Hindawi Publishing Corporation
Journal of Chemistry
Volume 2015, Article ID 685871, 6 pages
http://dx.doi.org/10.1155/2015/685871

Research Article

Heat Transport and Water Permeability during Cracking of the Landfill Compacted Clay Cover

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Received 27 July 2014; Revised 1 October 2014; Accepted 9 October 2014

Academic Editor: Peng Xu

The heat-moisture transport through the compacted clay was observed in laboratory. The hydraulic conductivity of cracked clay under wetting-drying cycles was also investigated. At the early phase of heating, the temperature of soil columns rose fast and moisture decreased dramatically; after this phase, the temperature rose at a lower speed and moisture loss stabilized gradually. The moisture content of compacted clay at 25 cm depth decayed to 0. The crack intensity factor (CIF) of compacted clay was 0.043 and 0.097; the crack depth was about 6.5 cm and 8.2 cm at 50°C and 60°C, respectively. The hydraulic conductivity of compacted clay was within 8.3×10^{-7} to 1.5×10^{-5} cm/s after four wetting-drying cycles. This value was 2~3 orders of magnitude higher than that of uncracked clay.

1. Introduction

In order to reduce the generation of landfill leachate, a cover system, as an important part of the antiseepage structure, must be set when landfill reaches its maximum reserve. Compacted clay is recommended to be used for building the cover system structure and the hydraulic conductivity of the clay must be less than 1×10^{-7} cm/s [1]. However, under the internal and external environmental effects, crack of the compacted clay cover system always occurs, which provides a convenient path for the infiltration of rainwater and then results in a sharp increase in landfill leachate which may take a severe toll on the ecological environment around the landfill.

Large amounts of heat are released by the degradation of solid waste, causing the rise of temperature in landfill. The temperature inside the landfill can go up to 70°C [2]. Due to the temperature dependence of vapor density and the temperature gradient between the landfill and surrounding atmospheric environment, vapor diffuses upward and out of the compacted clay cover. This strongly enhances the downward transport of liquid water by gravity [3, 4]. Therefore, vapor diffusion leads to the decrease in matric potential, causing the shrinkage and desiccation of compacted clay. When matric potentials become very small, the compacted clay shrinks horizontally and crack occurs [5–7]. For compacted clay cover systems with very low hydraulic conductivity, moisture will be slowly transported through landfill cover systems [8]. However, rainwater can directly leak into landfill if crack occurs in the compacted clay layer. Cracking leads to the changes of hydraulic conductivity (from 10^{-7} to 10^{-4} cm/s) and thermal conductivity of compacted clay [9, 10] and ultimately influences the heat-moisture transport in the cover system.

To investigate the surface cracking of soil columns and heat-moisture transport, the tests of heat-moisture transport through soil columns during cracking were conducted by the monitoring system of cracking. The permeability of compacted clay during wetting-drying cycles was measured with the PN3230M environmental soil flexible wall permeameter.

2. Materials and Methods

2.1. Materials. The clay used in the tests was taken from a construction site in Wuhan City of China. Basic physical properties and chemical composition of the clay are shown in Tables 1 and 2.

Table 1: The physical properties of the clay.

$\rho_{d\,max}$ (g/cm^3)	W_{opt} (%)	W_L (%)	W_p (%)	I_p (%)	Particle size distribution (%)			
					>0.05 mm	0.05~0.005 mm	0.005~0.002 mm	<0.002 mm
1.65	19	48.5	26.2	22.3	12	32	45	11

