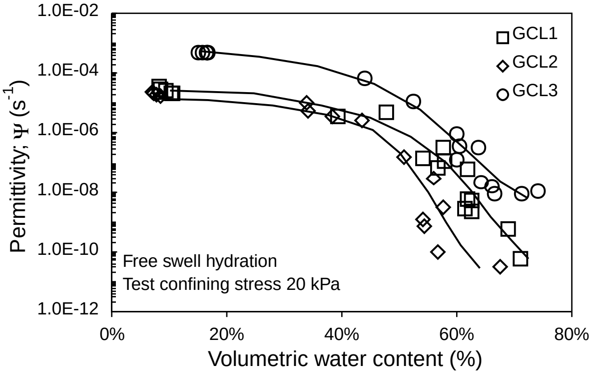

Fig. 3. Variation of gas permittivity with volumetric water content for free swell hydration (from Vangpaisal and Bouazza, 2001).

6. Slope stability

A waste containment facility liner or cover system must not only provide a sound hydraulic/gas barrier but must also be structurally stable during all phases of a given project (i.e. during construction, during and after placement of waste). In this respect, stability evaluation is a critical consideration for design. The potential use of GCLs on slopes as part of composite liners may subject them to a complex, long-term state of stress. The primary design concern when GCLs are placed against other geosynthetics or soils is the interface friction, which must be sufficiently high to transmit shear stresses that may be generated during the lifetime of the facility. Another concern is the possible internal failure of the GCL (in the bentonite or at the interface between the bentonite and geosynthetics in the GCL). The need for a more careful design of lining systems has been stressed by the recent failures generated by slip surfaces along liner interfaces (Byrne et al., 1992; Stark et al., 1998). Much effort has been made in the past decade to gain more knowledge of shear resistance of the different interfaces present in liner systems. As a result, very significant progress has been made in understanding and measuring GCL internal strength and GCL–soil/geomembrane interface strengths.

Shan and Daniel (1991), Stark and Eid (1996), Gilbert et al. (1996), Eid and Stark (1997), and Fox et al. (1998a) presented a comprehensive set of results on internal strength of unreinforced GCLs and reinforced (stitch bonded and needle punched) GCLs. Peak shear strengths for the unreinforced GCL products were found to be similar and comparable to those for bentonite (i.e. very low shear strength), which makes them very prone to instability. This is the reason they are not usually recommended for slopes steeper than 10H:1V (Frobel, 1996; Richardson, 1997). On the other hand, reinforced GCLs showed greater internal peak strength due to the presence of the fibres. However, it was also shown that their behaviour was governed by the fibres resistance against pull-out and/or tearing of the reinforcing fibres and the shear strength of the bentonite (at large displacements once the fibres are pulled out). It is worth noting that despite the fact that it was shown, in the laboratory, that internal failure could occur in reinforced (needle punched) GCLs, there are no known cases of slope failures, which can be attributed to internal shear failure of reinforced GCLs.

Laboratory interface shear tests are routinely conducted to evaluate interface friction between GCLs and soils or geosynthetics under operating conditions. As a result, a more extensive database is now available (Garcin et al., 1995; Bressi et al., 1995; Feki et al., 1997; Gilbert et al., 1996; Von Maubeuge and Eberle, 1998; Eid et al., 1999; Triplett and Fox, 2001). Probably, the major finding worth noting is the possible reduction in frictional resistance between a geomembrane and a GCL due to bentonite extrusion through woven geotextiles and nonwoven geotextiles with a mass of unit area $<220\,\mathrm{g/m^2}$ into the adjacent geomembrane interface. It is important to stress the fact that published values of interface friction cannot be used for design of a specific project, without at least careful review of test materials, test conditions and test methods. It is of a paramount importance to determine the interface strength on a site-specific basis for design purposes.

Tanays et al. (1994), Feki et al. (1997) and Daniel et al. (1998) reported the findings from full scale field tests of the internal and interface shear strength behaviour of unreinforced and reinforced GCLs configured with other liner components (geomembranes, geotextiles, and soils). Tanays et al. (1994) and Feki et al. (1997) presented results on an experimental cell where a stitch-bonded GCL was installed on slopes inclined at 2H:1V and 1H:1V, respectively. Displacements in the GCL were found to be very low on the 2H:1V slope and remained unchanged during the period of observation (500 days). One day after its installation on the 1H:1V slope, the GCL reached an average strain of 5.5% with extension occurring at the top of the slope. The displacements decreased with time of observation (3 months). It was assumed that partial failure of the GCL occurred at the measuring points due to excessive strain ($>2\%$). Significant informations on the interface behaviour have been garnered from Daniel et al (1998). It was reported that all geosynthetic configurations on test slopes inclined at 3H:1V performed satisfactorily. Three slides have occurred on steeper slopes (2H:1V). One slide occurred internally in an unreinforced GCL (a geomembrane backed GCL) because of bentonite hydration. Two slides occurred at the interface between a reinforced GCL and a geomembrane 20 and 50 days after construction. The slides were due to reduction in the interface strength caused by bentonite extrusion through a woven geotextile. Stark et al. (1998) presented a case study describing a slope failure involving an unreinforced GCL in a landfill liner system. It was observed that the failure occurred at the interface of a recompacted soil liner and the overlying hydrated bentonite of a geomembrane backed GCL due to changes in stress conditions.

