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

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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 CaCl2 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 CaCl2 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...
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 CaCl₂ 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 \( (k < 1 \times 10^{-9} \text{ m/s}) \), 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 influence of biological, physical, and chemical interactions on the percolation of leachate through compacted clay 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 CaCl₂ 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).

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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/cm³, 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.

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/cm³.

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 CaCl₂ 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 Ca²⁺ and Cl⁻ are the common pollutant ions in leachate (Yılmaz et al., 2008). Therefore, the acetic acid solution and CaCl₂ 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

![Fig. 1. Natural clay specimens with cracks.](image-url)
permeated with tap water before being permeated with solution. In this way, random errors induced by the soil difference and test procedure can be reduced. The criterion for ending the tests can be found in Bowders and Daniel (1987) and Petrov et al. (1997). The requirement that at least one to two pore volumes of permeating liquid pass through the soil specimen was satisfied.

3. Results and discussion

3.1. Typical test results

Fig. 2 shows some typical test results of hydraulic conductivity. It can be seen that the hydraulic conductivity fluctuates with the increase of the pore volume flux. In the following sections, the average value of hydraulic conductivity around 1.5—2 pore volumes is analyzed.

3.2. Test results with two permeameters

Fig. 3 shows the results from the permeameter tests with different specimen sizes, including the cutting ring specimen without cracks (NC-CU), the cylinder specimen without cracks (NC-CY), the cutting ring specimen with cracks (C-CU), and the cylinder specimen with cracks (C-CY). The average hydraulic conductivity of NC-CU was found to be 2.7 times greater than that of NC-CY, and the average hydraulic conductivity of C-CU was 1.5 times greater than that of C-CY. The single factor variance analysis indicates that there is no significant difference between the results from the two permeameters at the significance level of 0.1, with $F = 2.50$ and $F_{0.1} = 3.22$ for specimens without cracks, and $F = 1.16$ and $F_{0.1} = 3.59$ for specimens with cracks, where $F$ is the $F$ test statistic, and $F_{0.1}$ is the critical value of $F$ at the significance level of 0.1. Hence, the hydraulic conductivities from the two permeameters are combined for the analysis. Table 2 summarizes the results.

3.3. Effect of cracks of specimens permeated with tap water

Fig. 4 shows the results of different specimens permeated with tap water, including the bentonite-modified clay specimen without cracks (NC-BC), the bentonite-modified clay specimen with cracks (C-BC), the natural clay specimen without cracks (NC-NC), and the natural clay specimen with cracks (C-NC). The hydraulic conductivity of NC-BC ranged from $1.6 \times 10^{-8}$ cm/s to $1.0 \times 10^{-7}$ cm/s, the value of NC-NC ranged from $3.1 \times 10^{-7}$ cm/s to $1.5 \times 10^{-5}$ cm/s, the value of C-BC ranged from $8.9 \times 10^{-8}$ cm/s to $9.0 \times 10^{-7}$ cm/s, and the value of C-NC ranged from $1.8 \times 10^{-7}$ cm/s to $1.7 \times 10^{-5}$ cm/s. The addition of bentonite produces a 0.015-fold decrease in average hydraulic conductivity for the specimens without cracks, and a 0.0036-fold decrease for the specimens with cracks. Desiccation cracks cause a 25-fold increase in hydraulic conductivity for natural clay. However, for bentonite-modified clay, the ratio of the hydraulic conductivity of specimens with cracks to that of the specimens without cracks is only 5.7, indicating that bentonite is very effective in improving the hydraulic performance of soil with cracks.

3.4. Effect of simulated leachates

3.4.1. Natural clay

The hydraulic conductivity of the natural clay permeated with acetic acid solution is shown in Figs. 2 and 5, and Table 2. The hydraulic conductivity of the specimen without cracks saturated and permeated with acetic acid solution (NC-AA) is lower than that of the specimen without cracks...
saturated and permeated with tap water (NC-TT), and also lower than that of the specimen without cracks saturated with tap water and permeated with acetic acid solution (NC-TA) (Fig. 5(a)). The hydraulic conductivity of the specimen with cracks saturated with tap water and permeated with acetic acid solution (C-TA) is lower than that of the specimen with cracks saturated and permeated with tap water (C-TT), and also lower than that of the specimen with cracks saturated and permeated with acetic acid solution (C-AA) (Fig. 5(b)). The hydraulic conductivity of C-AA ranged from $1.3 \times 10^{-4}$ cm/s to $1.7 \times 10^{-4}$ cm/s, which was close to the average hydraulic conductivity of C-TT ($1.3 \times 10^{-4}$ cm/s). Therefore, it is believed that the acetic acid solution does not show a significant adverse effect on the hydraulic performance of the natural clay.