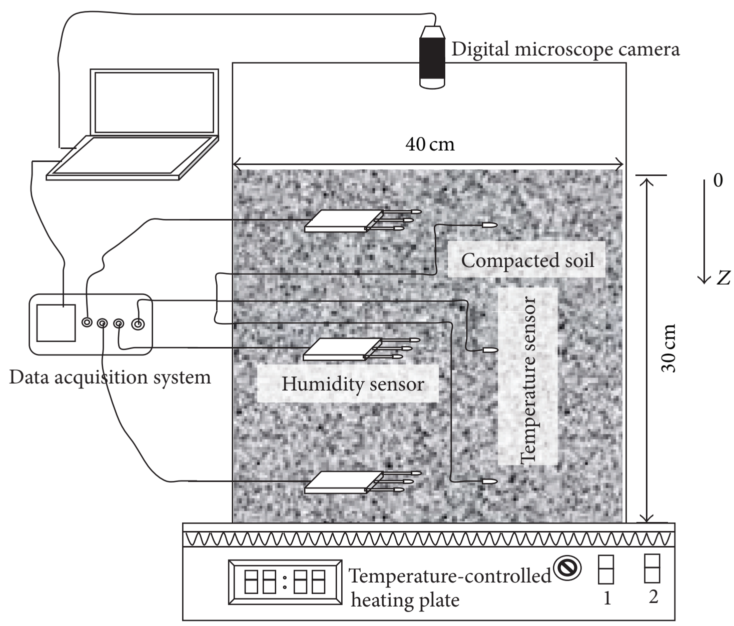


Figure 1: The monitoring system of cracking and heat-moisture transport in compacted clay.

Table 2: The chemical composition of the clay.

SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
58.42	25.23	0.24	0.51	0.12	5.32	2.67

2.2. Methods. The soil and moisture were mixed evenly, put into soil columns, and then compacted layer by layer. The compacted soil layer was formed at the maximum dry density in the column. The height and diameter of the soil columns were 30 cm and 40 cm, respectively. The bottoms of the soil columns were placed directly on the temperature-controlled heating plate (50°C and 60°C), surrounded by the insulation pad to prevent the dissemination of heat. Temperature and humidity sensors were placed in the depth of 5 cm, 15 cm, and 25 cm of the soil columns, monitoring temperature and moisture changes of compacted clay. A digital microscope camera was placed 50 cm above the soil column to observe the surface cracking (Figure 1).

The PN3230M environmental soil flexible wall permeameter, made by American GEOEQUIP, was used to test the permeability of the compacted clay under different wetting-drying cycles. The permeameter can prevent the sidewall leakage that might be caused by the specimen's volume change during the wetting-drying cycles. The specimen was initially sized at a diameter of 5 cm and a height of 5 cm for permeability tests. All samples were made by pressing soil of specific quantity into the cutting ring of the mentioned size. The samples were placed in a vacuum saturator can for 48 hr before permeability tests and then were placed in a dryer at 50°C for 72 hr after permeability tests. The aforementioned steps were repeated for four wetting-drying cycles.

3. Results and Discussion

3.1. Heat-Moisture Transport of Cracked Clay. Temperature variation at different depths of soil columns showed similar patterns at the heating source of 50°C or 60°C (Figure 2). Early in the heating, temperature at different depths rose quickly but then the growth trend attenuated significantly and eventually stabilized. The temperature was close to 50°C or 60°C at the depth of 25 cm after 22 hr of heating, indicating that the column bottom had cracks by now. The heat transport in soil columns was fast and able to achieve stability in a short time. Since the compacted clay layer can store heat, transport of heat in soil columns was significantly delayed with increasing distance from the heating source.

The soil moisture loss at various soil depths were given in Figures 3 and 4. The soil moisture loss near the bottom was highly sensitive to heat loading, and the effect was significantly attenuated and time lagged along with increasing distance from the heating source. The testing results of the heating source of 60°C indicated that soil moisture loss was very rapid within the first 20 hr and slowed down during 20 to 384 hr. Within 20 hr, at the depth of 25 cm,