7. Equivalency geosynthetic clay liners–compacted clay liners

The performance design trend imposes the quantitative evaluation of the equivalence of alternative liners and traditional liners. Therefore, in order to quantify the comparison between GCLs and CCLs, it is necessary to evaluate the following main features and parameters of GCLs which govern pollutant transport (Rowe, 2001): (1) hydraulic conductivity of GCLs permeated with nonstandard liquids, (2) effect of holes on GCL hydraulic conductivity, and (3) diffusion and sorption parameters. Rowe (1998), Shackelford et al. (2000) and Lake and Rowe (2000) have developed these topics in detailed and comprehensive manner. The comparison of GCL versus CCL in terms of actual performance is today one of the hot topics for the engineers involved in landfill design, construction, management and regulation. Moreover, when comparison between different products needs to be carried out, it is important to keep in mind that it is not possible to generalize about "equivalency" of liner systems since what is "equivalent" depends on what is being compared and how it is being compared (Rowe, 1998). Apart from their own features, the performances of liner systems are related to the contaminant amount, concentration and decay parameters, the aquifer characteristics and its distance from the bottom of the landfill, the efficiency of capping and drainage systems. A qualitative comparison of GCLs and CCLs provided by different authors referring to different criteria is given in Table 2. The performance of a GCL, for most criteria, should be either equivalent to or exceed that of a CCL. However, in terms of liner applications, the considerations of solute flux and breakthrough time, compatibility, and attenuation capacity favour CCLs. Some exceptions can be made for GCLs that use geomembrane supports instead of geotextiles and when an attenuation layer (AL) is provided.

8. Conclusions

There is no doubt that geosynthetic clay liners have gained over the past decade widespread popularity as a substitute for compacted clay liners in cover systems or as an augmentation to compacted clay liners in bottom liners of landfills, but they should not be seen as a panacea to all containment problems. Case histories reported in the present paper are a perfect reminder to our profession on how important it is to evaluate the use of geosynthetic clay liners on a site-specific basis.

Data available suggests that they have very low hydraulic conductivity to water and they can maintain their hydraulic integrity over the long term. The critical aspects about the service life of the GCL, as far as hydraulic integrity is concerned, can be related to long-term chemical compatibility problems, penetration, localized loss of bentonite, bentonite thinning, piping phenomena and ion exchange. With respect to gas migration, on-going studies suggest that it is dependent on moisture content and types of GCLs. The use of GCLs appears suitable or recommendable where important vertical settlements are foreseen, and for the capping of landfills where stresses are lower and a high degree of flexibility is required. More importantly, as rightly pointed out by Rowe and Jones (2000), it is important to emphasise that when designing GCL-lined slopes, it is essential to recognise the differences between different types of GCLs and consequently, differences in interface and internal shear strengths. Finally, geosynthetic clay liners, integrated

Table 2
Potential equivalency between geosynthetic clay liners (GCLs) and compacted clay liners (CCLs) (Manassero et al., 2000)

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

[a] Based only on total exchange capacity, TEC.
[b] Only for GCLs with a geomembrane.

with an attenuation layer can be considered as a possible alternative to compacted clay liners in composite liners. However, a careful comparison must be carried out between the two alternatives on a case by case basis. The actual boundary conditions into the time and space domains, the different pollutant transport phenomena, the contaminant lifespan and the active service life of the composite barrier materials and other landfill components must be taken into account.

