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Research article

Impact of biological clogging on the barrier performance of landfill liners

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ABSTRACT

The durability of landfill mainly relies on the anti-seepage characteristic of liner system. The accumulation of microbial biomass is effective in reducing the hydraulic conductivity of soils. This study aimed at evaluating the impact of the microorganism on the barrier performance of landfill liners. According to the results, *Escherichia coli*. produced huge amounts of extracellular polymeric substances and coalesced to form a confluent plugging biofilm. This microorganism eventually resulted in the decrease of soil permeability by 81%–95%. Meanwhile, the increase of surface roughness inside the internal pores improved the adhesion between microorganism colonization and particle surface. Subsequently, an extensive parametric sensitivity analysis was undertaken for evaluating the contaminant transport in landfill liners. Decreasing the hydraulic conductivity from 1×10^{-8} m/s to 1×10^{-10} m/s resulted in the increase of the breakthrough time by 345.2%. This indicates that a low hydraulic conductivity was essential for the liner systems to achieve desirable barrier performance.

1. Introduction

The production of municipal solid waste (MSW) significantly increased with the rapid growth of population over the past two decades. The associated question is how to manage these solid wastes (Tang et al., 2017, 2018). General management methods towards MSWs include recycling, composting, anaerobic digestion, incineration, dumping into the sea and landfilling (Tang et al., 2015). Due to the low cost, sanitary landfilling is the most prevalent method to eliminate MSWs especially in developing and underdeveloped countries (Zhan et al., 2014). For instance, in South Africa and China, approximately 100% and 73% of collected MSWs were landfilled (Blight, 2006; NBSC, 2013).

Although landfill management is widely adopted, it becomes an emerging threat to the environment as well. The landfill usually results in the groundwater contamination due to leachate leakage from landfill sites (Sibiya et al., 2017). Therefore, the anti-seepage and contaminant sorption capability of liners is crucial for landfill design. Rajasekaran et al. (2005) pointed out that the transport of contaminants through liner systems mainly depends on the permeability of bottom liner. To prevent leachate from leaking out of landfill, the standard for MSW sanitary landfill (CJJ 176-2012, China) requires that a compacted clay liner should have a minimum depth of 2 m, and have a maximum hydraulic conductivity of 1×10^{-7} cm/s. Composite liners are extremely popular in modern landfills, which usually consist of either a geomembrane (GMB) and a compacted clay liner (CCL), or a GMB, a geosynthetic clay liner (GCL), and a soil liner (SL) (Rowe et al., 2004; Xie et al., 2018). Parastar et al. (2017) concluded that the natural clay soil was a preferred liner material because of its high sorption capacity, long-term structural stability, and low permeability. However, clay minerals are natural non-renewable resources, but construction of a landfill liner always consumes a large amount of clay minerals to meet the anti-seepage requirements and contaminant blocking capability (Wu et al., 2017). Furthermore, in China, there are more mountainous areas than plain areas (Li and Sand, 2017). This results in a problem that natural clays suitable for landfill liners may not be locally available. Thus, it is critical to pretreat natural clay to achieve suitable hydraulic conductivity, which can save a large quantity of clay soil during the construction of landfill liner.

Microorganisms can develop biofilms in many natural and engineered porous media systems. Biofilm barriers are structures made by stimulating the activity of microorganisms in soils (Rowe, 2005). An excessive growth of bacteria in soil causes the biofilm-induced pore clogging, which thereby provides substantial decrease in permeability and groundwater flow (Rowe and Yu, 2013; Yu and Rowe, 2012a, 2012b). Rowe and Booker (1995) found that leachate passing through the drainage layer of MSW landfills can induce clogging, which raises the growth of biomass. Dennis and Thrner (1998) evaluated the

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reduction of permeability due to the formation of biofilm, and concluded that the bacterial treatment significantly decreased the hydraulic conductivity by 1–3 orders of magnitude. Kirk et al. (2012) confirmed that biomass greatly remains intact after acidification and continue reducing hydraulic conductivity of porous medium, even when considerable death occurs. Hence, biological clogging is effective in forming grout curtains to reduce the migration of heavy metals and organic pollutants, and thereby preventing leaking construction pit, landfill, or dike. However, the types of microorganisms used in the previous studies were not the main bacteria in the landfill leachate. It is known that a high salinity level and a low oxygen supply of leachate dramatically limit the growth of voluminous microorganisms (Aziz et al., 2013). Grisey et al. (2010) found the presence of microorganisms in leachate. They investigated the seasonal variations in abundance of total coliforms, Enterococci, Salmonella, *Pseudomonas aeruginosa*, and *Staphylococcus aureus*, and found that total coliforms were predominant in the landfill leachate. Herein, total coliforms are defined as aerobic or facultatively anaerobic, oxidase negative bacteria (Matejczyk et al., 2011). Organisms of genera such as Citrobacter, Enterobacter, Escherichia, Serratia, Klebsiella are also included (Baudisova, 1997). Among the coliforms, the *Escherichia coli* population was found extremely high in the leachate (Threedeach et al., 2012).