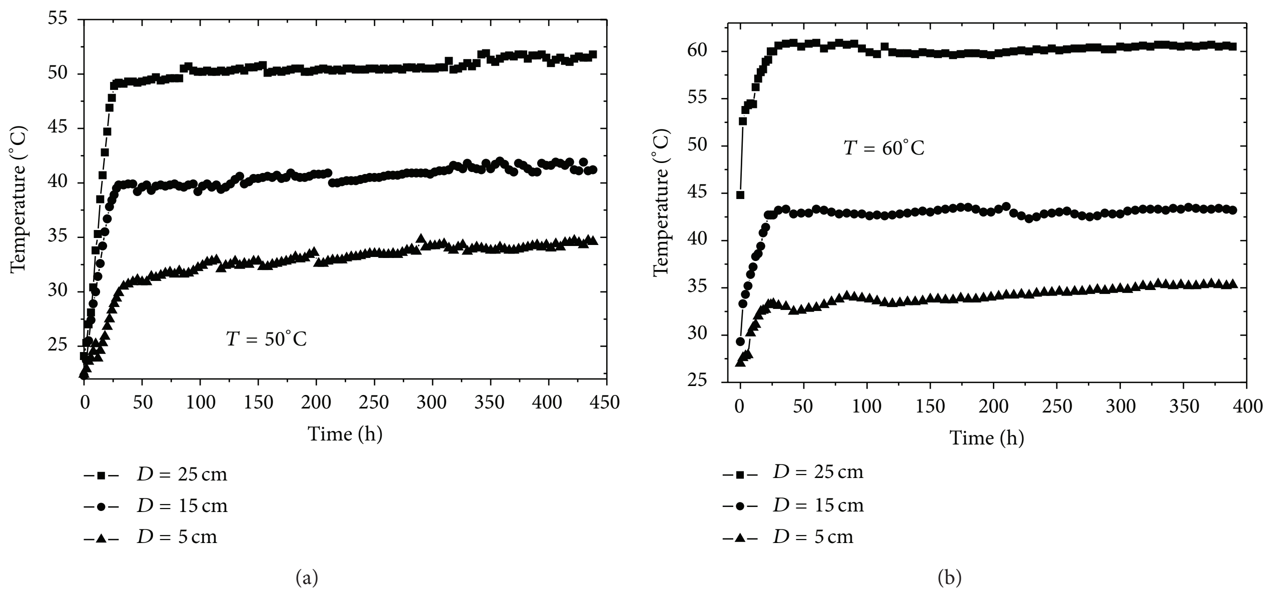


Figure 2: The temperature of compacted clay changes with time.

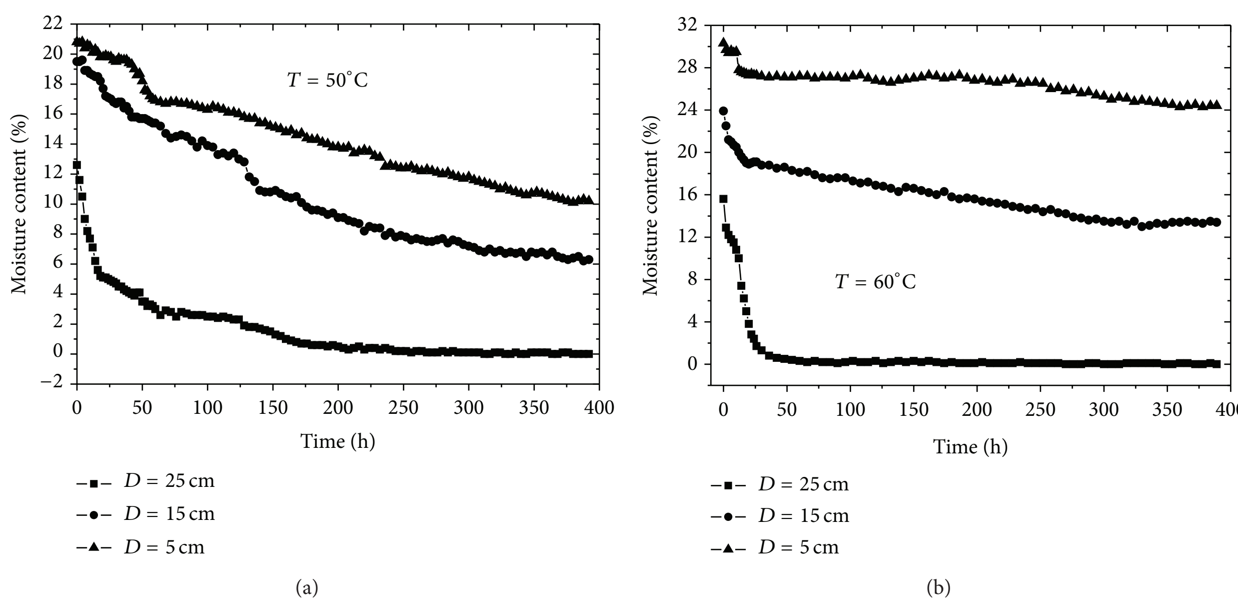


Figure 3: The moisture content of compacted clay changes with time.