Note to readers: The large number of references available on geosynthetic clay liners (GCLs) gives an indication on the rapid growth in research and development that this product has experienced over the past decade. Each paper has contributed to further and improve our knowledge of geosynthetic clay liners in one-way or the other. It is always difficult in these circumstances to single out a paper or a series of paper. However, there is ground to make exceptions to a rule. Indeed, it is fair to acknowledge that the contributions made by Rowe (1998), Shackelford et al. (2000), and Lake and Rowe (2000) represent an important step in understanding the migration of contaminants and chemical compatibility of GCLs. They have developed in detailed and comprehensive manner different aspects related to the above topics. The paper by Daniel et al. (1998) on slope stability gives a rare insight on field performance on different types of GCLs. Furthermore, it represents a good source of information on stability behaviour and construction aspects. The paper by Daniel (2000) summarises the different issues related to hydraulic performance and gives a very good overview on hydraulic durability and the factors that can affect it. Recognition of the importance of gas migration from waste containment facilities has resulted on a series of papers on gas–barrier interaction reported by Aubertin et al. (2000), Bouazza and Vangpaisal (2000) and Vangpaisal and Bouazza (2001). Their results illustrate the importance of moisture content variation on gas migration due to diffusion or advection. The importance of ion exchange, a topic which has received lot of attention recently, is highlighted in the papers by Lin and Benson (2000), Mazzieri and Pasqualini (2000) and Egloffstein (2000). Different views are reported and the reader is advised to consult the three papers to gain a better insight on this topic. Information on the design and construction involving GCLs can be found in the references given in this paper. The reader is referred to these papers for further information on factors influencing the performance of GCLs and factors to be considered in construction.

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References

Aubertin, M., Aachib, M., Authier, K., 2000. Evaluation of diffusive gas flux through covers with GCLs. Geotextiles and Geomembranes 18 (2–4), 215–233.

Bouazza, A., 1997. Performance of geosynthetic clay liners. Proceedings of the First ANZ Conference on Environmental Geotechnics, Melbourne, Australia, pp. 307–313.

Bouazza, A., Vangpaisal, T., 2000. Advective gas flux through partially saturated geosynthetic clay liners. Advances in geosynthetics uses transportation and geoenvironmental engineering, Geotechnical Special Publication No 101, pp. 54–67.

Bouazza, A., Van Impe, W.F., Van Den Broeck, M. (1996). Hydraulic conductivity of a geosynthetic clay liner under various conditions. Proceedings of the Second International Congress on Environmental Geotechnics, Vol. 1, Osaka, Japan, pp. 453–458.

Bressi, G., Zinessi, M., Montanelli, F., Rimoldi, P. (1995). The slope stability of GCL layers in geosynthetic lining system. Proceedings of the Fifth International Symposium on Landfills, Vol. 1, Cagliari, Italy, pp. 595–610.

Byrne, R.J., Kendal, J., Brown, S., 1992. Cause and mechanism of failure, Kettleman hills landfill B-19, unit 1A. Stability & Performance of Slopes and Embankments, Geotechnical. Special Publication No. 31, pp. 1188–1520.

Daniel, D.E., 2000. Hydraulic durability of geosynthetic clay liners. Proceeedings of the 14th GRI Conference (hot topics in geosynthetics), Las Vegas, USA, pp. 118–135.

Daniel, D.E., Koerner, R., Bonaparte, R., Landreth, R., Carson, D., Scranton, H., 1998. Slope stability of geosynthetic clay liner test plots. Journal of Geotechnical and Geoenvironmental Engineering 124 (7), 628–637.

Didier, G., Bouazza, A., Cazaux, D., 2000a. Gas permeability of geosynthetic clay liners. Geotextiles and Geomembranes 18 (2–4), 235–250.

Didier, G., Al Nassar, M., Plagne, V., Cazaux, D., 2000b. Evaluation of self healing ability of geosynthetic caly liners. International Conference on Geotechnical and Geological Engineering, Melbourne. Technomic Press, Lancaster, PA (CDROM).

Dobras, T.N., Elzea, J.M., 1993. In-situ soda ash treatment for contaminated geosynthetic clay liners. Proceedings of the Geosynthetics 93, Vancouver, pp. 1145–1159.

Egloffstein, T.A., 2000. Natural bentonites-influences on ion exchange and partial dessication on permeability and self healing capacity of bentonites used in GCLs. Proceeedings of the 14th GRI Conference (hot topics in geosynthetics), Las Vegas, USA, pp. 164–188.

Eid, H.T., Stark, T.D., 1997. Shear behaviour of an unreinforced geosynthetic clay liner. Geosynthetics International 4 (6), 645–659.

Eid, H.T., Stark, T.D., Doerfler, C.K., 1999. Effect of shear displacement rate on internal shear strength of a reinforced geosynthetic clay liners. Geosynthetics International 6 (3), 219–239.

Estornell, P., Daniel, D.E., 1992. Hydraulic conductivity of three geosynthetic clay liners. Journal of Geotechnical Engineering 118 (10), 1592–1606.

