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Note

Temperature effects on non-Darcy flow of compacted clay

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ABSTRACT

Due to biochemical reactions that can occur inside the landfills, accumulation and diffusion of the heat generated by the reaction can changes of internal temperature of landfills. The internal temperature can reaches 55 °C to 60 °C. The hydraulic conductivity and threshold gradient of clay liner could be affected by this high temperature field. A temperature-controlled flexible wall permeameter was developed to conduct the permeability study for a type of illite clay under different temperatures. The results showed that as temperature increased, the hydraulic conductivity increased and the threshold gradient decreased. The Zeta potential in clay disperse system was measured under different temperatures. It was found that that the greater the temperature, the smaller the Zeta potential, which indicated the changes of the interaction of the particles with water. As the temperature increased, the permeate viscosity decreased. Considering the temperature effects on the permeate viscosity and intrinsic permeability, and learning from the previous empirical relationship between the intrinsic permeability and temperature and relationship between the threshold gradient and apparent fluidity (k_{in}/η), an equation for calculating the hydraulic conductivity and threshold gradient with the changes of temperature was derived.

1. Introduction

Understanding water flow through low permeability media (such as compacted clay) is very important for some engineering applications. For instance, due to its low permeability, low diffusion coefficient, high retention capacity for radionuclide, and ability to self-seal fractures, clay is considered as potential host rock for geological disposal of high-level radioactive waste (Tsang et al., 2012). The traditional description of water seepage in porous media is based on Darcy's Law. However, Darcy's Law is not suitable for some porous media, especially compacted clay (Kutílek, 1972). In 1869, King Hagen first discovered that water in porous media seepage process presented non-Darcy phenomenon (Longmuir, 2004). Thereafter, a number of researchers also found that the seepage process in compacted clay deviated from Darcy's law in the case of low seepage velocity and there is a threshold gradient i_0 (Mitchell and Younger, 1967; Hansbo, 2001).

In order to prevent contamination of groundwater in landfills, the construction requirement for compacted clay liner is that the hydraulic conductivity must be no > 1.0×10^{-7} cm/s (Qian et al., 2002). Currently, many of the landfills in Asia lack the necessary protective barrier system (Karthikeyan et al., 2007; Sharholy et al., 2008). The leachate levels in these landfills tend to be very high and even reach >10 m (Chen and Zhan, 2007). In this case, if the threshold gradient i_0 exists in the clay, it can produce a good anti-seepage effect and also plays a blocking effect for contaminant transport in clay liner. On other hand, Don Augenstein and Ramin Yazdani (1995) noted that the landfill temperature can reach 55 °C to 60 °C. A number of researchers also had carried out thermo-osmosis of Saturated Clays research (Gonçalvès et al., 2012; Zagoršćak et al., 2016). Temperatures will affect the hydraulic conductivity and threshold gradient of compacted clay.

Florin (1951) noted that the bound water retained by the surface force of soil particles was not flowing in narrow and long pores. It could block the flow of free water. Only when the driving gradient was large enough to destroy the bound water, the flow could occur. Miller and Low (1963) insisted that there was a "quasicrystal" structure in the interface of the clay and water and there must be a shear stress to deform the water membrane structure to make seepage occur. Singh and Wallender (2008)used a modified Kozeny-Carman equation to predict the hydraulic conductivity. They pointed out that the water film at the surface of clay particles could not flow under the action of hydraulic gradient. Thus, the volume of this part of water should be deducted from the void to obtain an effective porosity. They modified Kozeny-Carman equation to obtain better predicted values of hydraulic conductivity. Liu and Birkholzer (2012) summarized previous research results for both fully and partially saturated clays to establish a relationship between permeability and threshold gradient. It was found that the threshold

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gradient increased with the decrease of permeability. Zhang et al. (1998) proposed that the water film in the pores reduced the radius of the effective pore throat, which has a great impact on the flow of fluid in the low-permeability media. Xu et al. (2007) carried out permeability tests using deionized water with independent microtubule. The microtubule diameter ranged from 2 to 30 μm. When the microtubule diameter was >16 μm, the seepage process fit well with Darcy's law. When the diameter is <16 μm, the seepage process deviated significantly from Darcy's law and the flow velocity appeared nonlinear relationship with hydraulic gradient. Wei et al. (2009) performed the mercury injection experiments and permeability tests at the Daqing Oil Field. The authors firstly obtained the aperture distribution curve by using the mercury injection experiment and then defined the value of 95% at the curve as the mainstream throat radius. Miller and Low (1963) conducted the research on the temperature effect on non-Darcy flow. It was found that as the temperature increased, the threshold gradient decreased and the hydraulic conductivity increased. They explained the main reason for this phenomenon was due to the increase in temperature reduced the interaction of particles with the water. Liu (2014) proposed that the changes in temperature caused the changes of permeate viscosity, which affected the permeability characteristics. Based on the temperature effect on permeate viscosity, he proposed an equation to calculate the threshold gradient with the changes of temperature.