the soil moisture content decreased from 0.16 to 0.038. The temperature gradient between the clay layer and the heat source was great at the early heating, resulting in fast moisture transmission. However, the soil moisture content at the depth of 25 cm decreased gradually from 0.038 to 0 during 20 to 384 hr, owing to the lower temperature gradient.

The cracking of compacted clay was characterized by the cracking intensity factor (CIF). The CIF value was the ratio of the cracking area (A_c) to the total area (A_t) [11–13]. Comparing the cracked and uncracked part of the surface, the former was obviously dim. The CIF was calculated by using the digital microscopy image analysis software. The surface CIF of compacted clay under heating source of 50°C or 60°C is shown in Figure 5. Compacted clay in the first 3-4 days showed no obvious cracks. Subsequently, the CIF increased dramatically from 0.0025 to 0.028 or from 0.0042 to 0.036. Then the CIF increased slowly to 0.043 and 0.097.

A kind of sticky black tracer was injected into soil columns to observe the crack depth. Soil material was colored in black at the tracer flow path. The crack depth was determined by the soil color change. After 4 hr, the soil column was cut along the cracking direction from top to bottom. It can be concluded that the surface crack depth of soils was about 6.5 cm and 8.2 cm at 50°C and 60°C, respectively.

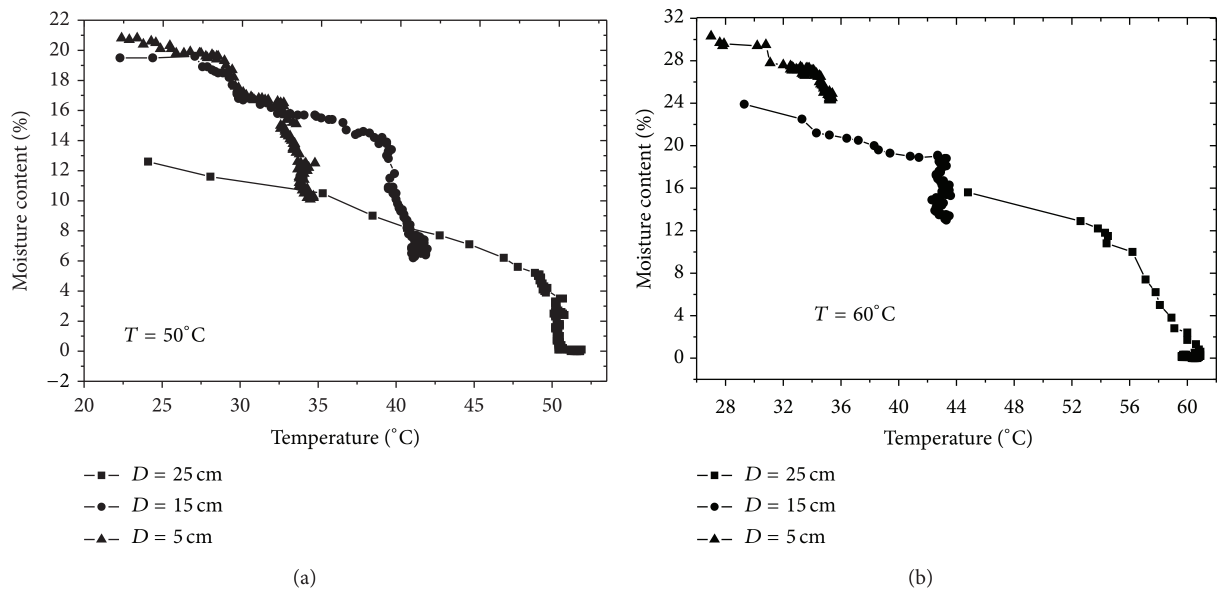


Figure 4: The moisture content of compacted clay changes with temperature.

