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Thermal conductivity of geosynthetics

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ABSTRACT

Thermal conductivity is a key property that controls heat migration in a variety of applications including municipal solid waste and/or mining/industrial containment facilities. In particular, heat may be encountered in cases where geosynthetic lining systems are exposed to elevated temperatures due to either waste biodegradation, solar radiation, or mining processes. This paper presents the results of an experimental investigation on thermal conductivity of nonwoven geotextiles, geosynthetic clay liners and an HDPE geomembrane. A steady state method was used to measure the thermal conductivity of a selected number of these materials. The thermal conductivity of the HDPE geomembrane was found to be consistent with the thermal conductivity of HDPE polymer. On the other hand, the thermal conductivity of the nonwoven geotextiles depended on water content and whether they are hydrophobic or hydrophilic. The form of bentonite, its mass per area and water content affected the thermal conductivity of GCLs. The results presented in this paper provide a lower bound of thermal conductivities of geosynthetics routinely used in waste containment facilities.

1. Introduction

Geosynthetic barrier components such as geomembranes (GM) and geosynthetic clay liners (GCLs) are extensively used in waste containment facilities either as part of cover lining or bottom lining systems. Their aim is to reduce water ingress into the containment and to control gas migration in the case of the cover liners and to limit contaminant migration to levels that will result in negligible impact in the case of bottom liners. Geotextiles (GT) are also used in containment facilities either as filtration/separation medium or protection to the geomembrane. In this respect a large body of work is available on various aspects related to the physical and/or the hydro-mechanical and chemical performance of these geosynthetics.

However, new issues [i.e. heat transfer and heat driven moisture flow in composite liners, desiccation of compacted clay liners (CCLs) or bentonite component of GCLs, thermo-mechanical behaviour of GCLs (Southen and Rowe, 2005, 2011; Abuel-Naga and Bouazza, 2013; Bouazza et al., 2013), etc.] are emerging as we are gaining a better understanding of the physico-chemical phenomenon taking place in municipal solid waste landfills and also as the use of geosynthetics is extended to applications where they are subjected to more aggressive conditions such as in mining or industrial applications (Hornsey et al., 2010; Bouazza, 2010; Fourie et al., 2010; Liu et al., 2013). These issues are mostly related to the presence of heat in the containment and the corresponding impact on the hydro-mechanical and chemical behaviour of the lining systems.

Biological decomposition of municipal solid waste in a landfill generates significant amount of heat due to its high organic content and may raise the temperature within the waste mass to 60 °C under normal landfill operations (Yesiller et al., 2005; Rowe, 2005; Koerner and Koerner, 2006; Rowe and Hoor, 2009; Rowe et al., 2010; Bouazza et al., 2011; Southen and Rowe, 2011; Hoor and Rowe, 2012). Even higher temperatures, up to 70 °C, may occur at the base of landfills if there is a significant leachate mound within the landfill (Yoshida et al., 1996). The application of geosynthetics in a mining environment (ex., uranium mill facility liners, brine evaporation ponds, heap leach pads, waste rock dumps, etc.) can expose them to even higher temperatures (up to 80 °C) generated from the various ore extraction processes (Thiel and Smith, 2004; Bouazza, 2010; Hornsey et al., 2010; Gassner and Scheirs, 2010). Solar ponds liners can experience temperatures ranging from 50 °C to 90 °C (Lu et al., 2001). Exposed geosynthetics such as in side wall liners can also be subjected to high temperatures (up to 70 °C) caused by solar radiation (Take et al., 2012).

Abuel-Naga and Bouazza (2013) indicated that the long-term thermo-mechanical performance of liners can be affected by high temperature variations and thermal gradients typically

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encountered in landfills. In particular they showed that GCLs can undergo irreversible thermally induced volumetric contraction or expansion upon subjection to a heating/cooling cycle. The presence of high temperatures in contact with liners can lead also to thermally driven moisture flow leading 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 case is described in detail by Mitchell (1991) and Rowe (2005); readers are referred to these two references for further information. In summary, the thermal gradient resulting from the increase in the temperature above the liner causes a downward migration of water vapour from the mineral liner and the underlying subsoil to a cooler depth where it condenses, leading to desiccation of the mineral liner (Rowe, 2005). In this respect, much effort has been made recently on modelling numerically the long term performance of composite liners subjected to elevated temperatures (Zhou and Rowe, 2003, 2005; Southen and Rowe, 2005, 2011; Azad et al., 2012) with particular focus on thermal driven moisture flow in composite liners and potential for desiccation of CCLs or the bentonite component of GCLs.