### 3.4.2. Bentonite-modified clay

The hydraulic conductivity of the bentonite-modified clay saturated with acetic acid solution and CaCl$_2$ solution is shown in Figs. 2, 6 and 7, and Table 2. In contrast to the results of the bentonite-modified clay saturated and permeated with tap water, the hydraulic conductivity of the bentonite-modified clay saturated with tap water and permeated with acetic acid solution does not show a significant increase, no matter whether the specimens are cracked or not. The ratio of the hydraulic conductivity of the specimen saturated with tap water and permeated with simulated leachate ($k_s$) to that of the specimen saturated and permeated with tap water ($k_t$) is lower than 1 (Fig. 7, where NC-TC is the specimen without cracks saturated and permeated with tap water).

### Table 2

Summary of test results.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Crack</th>
<th>Liquid</th>
<th>$k$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural clay</td>
<td>Without</td>
<td>Tap water + tap water</td>
<td>$(4.0 \pm 4.8) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water + acetic acid solution</td>
<td>$(2.6 \pm 1.9) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acetic acid solution +</td>
<td>$(5.4 \pm 3.5) \times 10^{-1}$</td>
</tr>
<tr>
<td></td>
<td>With</td>
<td>Tap water + tap water</td>
<td>$(1.0 \pm 0.6) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water + acetic acid solution</td>
<td>$(2.5 \pm 1.2) \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acetic acid solution +</td>
<td>$(1.4 \pm 0.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>Bentonite-modified clay</td>
<td>Without</td>
<td>Tap water + tap water</td>
<td>$(6.4 \pm 3.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water + acetic acid solution</td>
<td>$(2.3 \pm 1.5) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water + CaCl$_2$ solution</td>
<td>$(5.5 \pm 2.0) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>With</td>
<td>Tap water + tap water</td>
<td>$(3.7 \pm 3.7) \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water + acetic acid solution</td>
<td>$(1.1 \pm 0.5) \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tap water + CaCl$_2$ solution</td>
<td>$(1.7 \pm 0.8) \times 10^{-7}$</td>
</tr>
</tbody>
</table>

![Fig. 4. Box plot of hydraulic conductivity of specimens permeated with tap water.](image)

![Fig. 5. Box plots of hydraulic conductivity for natural clay under effect of acetic acid solution.](image)

![Fig. 6. Box plot of hydraulic conductivity for bentonite-modified clay under effect of acetic acid solution.](image)

![Fig. 7. Ratio of hydraulic conductivity of specimen saturated with tap water and permeated with simulated leachate to that of specimen saturated and permeated with tap water.](image)
saturated with tap water and permeated with CaCl₂ solution, and C-TC is the specimen with cracks saturated with tap water and permeated with CaCl₂ solution), indicating that the simulated leachates used in this study do not have a significant adverse effect on the hydraulic performance of the bentonite-modified clay. This result is similar to that of natural clay.

3.5. Discussion

3.5.1. Single factor variance analysis

Table 3 shows the results of the single factor variance analysis on the effects of desiccation cracks, bentonite, and simulated leachates, respectively. It can be determined that bentonite and desiccation cracks are important factors affecting the hydraulic performance, while simulated leachates are non-significant.

3.5.2. Relationship between hydraulic conductivity and desiccation cracks

He and Song (2011) concluded that one cycle of desiccation cracking can result in a 2- to 150-fold increase in hydraulic conductivity. The results in this study are within this range. The increase in hydraulic conductivity occurred because the crack could not be healed completely when the desiccation specimen was rehydrated (He et al., 2012). He and Wang (2013) conducted simulation tests of crack propagation for natural clay and bentonite-modified clay. The crack parameters during the dry-wet cycle are shown in Table 4, where the crack area rate is the ratio of the crack area to the total area, the crack length ratio is the ratio of the crack length to the total area, and the crack average width is the ratio of the crack area to the crack length. It can be seen that the crack area rate and crack length ratio of the bentonite-modified clay are significantly different from those of natural clay. The crack area rate and crack length ratio of the bentonite-modified clay are about 2.5 and 1.9 times as much as those of natural clay, respectively. However, the average crack width of the bentonite-modified clay is only a little greater than that of the natural clay (i.e., 30 mm versus 25 mm). The self-healing capability of the bentonite-modified clay helps the soil maintain good hydraulic performance.

