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Effects of leachate infiltration and desiccation cracks on hydraulic conductivity of compacted clay

Jun He*, Yu Wang, Yong Li, Xiao-chen Ruan

College of Civil and Architectural Engineering, Hubei University of Technology, Wuhan 430068, PR China

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Abstract

Both cracks in clay liner and the complex composition of landfill leachate might have effects on the hydraulic conductivity of a compacted clay liner. In this study, the hydraulic conductivities of natural clay and bentonite-modified clay with and without desiccation cracks were measured, respectively, using three types of liquids as permeating liquid: 2 500 mg/L acetic acid solution, 0.5 mol/L $CaCl_2$ solution, and tap water. When tap water was adopted as the permeating liquid, desiccation cracks resulted in increases in the average value of hydraulic conductivity: a 25-fold increase for the natural clay and a 5.7-fold increase for the bentonite-modified clay. It was also found out that the strong self-healing capability of bentonite helped to reduce the adverse impact of cracks on hydraulic performance. In contrast to tap water, simulated leachates (acetic acid and $CaCl_2$ solutions) show no adverse effect on the hydraulic conductivities of natural and bentonite-modified clays. It is concluded that desiccation cracks and bentonite have more significant effects on hydraulic performance than simulated leachates.

Keywords: Natural clay; Bentonite-modified clay; Hydraulic conductivity; Solution; Desiccation crack

1. Introduction

As a material with low permeability, compacted clay is frequently used in the final cover and bottom liner system in landfills. The low permeability of the clay liner is very useful in effectively disposing of waste. Much experience in design and construction of compacted clay liners has been accumulated, and it has been recognized that landfill leachate and cracks in liners might weaken the hydraulic performance. When applying geomembranes and geosynthetic clay liners in the liner system, the underlying soil is the ultimate barrier to the diffusion of pollutants, and the effects of landfill leachate and cracks on the hydraulic performance should be considered. Landfill leachate contains complex high-concentration pollutants. When leachate transports through the clay liner and underlying soil, chemical reactions, including dissolution, precipitation, ion exchange, and biochemical processes, might affect the hydraulic conductivity of the soil (Yilmaz et al., 2008). In addition, desiccation, freezing-thawing behavior, temperature gradients, and differential settlement may result in cracks in the clay liner and the soil (Omidi et al., 1996). Hence, a further understanding of the effects of leachate and cracks on the hydraulic performance of clay liners is highly valuable.

In the past two decades, several studies on the effects of leachate and cracks on the hydraulic conductivity k of compacted clay liners, bentonite-sand mixtures, and geosynthetic clay liners have been conducted. In general, the hydraulic behavior of fine soils is influenced by the interaction between pore fluid and minerals. For natural clay, inorganic salt (such as ferric chloride and nickel nitrate) does not significantly affect the hydraulic conductivity (Peirce et al., 1987). Yilmaz

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* Corresponding author.
E-mail address: hjunas@163.com (Jun He).
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et al. (2008) and Arasan (2010) determined that the hydraulic conductivity increased for clay with a high liquid limit and decreased for clay with a low liquid limit, with the increase of salt concentrations. Test results with acidic waste solution show a decrease in the hydraulic conductivity with time (Hamdi and Srasra, 2013). Pure organic chemicals can cause a large increase in the hydraulic conductivity of compacted clay, while diluted organic chemicals have little effect on the hydraulic conductivity (Bowders and Daniel, 1987). Kenney et al. (1992) focused on compacted mixtures of bentonite and sand, and suggested that the fabric of bentonite enclosed within the sand framework was little influenced by the change of system chemistry. Francisca and Glatstein (2010) studied the relative influence of biological, physical, and chemical interactions on the percolation of leachate through compacted silt-bentonite mixtures, and determined that pore clogging resulted in a decrease in the hydraulic conductivity. Due to the existence of hydrophilic montmorillonite in geosynthetic clay liners, low-electrolyte organics or highly concentrated salts (such as a $CaCl_2$ solution) result in syneresis cracks as well as an increase in the hydraulic conductivity up to four orders of magnitude (Petrov et al., 1997; Xu et al., 2009; Shackelford et al., 2010; Scalia and Benson, 2011). With different types of clay and test methods, the change in hydraulic conductivity ranged from insignificant to two orders of magnitude (Albrecht and Benson, 2001; Rayhani et al., 2007; Tang et al., 2011; He and Song, 2011; He et al., 2012).