The traditional liner systems are designed solely dependent on the permeability of material. However, even barriers with a zero permeability cannot completely prohibit the release of contaminants. This is because fluid flow will still occur from molecular diffusion of contaminants across the barrier (Daniel and Shackelford, 1988). Once the leachate releases into the soil, it will interact physically and chemically with both the adjacent ground water and the soil matrix (Yeh and Tripathi, 1989). Numerical modelling is capable of predicting the movement and transfer of contaminants in the landfill liner systems (Boddula and Eldho, 2017). Consequently, the assessment of groundwater pollution usually relies on an accurate numerical model for proper management and remediation of the contaminated sites (Xie et al., 2016). Chen et al. (2015) concluded that the main mechanism for inorganic contaminant transport in the composite liners is advection through GMB defects and advection-dispersion in the underlying GCL, CCL, or attenuation layer. They developed a breakthrough time based design method for landfill composite liners which ignored influences of both diffusion and advection. However, the advective transport of organic compounds through GMB defects cannot be ignored, especially in the case with a high leachate head (Xie et al., 2015).

To address the aforementioned research needs, this study evaluated the influence of biological clogging on the hydraulic properties of liner material based on a modified permeameter. The mechanisms of biological clogging were investigated through a series of physical and chemical experiments (e.g., Nitrogen adsorption (N_2-BET), X-ray Diffraction (XRD), X-ray Fluorescence (XRF), Scanning Electron Microscope (SEM), etc.) Subsequently, the finite element models were developed to investigate the transport of contaminant through a natural soil barrier system. The contaminant breakthrough time was calculated and the factors that affected breakdown time were examined. The final section summarized the major findings of this study.

2. Materials and methods

2.1. Soils

The soils used in the experiment were clay and sand. The clay was locally sampled from Tianzhiyun area in Suzhou, China (N31°32′, E120°56′). To avoid the disturbance of environmental change on soil properties, the clay was obtained from 3 to 4 m below the ground surface. The quartz-based sand with a quartz content of 99.3% was collected from Fengyang, Anhui, China. The particle size of the sand was 0.15–0.075 mm. The clay properties were summarized in http://www.sciencedirect.com/science/article/pii/S0013795215001349 Table 1. As shown in Table 1, the natural moisture content of the clay was 23.78%. The liquid limit and plastic limit of the clay were 41.54% and 16.57%, respectively. The swelling index was 2 mL/2g-solid, which demonstrated that the clay used in this experiment contained limited amount of expansive mineral (e.g., montmorillonite). The clay was slightly acidic and had a pH of 6.6, which was attributed to the acid rain in Suzhou region. The measured Electrical Conductance (EC) was 0.05 mS/cm, which represented that the soluble salt content in the clay was low. The particle size distributions of clay and sand were shown in Fig. 1.

Table 1
Physical and chemical properties of studied soil.

Property	Standard	Unit	Value
Physical-chemical properties			
Natural moisture content	JIS A 1203	%	23.78
Swelling index	ASTM D 5890-06	mL/2g-solid	2
Liquid limit	GB/T 50123-1999	%	41.54
Plastic limit	GB/T 50123-1999	%	16.57
pH	JGS 0211		6.6
EC	JGS 0212	mS/cm	0.05
N_2-BET			
Correlation coefficient (R^2)			0.999
Specific surface area		m^2/g	24.49
Average pore Diameter		nm	8.23
Total pore volume		cm^3/g	5.04×10^{-2}

For the N_2-BET adsorption tests, the correlation coefficient was 0.999. This indicated that the results obtained were reliable. The specific surface area of the clay used in this study is 24.49 m^2/g. The average pore diameter is 8.23 nm, and the total pore volume is 5.04×10^{-2} cm^3/g. The XRD spectra is shown in Fig. 2a (RAD-2B, Rigaku Corporation, Japan). Note that the experimental clay contained quartz (SiO_2), which was observed at $2\theta = 20.85°$, 26.58°, 45.76°, 73.42°, 75.61°, 79.83° and 90.83°. XRF results confirmed the presence of SiO_2 and SiO_2 accounts for 58.12% of the total soil (JSX-3400R, JEOL, Japan). Meanwhile, other mineral contents such as Albite, Calcite, Phosphosiderite, Antigorite, Magnesite and Monticellite were also found out at $2\theta = 27.95°$, (39.42°, 81.40°), (36.48°, 42.42°), (40.24°, 59.90°), 68.10° and 50.07°. The existence of Antigorite was proven by the SEM (SU-8020, Hitachi, Japan) image of clay, which was shown in Fig. 2b.

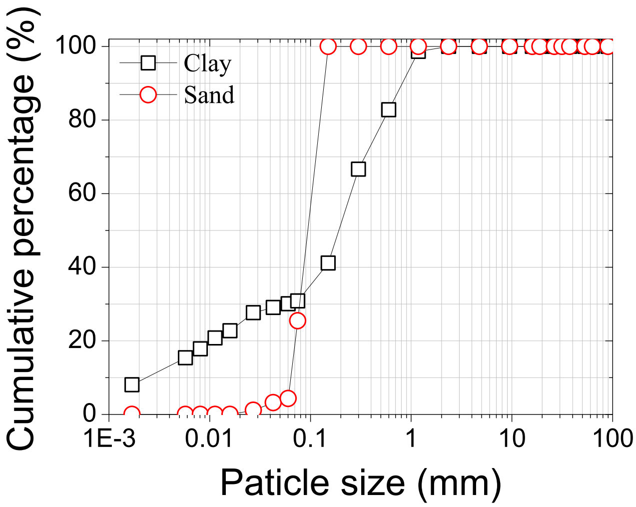

Fig. 1. Particle size distribution of clay and sand.