3.5.3. Relationship between hydraulic conductivity and solution

The Atterberg limits are important physical indices for clayey soil, and it is recognized that the liquid limit and plastic index are related to the nature of pore fluid. Researchers have argued that the Atterberg limits can be correlated to the hydraulic conductivity (Benson and Trast, 1995), and found out that the hydraulic conductivity is dependent on the liquid limit and the plastic index of the soil (Fig. 8). The present study shows that the hydraulic conductivity generally decreases with increasing liquid limit and plastic index (Fig. 9), the same trend as that in Fig. 8. However, the results from Benson and Trast (1995) are lower than those from the present study. The differences are considered to be induced from different test methods (flexible-wall permeameter versus rigid-wall permeameter), pressure conditions (20 kPa versus 0 kPa), and soil properties.

However, for a given soil, the decreasing trend in hydraulic conductivity with increasing Atterberg limits is not significant (Fig. 9). This is attributed to the complex interaction between soil particles and pore solution.

The hydraulic conductivities of specimens under the effect of the acetic acid solution are consistent with those from Bowders and Daniel (1987). When an organic liquid replaces the pore water in soil, the shrinkage of the diffuse double layer may produce cracks and an increase in hydraulic conductivity, while a dilute solution still has a sufficiently high dielectric constant to prevent shrinkage of the double layer. Acetic acid might dissolve some soil components of the specimens, which can precipitate in the following path and result in the decrease in hydraulic conductivity (Bowders and Daniel, 1987). The more significant decrease in hydraulic conductivity for

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Crack area rate (%)</th>
<th>Crack length ratio (mm⁻¹)</th>
<th>Average crack width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural clay</td>
<td>3.4</td>
<td>0.001 5</td>
<td>25</td>
</tr>
<tr>
<td>Bentonite-modified clay</td>
<td>8.6</td>
<td>0.002 8</td>
<td>30</td>
</tr>
</tbody>
</table>

Note: a means that the results of the specimens saturated with tap water and permeated with solution and those of the specimens saturated and permeated with solution are taken together as the results of the specimens under the effect of solution.
bentonite-modified clay with cracks might be due to the dissolution and precipitation nearby the cracks.

As mentioned before, the hydraulic conductivity of the geosynthetic clay liner (GCL) might increase by several orders of magnitude when permeated with CaCl₂ solution. However, for the bentonite-modified clay in this study, the results are different, but similar to those from Peirce et al. (1987) and Kenney et al. (1992). The liquid limit of the bentonite-modified clay permeated with CaCl₂ solution is lower than that of the bentonite-modified clay permeated with tap water (Table 1), which might result in shrinkage of the diffuse double layer and an increase in pore space. The content of bentonite in the modified clay is less than that in the GCL. The natural clay components in the bentonite-modified clay might be of buffer action to reduce the effect of CaCl₂ solution on the hydraulic conductivity.

4. Conclusions

(1) Application of Araldite glue to the inner surface of the rings and cylinders is effective in simulating cracks in clay and preventing side leakage. There are some differences between the hydraulic conductivities obtained from the two permeameters, but they are not significant in the statistical sense.

(2) As desiccation cracks cannot be healed completely, hydraulic conductivities of natural clay and bentonite-modified clay are strongly influenced by cracks. With tap water as permeating liquid, cracks cause a 25-fold increase in the average hydraulic conductivity of natural clay, from the order of 10⁻⁶ cm/s to 10⁻⁴ cm/s, and a 5.7-fold increase in the average hydraulic conductivity of bentonite-modified clay, from the order of 10⁻⁸ cm/s to 10⁻⁷ cm/s. The addition of bentonite helps to improve the hydraulic performance and reduce the adverse effect of cracks.

(3) In contrast to tap water, 2500 mg/L acetic acid solution shows a negligible effect on the hydraulic performance of natural clay. A similar phenomenon is observed in bentonite-modified clay with 2500 mg/L acetic acid solution and 0.05 mol/L CaCl₂ solution as permeating liquids.

(4) Under the experimental conditions in this study, bentonite and desiccation cracks are important factors affecting hydraulic performance, while simulated leachates have little effect on hydraulic performance.

References


