Waste Management 32 (2012) 463–470

Contents lists available at SciVerse ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Evolution of unsaturated hydraulic properties of municipal solid waste with landfill depth and age

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ARTICLE INFO

Article history:
Received 30 April 2011
Accepted 25 October 2011

Keywords:
Landfill
Municipal solid waste (MSW)
Unsaturated hydraulic properties
Pressure plate method
Water retention curve
Relative hydraulic conductivity

ABSTRACT

Successful modeling of liquid and air flow and hence designing of liquid and air addition systems in the landfills are constrained by the lack of key parameters of unsaturated hydraulic properties of municipal solid waste (MSW), which are strongly dependent on the depth of burial and the degree of decomposition. In this study, water retention curves (WRC) of MSW are measured using pressure plate method on samples repacked according to the *in situ* unit weight measured during borehole sampling, representing the MSW in shallow, middle, and deep layers. The measured WRC of MSW is well-reproduced by the van Genuchten–Mualem model, and is used to predict the unsaturated hydraulic properties of MSW, including water retention characteristics and unsaturated hydraulic conductivity. The estimated model parameters are consistent with other studies, suggesting that the pressure plate method yields reproducible results. As the landfill depth and age increase, the overburden pressure, the highly decomposed organic matter and finer pore space increase, hence the capillary pressure increases, causing increases in air-entry values, field capacity and residual water content, and decreases in steepness of WRC and saturated water content. The unsaturated hydraulic properties of MSW undergo changes with landfill depth and age, showing more silt loam-like properties as the landfill age increases.
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1. Introduction

To incorporate a long-term strategy for the control of emissions and climate change issues into positive aspects of past landfilling technology and achieve environmental equilibrium over one generation (20–30 years) (Cossu, 2009), sustainable landfilling has recently been proposed and become a focus of the scientific community in waste management worldwide (Batarseh et al., 2010; Cossu, 2010; Scharff et al., 2011; van Vossen, 2010). To achieve sustainability in landfilling, appropriate waste pretreatment and *in situ* treatment is essential. For a complete landfill site, *in situ* treatment through the addition of liquid and/or air to enhance the chemical and biological processes occurring within the landfill may constitute a feasible option. To date, researchers have mainly focused on evaluating the feasibility and potential benefits of air and liquid addition systems, but the data required to design and operate such systems are rare. The optimal design and operation parameters of these systems can be obtained from the numerical simulation of air and liquid flow within landfills (Fellner and Brunner, 2010; Haydar and Khire, 2005; Jain et al., 2010a,b; Khire and Mukherjee, 2007; McCreanor and Reinhart, 2000). To attain successful numerical simulations of air and liquid flow within landfills, hydraulic properties, including saturated and unsaturated hydraulic properties, as well as air permeability, are essential. The flow of water within the landfills occurs in unsaturated conditions and air permeability (usually referred to as relative air permeability in an unsaturated medium) can be expressed as a function of effective water saturation using the parameters derived from unsaturated hydraulic models (Kueper and Frind, 1991; Parker, 1989; Stoltz et al., 2010; Vigneault et al., 2004). Therefore, the unsaturated hydraulic properties of waste are key parameters that should be accurately estimated. This includes water retention characteristics and unsaturated hydraulic conductivity of waste, a set of relationships that govern moisture storage and impedance to water flow.

Currently, researchers pay more attention to the saturated hydraulic conductivity of waste, and several data have been reported based on laboratory (Hossain et al., 2009; Korfiatis et al., 1984; Powrie and Beaven, 1999; Reddy et al., 2009) and field tests (Jain et al., 2006; Landva and Clark, 1986; Machado et al., 2010; Oweis et al., 1990). However, seldom has data on unsaturated hydraulic properties of waste been reported. Kazimoglu et al. (2005, 2006) measured the water retention characteristics and unsaturated hydraulic conductivity of synthetic waste samples using a modified pressure plate method. Jang et al. (2002) and Han et al. (2011) obtained the capillary pressure–volumetric water content relationship and hydraulic conductivity of waste samples for various degrees of compaction using the pressure plate method

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doi:10.1016/j.wasman.2011.10.029