Thermal conductivity is an important and key thermal property since it controls heat flow at equilibrium and temperature field in the geomaterial. Thermal conductivity of the different geosynthetic components constituting a lining system needs to be measured under the conditions in which they are implemented in the field so that modelling of given scenarios involving heat transfer through liners can be done in a more confident way. Although a large number of studies have been reported for soils and rocks (Van Rooyen and Winterkorn, 1957; Nakshabandi and Kohnke, 1965; Penner et al., 1975; Farouki, 1986; Brandon and Mitchell, 1989; Abu-Hamdeh and Reeder, 2000; Chen, 2008; Choi et al., 2009; Abuel-Naga et al., 2008, 2009; Barry-Macaulay, 2013); no studies have been reported for geosynthetics resulting in most cases on assumptions of their thermal conductivities for numerical assessment. To date, no experimental investigation has been carried out to determine the thermal conductivity of geomembrane, geotextile and GCL materials routinely used in lining systems.

This paper presents the results of a study on the thermal conductivity of geosynthetics with particular focus on geosynthetic clay liners, nonwoven geotextiles and geomembranes. The laboratory test method is presented and discussed together with typical results obtained from the test.

2. Background on thermal conductivity tests

There are various methods available to measure the thermal conductivity of geomaterials. These methods can be divided into two categories; steady state and transient state. The steady state method also known as divided-bar method includes thermal conductivity measurement when the heat flux through a geomaterial sample, which is subjected to a fixed thermal gradient, reaches a steady value and does not change with time. The steady state method uses Fourier's solution to the heat conduction equation to determine the thermal conductivity for a known heat flux and a known thermal gradient. There are various available techniques of the steady state method e.g. guarded-hot-plate apparatus (ASTM C177-04), heat flow metre apparatus (ASTM C518-04), guarded-comparative-longitudinal heat flow technique (ASTM E1225-04), rhometer apparatus (Stolpe, 1970) and Rapid k method (Mitchell and Kao, 1978). The transient state method determines the thermal conductivity while the temperature of the geomaterial sample changes either due to heating or cooling. Transient methods include the thermal needle method (ASTM D5334-05) which is widely used in soils due to its simplicity and commercial availability (Barry-Macaulay, 2013). However, transient methods such as thermal needle probes are not possible to use in planar material such as geosynthetics. A guarded-comparative-longitudinal heat flow technique was used in the present study due to its relative versatility and ability to accommodate planar materials.

2.1. Theory

Winterkorn and Eyring (1946) and Jakob (1949) stated that there are three mechanisms of heat flow through any material; conduction, in which the excitation of an atom or molecule is transmitted to its neighbour by direct contact, oscillation-like in solids and liquids and by impact and exchange of momentum in gases; convection, in liquids and gases, where a portion of matter at a higher temperature is mechanically mixed with matter at a lower temperature; radiation by means of waves traversing space from one body to another without affecting the interlying space. Heat flow through GM can occur only by conduction as it is a relatively non-porous solid material. While heat flows through GCL and GT is entirely by conduction with radiation unimportant and convection important, only if there is high flow rate of water or air (Mitchell, 1993) (i.e. in very porous GT). Johansen (1975) considered thermal radiation across soil air spaces and concluded that it is only significant for very coarse material at low moisture contents. Heat transfer is also found to occur due to chemical concentration gradients. This effect is commonly referred to as the Dufour effect. Mitchell (1993) stated that the Dufour effect was known to be of significance in soils. The thermal conductivity is an intrinsic property of a material which is related to its ability of conducting heat. Thermal conductivity is defined as the heat flux transmitted through a unit thickness due to a unit temperature difference in a steady state. The heat flux is equal to amount of heat energy passing through unit area per unit time. The fundamental equation for heat conduction as derived by Fourier (1822) is as follows:

$$Q = -\lambda \nabla T \tag{1}$$

$$\nabla T = \frac{\Delta T}{L} \tag{2}$$

where λ (W/mK) is the thermal conductivity, Q (W/m^2) is the heat flux, ∇T (K/m) is the temperature gradient, ∇T (K) is the temperature difference and L (m) is the thickness. Therefore, measurement of thermal conductivity involves measurement of heat flux and temperature difference. The difficulty of the measurement is always associated with the heat flux measurement. Where the measurement of the heat flux is done directly (e.g. by measuring the electrical power going into the heater), the measurement method is termed primary or absolute. Where the flux measurement done indirectly (by comparison), the method is termed secondary or comparative.

3. Material and methodology

The materials used in the present investigation consist of a nonwoven, continuous filament needle punched polyester geotextile (GT), various types of needle punched geosynthetics clay liners (GCLs) and a high density polyethylene geomembrane (GM). All these materials are commercially available and routinely used in waste containment facilities. The tests on geotextiles were conducted on samples as received from the manufacturers and on plasma surface treated samples (Jeon and Bouazza, 2007; Nahlawi, 2009). Plasma surface treatment of the geotextile samples was carried out to make them hydrophilic. Low pressure pulsed O_2 plasma treatment was conducted in a 1.7 L electrode-less plasma reaction chamber developed at the CSIRO Materials Science and