Feki, N., Garcin, P., Faure, Y.H., Gourc, J.P., Berroir, G., 1997. Shear strength tests on geosynthetic clay liner systems. Proceedings of the Geosynthetics 97, Long Beach, USA 2, pp. 899–912.

Fox, P.J., De Battista, D.J., Chen, S.H., 1996. Bearing capacity of GCLs for cover soils of varying particle size. Geosynthetics International 3 (4), 447–461.

Fox, P.J., Rowland, M.G., Scheite, J.R., 1998a. Internal shear strength of three geosynthetic clay liners. Journal of Geotechnical and Geoenvironmental Engineering (ASCE) 124 (10), 933–944.

Fox, P.J., Triplett, E.J., Kim, R.H., Olsta, J.T., 1998b. Filed study of installation damage for geosynthetic clay liners. Geosynthetics International 5 (5), 491–520.

Fox, P.J., De Battista, D.J., Mast, D.G., 2000. Hydraulic performance of geostnthetic clay liners under gravel cover soils. Geotextiles and Geomembranes 18 (2–4), 179–201.

Frobel, R.K., 1996. Geosynthetic clay liners, part four: interface and internal shear strength determination. Geosynthetics Fabric Report 14 (8), 20–23.

Garcin, P., Faure, Y.H., Gourc, J.P., Purwanto, E. (1995). Behaviour of geosynthetic clay liner (GCL): laboratory tests. Proceedings of the Fifth International Symposium on Landfills, Vol. 1, Cagliari, Italy, pp. 347–358.

Gilbert, R.B., Fernandez, F., Horsfield, D.W., 1996. Shear strength of reinforced GCLs. Journal of Geotechnical Engineering 122 (4), 259–266.

Giroud, J.P., Soderman, K.L., 2000. Criterion for acceptable bentonite loss from a GCL incorporated into a liner system. Geosynthetics International 7 (4–6), 529–581.

James, A.N., Fullerton, D., Drake, R., 1997. Field performance of GCL under ion exchange conditions. Journal of Geotechnical and Geoenvironmental Engineering 123 (10), 897–901.

Jo, H.Y., Katsumi, T., Benson, C.H., Edil, T.B., 2001. Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single species salt solutions. Journal of Geotechnical and Geoenvironmental Engineering 127 (7), 557–567.

Koerner, R.M., Narejo, D., 1995. Bearing capacity of hydrated geosynthetic clay liner. Journal of Geotechnical Engineering 121 (1), 82–85.

LaGatta, M.D., Boardman, B.T., Cooley, B.H., Daniel, D.E., 1997. Geosynthetic clay liners subjected to differential settlement. Journal of Geotechnical and Geoenvironmental Engineering 123 (5), 402–410.

Lake, C.B., Rowe, R.K., 2000. Diffusion of sodium and chloride through geosynthetic clay liners. Geotextiles and Geomembranes 18 (2–4), 103–131.

Lin, L.C., Benson, C.H., 2000. Effect of wet dry cycling on swelling and hydraulic conductivity of GCLs. Journal of Geotechnical and Geoenvironmental Engineering 126 (1), 40–49.

Manassero, M., Benson, C., Bouazza, A., 2000. Solid waste containment systems. Proceedings of the International Conference on Geological and Geotechnical Engineering, GeoEngineering 2000, Vol. 1, Melbourne, Australia, pp. 520–642.

Mazzieri, F., Pasqualini, E., 1997. Field performance of GCLs: a case study. Proccedings of the First ANZ Conference on Environmental Geotechnics, Melbourne, pp. 289–294.

Mazzieri, F., Pasqualini, E., 2000. Permeability of damaged geosynthetic clay liners. Geosynthetics International 7 (2), 101–118.

Mazzieri, F., Pasqualini, E., Van Impe, W.F., 2000. Compatibility of GCLs with organic solutions. International Conference on Geotechnical and Geological Engineering, Melbourne, Technomic Press, Lancaster, PA (CDROM).

Melchior, S., 1997. In-situ studies on the performance of landfill caps. Proceedings of the International Conference on Containment, St. Petersburg, USA, pp. 365–373.

Orsini, C., Rowe, R.K., 2001. Testing procedure and results for the study of internal erosion of geosynthetic clay liners. Proceedings of the Geosynthetics 2001, Portland, USA, pp. 189–201.

Peggs, I.D., Olsta, J.T., 1998. A GCL and incompatible soil case history: a design problem. Proceedings of the 12th GRI Conference, Philadelphia, USA, pp. 117–138.

