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Evolution of saturated hydraulic conductivity with compression and degradation for municipal solid waste

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ABSTRACT

Municipal solid waste (MSW) specimens were created from synthetic fresh MSW degraded in a laboratory scale enhanced degradation reactor. The degree of degradation and saturated hydraulic conductivity k_s were measured to study the effects of compression and degradation on k_s of MSW. The degree of degradation was characterized through the ratio of cellulose content to lignin content (i.e., C/L) and the loss ratio of volatile solid (i.e., DOD). k_s of MSW specimens with different degrees of degradation was measured through triaxial permeameter tests under different confining pressures. It was found that, when the degradation time increased from 0 month to 18 months, k_s decreased less than 1 order of magnitude for specimens with the same porosity (i.e., $n = 0.63$ or 0.69). However, for specimens with the same degradation time, the decrease of k_s could reach 2 orders of magnitude with n decreasing from 0.8 to 0.6. It indicates that compression has much greater influence on the reduction of k_s than that of degradation. Based on the Kozeny-Carman model and first-order kinetics, a prediction model related to n and C/L (or DOD) of MSW was proposed to analyze the evolution of k_s with compression and biodegradation. The methods to determine the values of model parameters were also proposed.

1. Introduction

Landfilling remains one of the main municipal solid waste (MSW) disposal methods worldwide. Leachate generated in landfill flows downward under gravity and is collected by leachate collection and removal system (LCRS). The hydraulic conductivity of MSW affects the transport and remove of leachate and is important for the design of LCRS (Sharma and Reddy, 2004; Reddy et al., 2009). Furthermore, to enhance MSW degradation and stabilization process, leachate and other liquids are recirculated to increase the moisture and biomass content of the waste in bioreactor landfills (Jain et al., 2006; Benson et al., 2007; Erses et al., 2008; Cossu, 2010). The hydraulic conductivity of MSW affects the flow and distribution of leachate injected into the waste. The design of leachate recirculation system, such as the location of injection point and the control of injection rate, is highly dependent on the hydraulic conductivity of landfilled MSW (Pohland, 1975; Benson et al., 2007; Bareither et al., 2010; Barlaz et al., 2010; Jain et al., 2014).

For unsaturated MSW, the hydraulic conductivity k_L is a combination of the saturated hydraulic conductivity k_s and relative liquid permeability k_{rL} (Eq. (1)). k_s is related to the intrinsic permeability k_i and liquid properties including liquid density ρ_L and liquid viscosity μ_L (Eq. (2)). In traditional landfills without a properly operating LCRS and bioreactor landfills with leachate recirculation, the moisture content of MSW may be significantly higher. The waste may even become submerged in leachate in landfills with high leachate level (Jang et al., 2002; Zhan et al., 2015). Under this condition, for the saturated MSW, k_L is theoretically equal to k_s, as k_{rL} could be set as 1.

$$k_L = k_s k_{rL} \tag{1}$$

$$k_s = \frac{k_i \rho_L g}{\mu_L} \tag{2}$$

where k_L (m/s) is the hydraulic conductivity, k_s (m/s) is the saturated hydraulic conductivity, k_{rL} is the relative liquid permeability, k_i (m^2) is the intrinsic permeability, ρ_L (kg/m^3) is the liquid density, μ_L (kg m^{-1} s^{-1}) is the liquid viscosity, and g (N/kg) is the gravitational acceleration.

Laboratory and field studies indicate that k_s of MSW depends on the waste composition, compaction, overburden pressure and

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Nomenclature

A	parameter of the proposed prediction model for k_0 (m^2)
A_{initial}	initial value of A for the fresh MSW (m^2)
A_{final}	final value of A for the completely degraded MSW (m^2)
B	parameter of the proposed prediction model for k_0
C_A	decay coefficient of A (month^{-1})
$C_{C/L}$	decay coefficient of C/L (month^{-1})
C_{DOD}	decay coefficient of DOD (month^{-1})
$C_{K\text{-}C}$	Kozeny-Carman empirical coefficient
C/L	ratio of cellulose content to lignin content in MSW
$(C/L)_{\text{final}}$	initial value of C/L for the fresh MSW
$(C/L)_{\text{initial}}$	final value of C/L for the completely degraded MSW
c	parameter in $C_{K\text{-}C}$
DOD	loss ratio of volatile solid in MSW
d	mean diameter of particles (m)
e	void ratio
e_0	initial void ratio
G_s	grain specific gravity
g	acceleration of gravity (N/kg)
i	liquid pressure head gradient (m/m)
k_0	intrinsic permeability coefficient (m^2)
k_i	intrinsic permeability (m^2)
k_L	hydraulic conductivity (m/s)
k_{rL}	relative liquid permeability
k_s	saturated hydraulic conductivity (m/s)
n	porosity
R_e	Reynolds number
S_0	specific surface area per unit volume of particles (m^{-1})
t	degradation time of MSW (month)
u	osmotic pressure (kPa)
v	specific fluid velocity (m/s)
w	water content (kg/kg, wet weight)
w_0	initial water content (kg/kg, wet weight)
X_f	volatile solid content of MSW (kg/kg, dry weight)
X_{f0}	initial volatile solid content of fresh MSW (kg/kg, dry weight)
γ_d	dry unit weight (kN/m^3)
μ_L	fluid viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	density (kg/m^3)
ρ_0	initial density (kg/m^3)
ρ_L	fluid density (kg/m^3)
σ	confining pressure (kPa)
σ_1	horizontal confining pressure (kPa)
σ_3	vertical confining pressure (kPa)
σ'_{ave}	average effective stress (kPa)
σ'_{inlet}	effective stress near water inlet (kPa)
σ'_{outlet}	effective stress near water outlet (kPa)
τ	tortuosity of the porous media