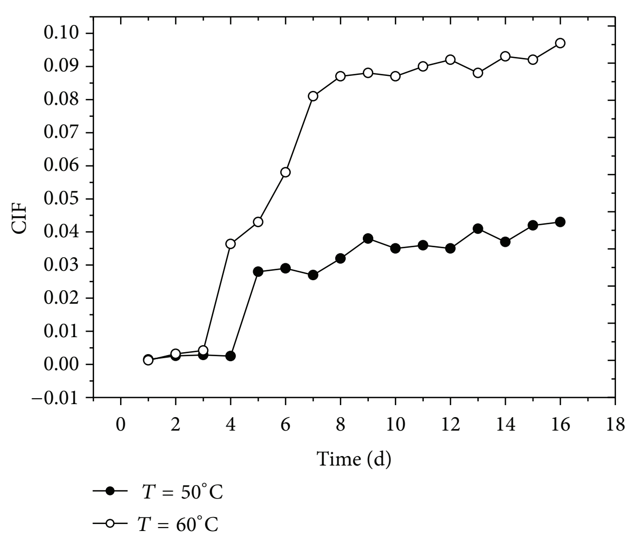
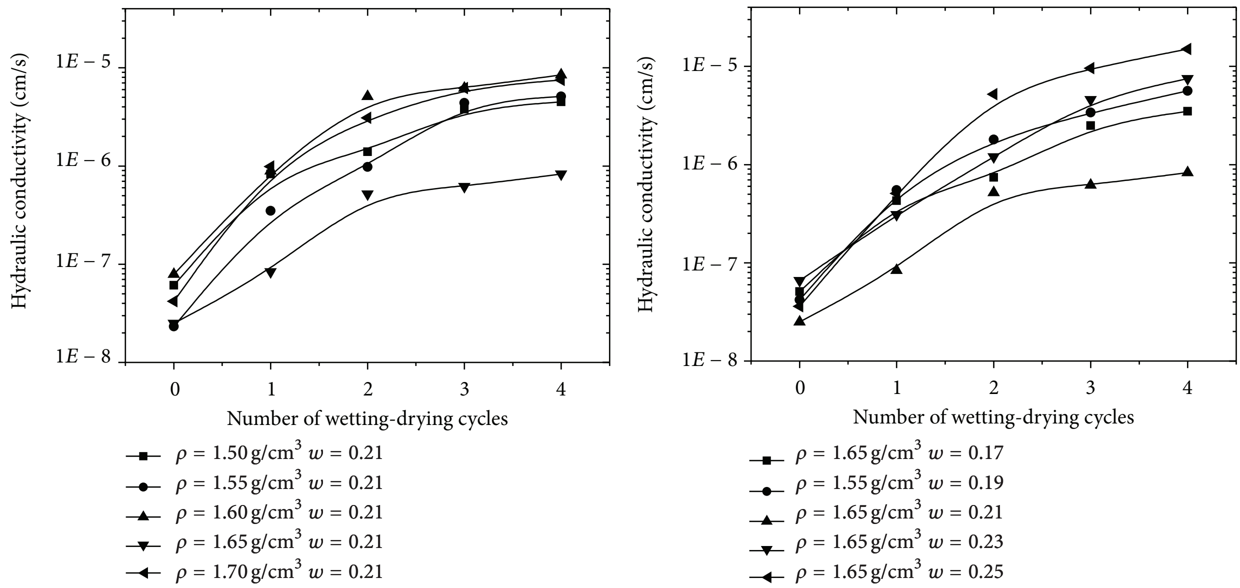


Figure 5: CIF of compacted clay under temperature gradient.

3.2. Hydraulic Conductivity of Cracked Clay. As shown in Figures 6 and 7, the influence of wetting-drying cycles on hydraulic conductivity of the compacted clay is remarkable. After four wetting-drying cycles, under the dry density ($\rho = 1.65\,\mathrm{g/cm^3}$) and moulding moisture content ($w_0 = 0.25$), the hydraulic conductivity of the compacted clay showed a significant increase, with its value jumping from 3.6×10^{-8} cm/s to 1.5×10^{-5} cm/s. The hydraulic conductivity of the compacted clay ($\rho = 1.65\,\mathrm{g/cm^3}$, $w_0 = 0.21$) increased from 2.5×10^{-8} cm/s to 8.3×10^{-7} cm/s. The hydraulic conductivity of other samples is two orders of magnitude higher than that of uncracked soils. It was also observed that the hydraulic conductivity of compacted clay samples is close to equilibrium after three wetting-drying cycles. The cracks presented in the clay surface provided a path for water seepage after wetting-drying cycles.