In order to attain the values of hydraulic conductivity specified by international regulations ($k < 1 \times 10^{-9}$ m/s), addition of bentonite to local soils is a commonly adopted method (Francisca and Glatstein, 2010). The strong swelling-shrinkage capability of bentonite might create more desiccation cracks in clay liners. The self-healing ability and hydraulic performance of bentonite-modified clay under the effects of cracks and leachate need further research. The present study aims to (1) investigate the effect of simulated leachate on the hydraulic conductivity of natural clay and bentonite-modified clay, (2) investigate the effects of desiccation cracks on the hydraulic conductivity of natural clay and bentonite-modified clay, and (3) investigate the mutual effect of leachate and cracks on the hydraulic conductivity.

2. Experiment

The natural clay used in this study was obtained from the Changshankou landfill in Wuhan City. The optimum water content and the maximum dry density were 23.0% and 1.61 g/cm^3, respectively. The Na-bentonite in which the montmorillonite content was about 85% was obtained from Beipiao City in Liaoning Province. The natural clay and bentonite-modified clay were air-dried and mechanically pulverized. After they passed through 2-mm and 0.075-mm sieves, the two types of soils were mixed with a dry mass ratio of 1:10. The Atterberg limits of the soils are listed in Table 1.

Table 1
Atterberg limits of test soils.

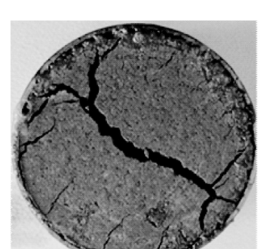
Soil type	Liquid	Liquid limit (%)	Plastic limit (%)	Plastic index (%)
Natural clay	Tap water	39.7	25.3	14.4
	Acetic acid solution	36.5	24.3	12.2
Bentonite-modified clay	Tap water	49.6	28.0	21.6
	Acetic acid solution	47.0	25.7	21.3
	$CaCl_2$ solution	48.1	24.9	23.2

The typical water content of the soils used in landfills is about 2% above the optimum water content. Natural clay and bentonite-modified clay were moistened to water contents of 25% and 28%, respectively, and were compacted to the dry density of 1.56 g/cm^3.

The composition of landfill leachate is very complex. Generally, it can be divided into two categories: inorganic pollutants and organic pollutants. The liquids used in the tests were tap water, 2 500 mg/L acetic acid solution, and 0.05 mol/L $CaCl_2$ solution. The tap water was de-aired. The acetic acid is the main organic acid of high concentration in the initial landfill stage (Lou et al., 2011), and Ca^{2+} and Cl^- are the common pollutant ions in leachate (Yilmaz et al., 2008). Therefore, the acetic acid solution and $CaCl_2$ solution were chosen as representatives of organic and inorganic pollutants in leachate, respectively.

The hydraulic conductivity tests were performed with the falling head technique with two fixed-wall permeameters. In the QY1-2 type permeameter, a cutting ring with an inner diameter of 61.8 mm was used to prepare specimens. In order to reduce boundary effects on cracking, the other permeameter with a 103 mm-inner diameter PVC cylinder was used. The thicknesses of the specimens were 2 cm and 3 cm, respectively. To prevent the separation between soil and the inner wall as well as the occurrence of side leakage, Araldite glue was applied to the inner surface of the ring and cylinder (Kodikara et al., 2002; He et al., 2012). Typical specimens are shown in Fig. 1.

In order to simulate the effects of leachate on the liner and underlying soil in landfills, three cases were considered: specimens saturated and permeated with tap water (i.e., tap water + tap water), specimens saturated with tap water and permeated with solution (i.e., tap water + solution), and specimens saturated and permeated with solution (i.e., solution + solution). In the second case, the specimens were


(a) Cutting ring specimen (inner diameter: 61.8 mm)

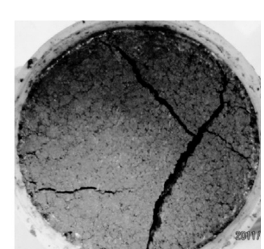

(b) Cylinder specimen (inner diameter: 103 mm)

Fig. 1. Natural clay specimens with cracks.