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Research article

Hydraulic performance of compacted clay liners under simulated daily thermal cycles

A.A. Aldaeef*, M.T. Rayhani

Department of Civil and Environmental Engineering – Carleton University, Ottawa, Ontario, Canada

A R T I C L E I N F O

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A B S T R A C T

Compacted clay liners (CCLs) are commonly used as hydraulic barriers in several landfill applications to isolate contaminants from the surrounding environment and minimize the escape of leachate from the landfill. Prior to waste placement in landfills, CCLs are often exposed to temperature fluctuations which can affect the hydraulic performance of the liner. Experimental research was carried out to evaluate the effects of daily thermal cycles on the hydraulic performance of CCLs under simulated landfill conditions. Hydraulic conductivity tests were conducted on different soil specimens after being exposed to various thermal and dehydration cycles. An increase in the CCL hydraulic conductivity of up to one order of magnitude was recorded after 30 thermal cycles for soils with low plasticity index (PI = 9.5%). However, medium (PI = 25%) and high (PI = 37.2%) plasticity soils did not show significant hydraulic deviation due to their self-healing potential. Overlaying the CCL with a cover layer minimized the effects of daily thermal cycles, and maintained stable hydraulic performance in the CCLs even after exposure to 60 thermal cycles. Wet-dry cycles had a significant impact on the hydraulic aspect of low plasticity CCLs. However, medium and high plasticity CCLs maintained constant hydraulic performance throughout the test intervals. The study underscores the importance of protecting the CCL from exposure to atmosphere through covering it by a layer of geomembrane or an interim soil layer.

1. Introduction

Landfills have long been used as engineered containment systems to mitigate the environmental footprint of disposed waste. Due to their low permeability, compacted clay liners (CCLs) are used as barrier systems in landfill design to minimize the escape of contaminants from landfills and mitigate their impact on public health and the environment. Therefore, the functional integrity of landfills depends heavily on the hydraulic performance of the barrier systems. CCLs can be used alone or in combination with a geomembrane for landfill barrier systems. Prior to waste placement, CCL might be exposed to daily thermal cycles induced by solar radiation as well as wet-dry cycles. Overlaying the CCL with geomembrane, on one hand, may eliminate the effect of wet-dry cycles, however, the dark color of the geomembrane, on the other hand, was found to enhance the effect of the solar radiation. Thiel et al. (2006) recorded temperature readings underneath the geomembrane as high as 60 °C . Therefore, CCLs in both barrier systems may experience damage due to climatic effects and volume shrinkage which may lead to changes in hydraulic performance.

Desiccation and evaporation cause reductions in water content of the soil, which may lead to a decrease in pore-water content and gradually an increase in matric suction (Konrad and Ayad, 1997; Nahlawi and Kodikara, 2006; Tang et al., 2011). Outgoing water flow generates voids within soil particles. Following generation of these voids, the soil particles are reorganized due to an internal compression effect, which increases with an increase in soil suction (Albrecht and Benson, 2001; Peron et al., 2009; Tang et al., 2011). As a result, a reduction in the soil matrix volume, known as shrinkage, occurs. This shrinkage could induce volumetric change and crack formation in the soil matrix that may lead to a considerable increase in permeability of the CCL.

The shrinkage behavior of CCLs is influenced by several factors including clay content, clay mineralogy (Rayhani et al., 2007, 2008; Zubaydi, 2011), and the exposure conditions (Rowe, 1998). Albrecht and Benson (2001) reported considerable volumetric shrinkage as the clay content increased in soils where smectite clays dominated, while illite, kaolinite, and quartz soils demonstrated less shrinkage. Similarly, Omidi et al. (1996) reported higher volumetric shrinkage

* Corresponding author.
E-mail address: abdulghader.abdulrahman@carleton.ca (A.A. Aldaeef).

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in smectite soils compared to illite soils. This was linked to the capability of smectite clays to absorb more interlayer water and consequently undergo higher volumetric shrinkage upon drying. If the volumetric shrinkage is restricted, cracks may occur when the soil's tensile strength fails to resist the growing tensile stresses (Nahlawi and Kodikara, 2006; Tang et al., 2011). Volume shrinkage and cracking were shown to significantly affect the hydraulic performance of CCLs (e.g., Omidi et al., 1996; Rayhani et al., 2007, 2008). Omidi et al. (1996) suggested that soils with volumetric shrinkage of less than 11% would result in quite stable hydraulic performance under desiccation. However, clayey soils with volumetric shrinkage higher than 11% would experience an increase in their permeability. Tang et al. (2011) identified soil suction as the mechanical initiator of cracking, and any parameter influenced by soil suction or soil tensile strength would widely influence the desiccation cracking behavior. Moreover, the generation of tension stresses due to soil shrinkage is mainly related to boundary conditions. If the soil is free to uniformly shrink and no considerable friction is provided by the subgrade, then stresses will not be generated. However, in field conditions, non-uniform shrinkage is the case, when the upper portion of the soil is only exposed to the atmosphere. This non-uniformity leads to the creation of friction between upper soils and the underlying layer, which eventually results in cracking.