degradation (Oweis et al., 1990; Chen and Chynoweth, 1995; Powrie and Beaven, 1999; Beaven, 2000; Jang et al., 2002; Qu et al., 2005; Jain et al., 2006; Hossain et al., 2009; Reddy et al., 2009, 2011; Stoltz et al., 2010; Wu et al., 2012; Xu et al., 2014). Powrie and Beaven (1999) and Beaven (2000) did laboratory large-scale hydraulic tests on MSW, and found k_s of MSW decreased from nearly 1×10^{-4} m/s to 1×10^{-7} m/s with average applied vertical effective stress increased from 50 kPa to 500 kPa. The decrease of k_s with increasing compaction or overburden pressure might be due to the reduction in pore size and change in geometry and continuity of pores resulting in a decrease in area of flow. Hossain et al. (2009) conducted a series of constant head permeability tests on MSW samples with different degrees of degradation. In their study, for MSW with the density of 600–800 kg/m^3, k_s was in the order of 10^{-4} m/s after the phase 1 of degradation (i.e., 25 days) and decreased to the order of 10^{-5} m/s at the phase 4 of degradation (i.e., 253 days). The decrease might be due to the increase in percentage of finer fraction with degradation, as the fine particles occupying the pore spaces would decrease the size of the flow path (Hossain et al., 2009). MSW samples exhumed from the bioreactor cells at different phases of degradation were tested for hydraulic conductivity by Reddy et al. (2011). They found k_s of fresh and degraded MSW ranged from 10^{-5} m/s to 10^{-10} m/s. Degradation produced more fines and higher unit weight (i.e., dry unit weight γ_d increased from about 6 kN/m^3 to 12.5 kN/m^3), which resulted in lower k_s of degraded MSW (Reddy et al., 2011). Field tests conducted by Jain et al. (2006) and Wu et al. (2012) indicated a decrease of k_s with landfill depth and age. k_s decreased up to one order of magnitude within a depth of 18–25 m in their study. This is mainly attributed to the greater overburden pressure and more fine particles in the deeper layer. It should be noted that, k_s estimated through k_i derived from gas permeability tests should be used with care. Due to the entrapped gas, MSW cannot be fully saturated. Under this condition, k_s can be 1 (in lab) or 2 (in field) orders of magnitude lower than that calculated using k_i derived from gas permeability tests (Jain et al., 2006; Stoltz et al., 2010; Wu et al., 2012; Xu et al., 2014).

To the authors' knowledge, there are few prediction models for estimating k_s of MSW, due to the complex nature of MSW. Powrie and Beaven (1999) and Beaven (2000) developed empirical relationships between k_s and vertical effective stress σ'_v (i.e., $k_s = 2.1 \times \sigma'_v{}^{-2.71}$) through laboratory large-scale hydraulic tests. Reddy et al. (2011) proposed a model to link k_s with the degree of degradation. The parameter DOD expressed as the loss ratio of volatile solid in MSW was used (i.e., $k_s = 5 \times 10^{-4} \exp^{-0.08\text{DOD}}$). In this relationship, the tested k_s actually combines the effects of more fines and higher unit weight caused by degradation (i.e., greater DOD). As MSW is a heterogeneous porous media which can decompose with time, a good prediction of k_s of MSW by considering the effects of both compression and degradation is still a challenge.

Many western European countries have seen a large reduction in organic content of landfilled MSW during the last two decades and similar trends are occurring elsewhere. However, in many countries (e.g. USA and China), the fresh MSW deposited in landfills is still high in organic content. Furthermore, many landfills face the problem of vertical expansion due to the shortage of land resources. Therefore, the landfilled MSW could experience significant compression and degradation. Based on the former studies mentioned above, in order to take a step further to study the effects of compression and degradation on k_s of MSW, specimens with different degrees of degradation and different porosity n were created for triaxial permeability tests. Furthermore, the Kozeny-Carman model (Kozeny, 1927; Carman, 1939) was applied to analyze the testing results, so as to look into the effects of degree of degradation and n on k_s separately. In this study, MSW specimens with different degrees of degradation were created through enhanced biodegradation test on synthetic fresh Chinese MSW. The ratio of cellulose content to lignin content (i.e., C/L) and the loss ratio of volatile solid (i.e., DOD) were measured to represent the degree of degradation. A prediction model related to n and C/L (or DOD) of MSW was finally proposed to analyze the evolution

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