Petrov, R.J., Rowe, R.K., 1997. GCL-chemical compatibility by hydraulic conductivity testing and factors impacting its performance. Canadian Geotechnical Journal 34 (6), 863–885.

Petrov, R.J., Rowe, R.K., Quigley, R.M., 1997a. Selected factors influencing GCL hydraulic conductivity. Journal of Geotechnical and Geoenvironmental Engineering 123 (8), 683–695.

Petrov, R.J., Rowe, R.K., Quigley, R.M., 1997b. Comparison of laboratory measured GCL hydraulic conductivity based on three permeameter types. Geotechnical Testing Journal 20 (1), 49–62.

Rad, N.S., Jacobson, B.D., Bachus, R.C., 1994. Compatibility of geosynthetic clay liners with organic and inorganic permeants. Proceedings of the Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore (CD ROM).

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.

Rowe, R.K., 2001. Liner Systems. Chapter 25 of Geotechnical and Geoenvironmental Engineering Handbook. Kluwer Academic Publishing, Norwell, USA, pp. 739–788.

Rowe, R.K., Jones, C.J.F.P. (2000). Geosynthetics:Innovative materials and rational design. Proceedings of the International Conference on Geological and Geotechnical Engineering, GeoEngineering 2000, Vol. 1, Melbourne, Australia, pp. 1124–1156.

Richardson, G.N., 1997. GCL internal shear strength requirements. Geosynthetics Fabric Report 15 (2), 20–25.

Ruhl, J.L., Daniel, D.E., 1997. Geosynthetic clay liners permeated with chemical solutions and leachates. Journal of Geotechnical and Geoenvironmental Engineering 123 (4), 369–381.

Shackelford, 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.

Shan, H.Y., Daniel, D.E. (1991). Results of laboratory tests on a geotextile/bentonite liner material. Proceedings of the Geosynthetics 91, Vol. 2, pp. 517–535.

Stam, T.G., 2000. Geosynthetic clay liner field performance. Proceeedings of the 14th GRI Conference (Hot Topics in Geosynthetics), Las Vegas, USA, pp. 242–254.

Stark, T.D. (1998). Bentonite migration in geosynthetic clay liners. Proceedings of the Sixth International Conference on Geosynthetics, Vol. 1, Atlanta, pp. 315–320.

Stark, T.D., Eid, H.T., 1996. Shear behaviour of reinforced geosynthetic clay liners. Geosynthetics International 3 (6), 771–786.

Stark, T.D., Arellano, D., Evans, W.D., Wilson, V.L., Gonda, J.M., 1998. Unreinforced geosynthetic clay liners case history. Geosynthetics International 5 (5), 521–544.

Tanays, E., Le Tellier, I., Bernhard, C., Gourc, J.P., 1994. Behaviour of lining systems on waste landfill slopes: an experimental approach. Proceedings of the Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore (CDROM).

Triplett, E.J., Fox, P.J., 2001. Shear strength of HDPE geomembrane/geosynthetic clay liner interface. Journal of Geotechnical and Geoenvironmental Engineering 127 (6), 543–552.

Vangpaisal, T., Bouazza, A., 2001. Gas permeability of three needle punched geosynthetic clay liners. Proceedings of the Second ANZ Conference on Environmental Geotechnics, Newcastle, Australia, Nov.2001, in press.

Von Maubeuge, K.P., Eberle, M. (1998). Can geosynthetic clay liners be used on slopes to achieve long-term stability. Proceedings of the Third International Congress on Environmental Geotechnics, Vol. 1, Lisbon, Portugal, pp. 375–380.

Von Maubeuge, K.P., Heerten, G., 1994. Needle punched geosynthetic clay liners. Proceedings of the Eighth GRI Conference, Philadelphia, USA, pp. 129–207.

Further reading

USEPA, 1993. Report on workshop on geosynthetic clay liners, EPA/600/R-93/171.

Koerner, R.M., Gartung, E., Zanzinger, H. (Eds.), 1995. Proceedings of the International Symposium on Geosynthetic Clay Liners, Nurenberg, Germany. Balkema, Rotterdam.

ASTM STP 1308, 1997. In: Larry W. Well (Ed.), Testing and acceptance criteria for geosynthetic clay liners, ASTM, West Conshohocken, PA, USA.

Proceedings Geo-Bento 98, Geosynthetic Clay Liners: State of the Art, Paris, France, February 1998. INSA-Lyon.

Bouazza, A. (Ed.), 2000. Geosynthetic Clay Liners (special issue). Geotextiles and Geomembranes 18 (2–4).