In the field, CCLs are often exposed to several wet-dry and/or freeze–thaw cycles during the year. These cycles may result in crack formation as the soil desiccates or freezes. However, subsequent wetting or thawing can lead to partial crack closure which results in what is known as the self-healing phenomenon. Investigations into the effects of wet-dry cycles on soil shrinkage and crack formation were widely conducted (DeJong and Warkentin, 1965; Albrecht and Benson, 2001; Zubaydi, 2011). All reported significant crack formation and volumetric shrinkage after the first wet-dry cycle, but the following cycles exhibited a lower impact. Rayhani et al. (2007, 2008) reported an increase of about one order of magnitude in the soil permeability due to shrinkage and crack formation at first wet-dry cycles. However, after drying, fractured soils demonstrated a decrease in hydraulic conductivity due to wetting and self-healing which was more pronounced in soils with medium to high plasticity and swelling potential. Albright et al. (2004) investigated the effect of weathering on hydraulic performance of conventional and alternative landfill covers using 24 test sections located at 11 locations throughout the US. The results recorded at humid climate locations showed that both conventional and alternative landfill covers resulted in high percolation rates. This was attributed to the presence of cracks and other defects that enhanced preferential flow occurrence. However, using a layer of geomembrane on top of the soil barrier minimized the water percolation through the barrier (Albright et al., 2004, 2006).

Desiccation cracking and the relevant changes in hydraulic behavior of fine-grained soils have been widely investigated. However, field conditions that CCL materials would be exposed to were neither adequately, nor accurately, simulated. In the literature, most desiccation and dewatering processes were initiated by putting the entire test specimen in an oven thereby exposing it to an all-around (3D) heat (e.g., Omidi et al., 1996; Rayhani et al., 2008). Furthermore, the heating interval, in many cases, was prolonged for several days (e.g. Omidi et al., 1996). This exaggeration of circumstances could result in severe shrinkage and a subsequent increase in permeability of the CCL. This study aims to evaluate the effects of daily thermal cycles experienced in the field on the hydraulic performance of CCLs under simulated field conditions. This will be achieved by enhancing one dimensional heat and moisture transfer providing simulated boundary conditions that the CCLs would be exposed to in the field in case of drying. Hydraulic conductivity tests were conducted prior to, and after, several daily thermal cycles. Different types of clayey soils with variation in plasticity indices of 9–37% were used in this experiment in an attempt to represent samples from common CCLs used in practice.

2. Soil properties

Clayey soils used as CCL specimens in this research were extracted from the Halton landfill in Toronto (Halton Clay) and the Navan landfill in Ottawa (Leda Clay). Two soil mixtures were also created by adding sodium bentonite to the Halton clay (Halton clay + 10% Bentonite) and Leda clay (Leda clay + 5% Bentonite) (Table 1). The sodium bentonite used in mixtures has a plasticity index of 262% and smectite content of 55%. The percent of bentonite mixed with the natural soils was measured by the total mass of the mixture. The variability in soil types aimed at creating a variety of plasticity values and clay contents.

The physical properties of the test soils are summarized in Table 1. Liquid limits (LL) for test soils ranged from 23.5% to 60.0%, while plasticity indices (PI) varied from 9.5% to 37.2% based on the Atterberg test results (ASTM D4318, 2010). Soil-Water Characteristic Curves (SWCC) for all test soils were also established in accordance with ASTM procedure (ASTM D6836, 2008). Axis translation technique was used to establish the drying SWCC for suction ranges of 0–1500 kPa, while the Dewpoint Potentiometer technique was utilized to measure the water content corresponding to relatively higher suctions (i.e., higher than 1500 kPa) along the transition and residual stages (ASTM D6836, 2008). Matric suction (u_a-u_w) was applied on a saturated soil sample placed on a high air entry ceramic disk inside an air tight stainless steel chamber. Gravimetric water content was recorded at different metric suctions when moisture equilibrium achieved. The experimental result showed an air entry value that varied from 400 kPa for Halton clay to 950 kPa for Leda clay + 5% bentonite mixture (Fig. 1).

3. Experimental setup

3.1. Experimental cells and specimen preparation

Plexiglas cells 140 mm in diameter and 150 mm in height were used to simulate a typical CCL profile in landfills. The Plexiglas cells were equipped with upper and lower aluminum lids with dimensions of 200 mm × 200 mm × 10 mm. The upper lids were manufactured with influent and venting ports, whereas the lower lids featured effluent ports in order to enable the permeant to move throughout the soil columns. Prior to soil compaction, rubber membranes were stretched inside the cells to eliminate the effect of side-wall leakage (Fig. 2(a)).

Prior to sample preparation, bulk soil samples were crushed to pass through sieve No. 4 (4.75 mm). For soil mixtures, different proportions of sodium bentonite were added to the natural soil powders and carefully mixed in order to obtain uniform mixtures. To prepare the experimental cells, water was added to the dry soil until a moisture content of w_{opt} +2% was achieved for all soils. The hydrated soils were then allowed to cure in airtight plastic bags for at least 48 h to ensure uniform moisture distribution. The soil was then compacted in three layers into the cells (95% of the maximum dry density) using 2.5 kg hammer falling 30 cm, in accordance with ASTM standard (ASTM D698, 2012). At each compaction layer, a specimen of soil was obtained to measure the moisture content of the soil throughout the cell.

3.2. Hydraulic conductivity testing

Saturated hydraulic conductivity tests were performed on the