During waste degradation, a high temperature field may form in landfills. The former found that the changes of temperature could affect the hydraulic conductivity k and threshold gradient i_0, but its internal mechanism is unclear. In order to solve this problem, first of all, the temperature effect on the hydraulic conductivity for compacted clay was investigated; Secondly, the temperature effects on the permeate viscosity and Zeta potential were also studied; And then, by considering the temperature effect on the permeate viscosity and the interaction between soil particle and water, an equation for calculating the hydraulic conductivity and threshold gradient with the changes of temperature was proposed in this study.

2. Experimental materials and method

2.1. Experimental materials

The clay used in this study was taken from Nanjing, Jiangsu province, China. The main mineral component of this clay was illite. Liquid limit (LL), Plastic limit (PL) and Specific gravity (G_s) tests were conducted per GB/T 50123-1999 method (China MOC, 1999). From the relationship established between the water content of soil and the cone penetration depth, the water content corresponding to a depth of 17 mm is the liquid limit, and that corresponding to a depth of 10 mm is the plastic limit. The particle distribution was tested by using Malvern 2000 laser particle analyzer. Based on Usual Soil Classification System (USCS), it was low liquid-limit clay (CL). The mineral components were tested by X-ray diffraction (XRD) atlas analysis. The cation exchange capacities (CEC) of the materials were determined using the JC/T593-1995 method (State Construction Materials Industry Administration, 2004). Measurement of the interchangeable Calcium and Magnesium was tested by the ammonium acetate exchange-EDTA complexometric titration method. The interchangeable Potassium and Sodium was tested by the ammonium acetate exchange-flame photometry rule. The index properties of the clay were presented in Table 1. Ordinary deionized water method was used as the dialysate in the tests.

Table 1
Basic properties of tested clay.

Properties	Values
Specific gravity, G_s	2.72
Liquid limit, w_L (%)	48.33
Plastic limit, w_P (%)	23.73
Plasticity index, I_P (%)	24.60
Zeta potential ζ (mV)	−13.50
Particle size distribution (%)	
Sand (0.075–2 mm)	0.1
Silt (0.002–0.075 mm)	92.8
Clay (<0.002 mm)	7.1
Main minerals (weight proportion, %)	
Kaolinite	11
Illite	58
Montmorillonite	12
Quartz	19
Cation exchange capacity, CEC (cmol/kg)	
Na^+	4.96
K^+	2.11
Ca^{2+}	17.15
Mg^{2+}	0.11
Sum	24.33

2.2. Modification of permeameter

A flexible-wall permeameter was used in the permeability test, which could effectively prevent the lateral seepage penetration problem generated in the testing process and rapidly determine the hydraulic conductivity of the samples. In order to investigate temperature effect on the hydraulic conductivity of the clayey samples, the vertical heating rods were mounted in both the sample pressure chamber and the permeability pressure chamber. The thermocouple was installed to measure the temperature in the pressure chamber. A temperature control panel was installed to regulate the temperature, so as to achieve the required temperature settings (Fig. 1). A schematic diagram and a photograph of an improved permeameter are shown in Fig.1.

2.3. Sample preparation

The soils were air-dried, crushed, and screened to make particle size <1 mm. The deionized water was added with stirring to make a moisture content of 22%. The soil material was divided into three layers and pressed into a cutting ring with a diameter of 7 cm and a height of 4 cm. The first two layers were filled with 93 g and the last layer was filled with 94 g. Before the next layer was filled, the previous layer must be scarified to make seepage-proofing of the interface between two contact layers. Then, the test samples were placed into a saturation tank for vacuuming saturation to achieve the final saturation over 98%.

2.4. Permeability test

The sample was loaded into a pressure chamber after saturation. Each sample was experienced four processes of venting, heating, consolidation, and permeation. Four levels of temperature were set during test. They were 25, 35, 50, and 60 °C. The consolidation pressure σ should be equal to 200 kPa. If the water level in the drainpipe did not change under a certain consolidation pressure, it means that the sample had reached its consolidation stability. Then, the seepage pressure could be applied on the sample. At each level of seepage pressure, the water level in the drainpipe was read at intervals of 2 h. The next level of seepage pressure was not applied until the water level in the drainpipe became stable.

2.5. Viscosity measurement

A common coaxial cylinder topspin-type viscometer, NXS-11B, was selected to measure the viscosity. The coefficient of water dynamic viscosity was obtained by measuring the relationship between shear rate and shear stress at different rotating speeds. The instrument was equipped with a water bath temperature control device and was

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