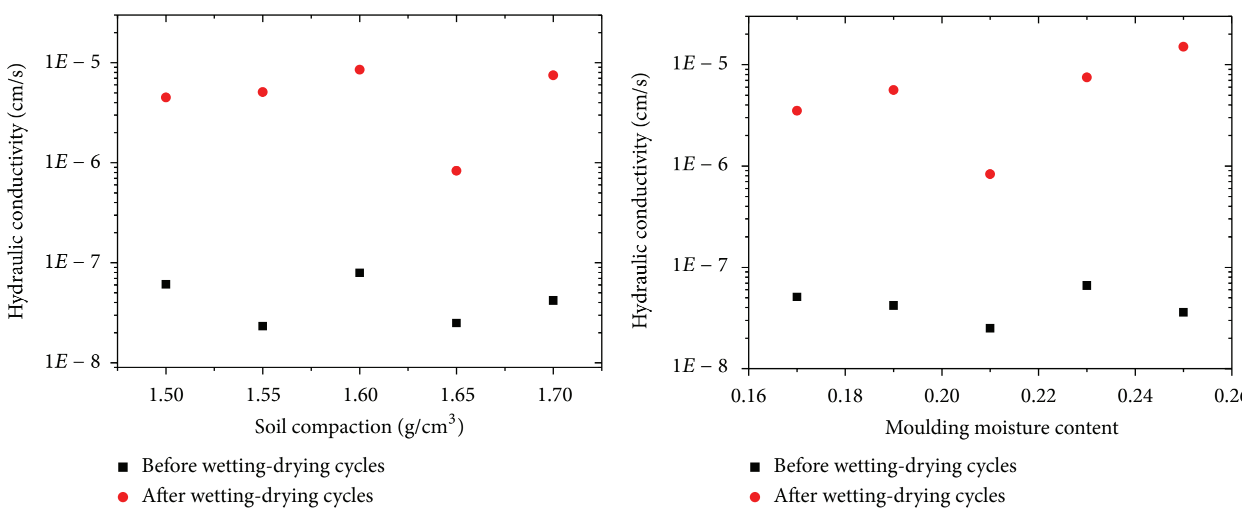
4. Conclusions

The main purpose of the study was to observe the heat-moisture transport and water permeability of compacted clay during cracking of compacted clay. To fulfill this purpose, a series of tests of heat-moisture transport through soil columns during cracking were performed, and the hydraulic



(a) (b)

Figure 6: The hydraulic conductivity of compacted clay during wetting-drying cycles.



(a) (b)

Figure 7: The hydraulic conductivity of compacted clay before and after wetting-drying cycles.

conductivity of soil under different wetting-drying cycles was also investigated.

In the early phase of heating, the temperature of soil columns rose fast and the moisture loss was serious. The speed of temperature increased and then attenuated significantly, with a long period of slow dehydration. After heating for 16 consecutive days at 50°C and 60°C, at the depth of 25 cm, the temperature increased to 48.5°C and 59.1°C and the soil moisture content decreased to 0. Cracks appeared at the surface of soil columns. The CIF was 0.043 and 0.097 and the crack depth was about 6.5 cm and 8.2 cm, respectively.

After four wetting-drying cycles, the hydraulic conductivity of compacted clay was within 8.3×10^{-7} to 1.5×10^{-5} cm/s. This value increased by 2~3 orders of magnitude compared to that of uncracked clay, suggesting that the compacted clay completely lost its antiseepage capability.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would like to express their great appreciation of the funding provided by the National Natural Science

Foundation of China (11002102 and 51474168) and Wuhan Youth Chenguang Program of Science and Technology (201271031419).

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