Geotextiles and Geomembranes xxx (2014) 1–9

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Heat and moisture migration in a geomembrane–GCL composite liner subjected to high temperatures and low vertical stresses☆

A. Bouazza [a, *], R.M. Singh [a, 1], R.K. Rowe [b, 2], F. Gassner [c, 3]

[a] Monash University, Department of Civil Engineering, 23 College Walk, Wellington Road, Clayton, Vic. 3800, Australia
[b] GeoEngineering Centre at Queen's-RMC, Queen's University, Ellis Hall, Kingston, Ontario, Canada K7L 3N6
[c] Golder Associates Pty. Ltd., Building 7, Botanicca Corporate Park, 570–588 Swan Street, Richmond, Vic. 3121, Australia

ARTICLE INFO

Article history:
Received 29 March 2014
Received in revised form
25 June 2014
Accepted 23 August 2014
Available online xxx

Keywords:
Ponds
Elevated temperatures
Geomembrane
Geosynthetic clay liner
Heat migration
Moisture migration

ABSTRACT

This paper presents the results of an experimental and numerical modelling of heat and moisture migration conducted on a composite liner comprised of a geomembrane (GMB) and a geosynthetic clay liner (GCL), over a compacted subgrade and subjected to prolonged elevated temperatures at low overburden stresses typical of brine storage ponds or solar evaporation ponds. Results are presented for a GMB sitting on a fully hydrated GCL. Heating the top of the composite liner caused a measurable increase in subgrade temperature to at least to 250 mm below the GCL. However, the presence of an air gap, simulating the presence of a wrinkle in the geomembrane, at the interface between the GMB and the GCL reduced the impact of the high temperatures on the subgrade temperature profile with depth. The change in temperature profile was accompanied by moisture migration from the GCL to the subgrade material. However no desiccation cracks were observed in the GCL and the bentonite was still in a gel form at the end of the time period investigated. Numerical modelling using finite element method (FEM) was performed to simulate the results obtained experimentally. It was found to predict accurately the temperature changes that have occurred in the subgrade material and moisture changes that occurred in both the GCL and subgrade materials.

1. Introduction

Geosynthetic clay liners (GCLs) are thin (typically 5–10 mm) manufactured hydraulic barriers having a very low hydraulic conductivity to water ($k < 10^{-10}$ m/s) (Bouazza, 2002). Nowadays, they are commonly used in combination with geomembranes (GMB) in municipal solid waste (MSW) landfill liners (Bouazza et al., 2002; Rowe et al., 2004; Bouazza and Bowders, 2010). However, as their use has recently extended to mining and other industrial facilities they are exposed to a new variety of environmental conditions (Gates et al., 2009; Hornsey et al., 2010; Gates and Bouazza, 2010; Bouazza, 2010; Fourie et al., 2010; Shackelford et al., 2010; Mazzieri et al., 2013; Liu et al., 2013, 2014; Bouazza and Gates, 2014). In particular the effect of elevated temperatures has been identified as one of the factors governing the GCL's lining performance and longevity (Rowe, 2005; Bouazza, 2010; Bouazza et al., 2013; Abuel-Naga et al., 2013).

Unlike in municipal solid waste landfills where temperatures on liners can reach up to 60 °C (Yesiller et al., 2005; Rowe, 2005, 2012; Koerner and Koerner, 2006; Bouazza et al., 2011) and then are expected to decay with time as biodegradation of wastes slows down, lining systems for mining and industrial infrastructures are exposed to prolonged elevated temperatures even higher than currently common in MSW landfills (Thiel and Smith, 2004; Bouazza, 2010; Hornsey et al., 2010). Recent research has indicated that liners in mining facilities (e.g., heap leach pads) can be continuously exposed to temperatures as high as 80 °C which are generated from the various ore extraction processes (Smith, 2008). Solar ponds liners can also experience high temperatures ranging from 30 °C at the surface to 90 °C at the liner (Lu et al., 2001; Silva and Almanza, 2009). Similarly, warm liquid (generated from industrial processes) storage pond liners can reach temperatures up to 80 °C due to the dual effect of solar radiation and initial liquid temperatures, with long-term (>5 years) temperatures ranging between 60 °C and 80 °C continuously acting on the lining system.

☆ Dr. N. Touze-Foltz acted as Editor for the review of this paper.

* Corresponding author. Tel.: +61 3 9905 4956; fax: +61 3 9905 4944.
E-mail addresses: malek.bouazza@monash.edu (A. Bouazza), rao.singh@monash.edu (R.M. Singh), kerry@civil.queensu.ca (R.K. Rowe), fgassner@golder.com.au (F. Gassner).
[1] Tel.: +61 3 9905 4981; fax: +61 3 9905 4944.
[2] Tel.: +1 613 533 3113; fax: +1 613 533 2128.
[3] Tel.: +61 3 8862 3584; fax: +61 3 8862 3501.

http://dx.doi.org/10.1016/j.geotexmem.2014.08.002
0266-1144/© 2014 Published by Elsevier Ltd.

Understandably, these high temperatures operating on the geosynthetic components of the lining systems have the potential to cause intense degradation of their physico-mechanical properties which in turn may impact on their service life under either low or high overburden stresses. In particular, the integrity of the hydraulic barrier (i.e., GCL in this case) may be compromised if it undergoes cracking due to desiccation caused by the presence of high thermal gradients. The presence of high temperatures in contact with liners can lead to thermally driven moisture flow and potentially to desiccation of the mineral component of the liner (i.e. compacted clay liners or geosynthetic clay liners). The coupled heat-moisture transfer process taking place in such cases (Mitchell, 1991; Rowe, 2005) causes a downward migration of water vapour from the mineral liner and the underlying subsoil to a cooler depth where it condenses, leading potentially to desiccation of the mineral liner, this is further exacerbated by the presence of the geomembrane which prevents moisture reaching the GCL from above (Southen and Rowe, 2005, 2011; Azad et al., 2011, 2012; Rowe and Verge, 2013; Hoor and Rowe, 2013).

This paper presents the results of a study aimed at quantifying heat and moisture migration in a composite liner comprising a geomembrane (GMB), with the presence of a wrinkle, and a fully hydrated GCL, overlying a compacted subgrade. Although the effect of wrinkles and their frequencies in landfills are well documented (Chappel et al., 2012a,b; Rowe et al., 2012a,b; Take et al., 2007), their occurrences and frequencies in brine storage ponds or solar evaporation ponds are yet to be quantified. The liner system in the current study is subjected to high temperatures and low overburden stresses typically encountered in lined liquid ponds. In addition to the experimental work, thermo-hydraulic numerical modelling of the composite liner system was conducted. The modelling was carried out using a finite element method (FEM) code referred to as COMPASS (Code for Modelling Partially Saturated Soils). This paper presents its main features and governing equations used for the numerical analysis as well as the main numerical model results.

2. Experimental work

2.1. Materials

The GCL used in the present investigation is composed of powdered sodium bentonite, needle-punched and thermally locked, between a nonwoven polypropylene geotextile cover layer and a woven polypropylene geotextile carrier (Table 1). The subgrade material was sourced from a site where a liquid storage pond was to be constructed. It had a liquid limit (LL) of 57%, plastic limit (PL) of 27% and specific gravity (G_s) of 2.66. It contained mostly fine grained soil particles with 82% particles finer than 60 μm. The maximum dry density and optimum moisture content from the standard Proctor compaction curve were 1520 kg/m^3 and 20%, respectively. A standard HDPE geomembrane (GMB) having a nominal thickness of 2 mm was used in this study.

Table 1
Technical data sheet of the GCLs as provided by manufacturer.

Property	Test method	Unit	GCL
Bentonite mass (@ 0% moisture) content)	ASTM D5993	g/m^2	4000[a]
Swell index	ASTM D5890	ml/2 g	≥24
Fluid loss	ASTM D5891	ml	≤15
GCL total mass (@ 0% moisture) content)	ASTM D5993	g/m^2	4380[a]
Hydraulic conductivity	ASTM D5887	m/s	2×10^{-11}

PP = polypropylene geotextiles.
[a] MARV (minimum average roll value) is a mean value less 2 standard deviations.

2.2. Apparatus

A specially designed column was developed to simulate, as accurately as practical, the conditions occurring at the base of a liner subjected to low overburden pressures and elevated temperatures to allow an assessment of the potential for GCLs to desiccate under elevated thermal gradients.

The arrangement of the column allowed a temperature gradient to be applied across a composite liner and a subsoil of known initial conditions under controlled conditions. The apparatus was composed of three parts. The upper part consisted of a stainless steel water reservoir with the top cap fitted with a coil heater. This allowed for heating of the uppermost surface to simulate the heat present in a pond. Temperature changes were monitored by a thermocouple located in the reservoir. The heater and thermocouple were both connected to an automatic heating control unit which maintained the set temperature by thermostatically switching the heat on and off. This allowed the temperature of water to be raised in steps from room temperature to a target temperature. The top cap contained an inlet and an outlet to allow drainage and pressurisation of the water if needed.

The central part consisted of a polytetrafluoroethylene (PTFE) cylinder of 100 mm diameter and 400 mm height. PTFE has a very low thermal conductivity which limits radial heat losses during the experiment. This part provided access to both the upper and lower chambers and hosted the composite liner and the compacted subgrade material. Once the upper section was in place, it pinched the edges of both the geomembrane and GCL. Bentonite paste was then applied to the edge of the geomembrane to provide a seal at the interface. The pinching process allowed the creation of an air gap (i.e simulation of the presence of a wrinkle in the geomembrane) between the GMB and the GCL due mostly to the rigidity of the HDPE GMB. Heat application during the test increased the size of the gap due to the high thermal expansion of the HDPE GMB. The average size of the air gap was about 5 mm. Staggered ports in the wall of the PTFE cylinder allowed installation of 3 relative humidity (RH) sensors (capable also of monitoring temperature) and 4 thermocouples. All instrumentation was connected to a data-logger allowing continuous monitoring. The relative humidity sensors were installed in the upper portion of the central section while the thermocouples were installed in the bottom half of the central part.

The lower end of the subgrade material was maintained at constant temperature of 21 ± 1 °C through the lower chamber (3rd part of the column). This chamber was connected to a heating/cooling unit system and had inlets to allow recirculation of water within the chamber at constant temperature. In this way the heat generated in the upper reservoir and migrating via the composite liner and subgrade material was absorbed by the circulating water resulting in a constant temperature applied at the bottom end of the subgrade. A thermocouple located at the interface between the lower chamber and the compacted subgrade gave a continuous reading of the temperature. The bottom boundary was sealed (no flow boundary) to prevent any moisture changes. Once the column was assembled, the upper chamber was tightly screwed with tie rods to the lower chamber and left for 10 days to reach equilibrium under room temperature prior to commencing the test.

The procedure followed to raise the temperature in the upper chamber to the target temperature (70 °C) consisted of increasing the temperature in increments from room temperature (21 ± 1 °C) to 30 °C for 24 h, then to 50 °C for another 24 h. It was kept at this temperature for 5 days before it was raised to 65 °C, and then 10 days later the temperature was raised to the target temperature of 70 °C. The temperature conditioning process therefore took in total 16 days to complete. The upper chamber was kept at the target