Nomenclature

e	void ratio of waste [$cm^3\ cm^{-3}$]
G_s	specific gravity of waste [$g\ g^{-1}$]
h_e	air-entry value of waste [kPa]
l	van Genuchten–Mualem model parameter, defined as a pore-connectivity parameter, estimated to be 0.5 for average soil
K_s	saturated hydraulic conductivity [$cm\ s^{-1}$]
$K(\psi)$	unsaturated hydraulic conductivity as a function of *matrix* suction head [$cm\ s^{-1}$]
$k_r(\psi)$	relative hydraulic conductivity as a function of *matrix* suction head [–]
$k_r(S_e)$	relative hydraulic conductivity as a function of effective water content [–]
n	van Genuchten–Mualem model parameter, defined as the pore-size distribution index that determines the slope of the water retention curve [–]
m	van Genuchten–Mualem model parameter, often assumed to be equal to $(1-1/n)$ [–]
S_e	effective water content [–]
W_1	weight of pycnometer and water [g]
W_2	weight of pycnometer, sample, and water [g]
W_s	weight of the dry sample [g]
α	van Genuchten–Mualem model parameter, defined as the inverse of air-entry pressure [kPa^{-1}]
ρ_d	dry bulk density [$g\ cm^{-3}$]
ρ_w	water density [$g\ cm^{-3}$]
θ_w	volumetric water content [$cm^3\ cm^{-3}$]
M_c	gravimetric water content [$g\ g^{-1}$]
$S_e(\psi)$	effective saturation as a function of *matrix* suction head [–],
ψ	*matrix* suction [kPa]
θ	actual volumetric water content [$cm^3\ cm^{-3}$]
θ_s	saturated volumetric water content [$cm^3\ cm^{-3}$]
θ_r	residual volumetric water content [$cm^3\ cm^{-3}$]

and multi-step outflow method, respectively. Despite these contributions, data on unsaturated hydraulic properties of waste are scarce. It is believed that as waste ages, its unsaturated hydraulic properties become more dependent on the depth of burial and the degree of decomposition (Dixon and Jones, 2005). Jang et al. (2002), Han et al. (2011), Breitmeyer and Benson (2011) and Stoltz et al. (2011) reported the variation in unsaturated hydraulic properties of waste with the degree of compaction, which has a similar effect to the depth of burial. However, to the best of our knowledge, no measurements of the effect of the combination of depth of burial and the degree of decomposition (characterized by landfill age) on the unsaturated hydraulic properties of waste have been conducted, which is the focus of this study.

Measurement of unsaturated hydraulic properties of waste is usually developed based on the existing methods for soils. Several methods are available to determine the unsaturated hydraulic properties experimentally using physical and thermodynamic techniques, such as instantaneous profile (Watson, 1966), sprinkling infiltration (Youngs, 1964) and internal drainage (Richards and Weeks, 1953). Most methods require restrictive initial and boundary conditions, which make measurements time consuming, range restrictive, and expensive (Green et al., 1986; Gribb et al., 2004; Klute, 1986; Šimůnek and van Genuchten, 1996). As a result, several semi-empirical procedures have been developed to estimate unsaturated hydraulic properties using the water retention curve (WRC) (Brooks and Corey, 1964; Fredlund et al., 1994; van Genuchten, 1980), defined as the relationship between the volumetric water content and suction in unsaturated media. Among the existing methods for the measurement of WRCs, the pressure plate or the Tempe cell method is the most promising for landfilled MSW. This is because it allows relatively large samples to accommodate the natural properties of wide pores and particle size ranges in landfilled MSW, and adapts to changing leachate chemistry resulting from the biochemical processes of landfilled MSW. The pressure plate method has been employed in landfilled waste by Kazimoglu et al. (2005, 2006) and Jang et al. (2002) with successful results. However, further work is essential before this method can be applied to a wider range of landfill sites.

Therefore, the aims of the study are 2-fold: (1) to provide WRC data of landfilled MSW using the pressure plate method; and (2) to investigate the impact of landfill depth and age on the water retention characteristics and unsaturated hydraulic conductivity of waste.

2. Materials and methods

2.1. Site description and sampling

MSW samples were collected from a landfill located south of Beijing, China, which annually receives approximately 350,000 tons of MSW mainly comprised of commercial and industrial solid waste. The landfill has been in operation since 1996, and is expected to close in 2022. Waste in the test site was disposed between 2000 and 2007, whose detailed compositions can be found in Li et al. (2009). The cover soil used was sandy clay and represented about 10% of the landfill (by volume). Borehole sampling was carried out in September 2010. The borehole was drilled to the depth of the landfill (~26 m). Waste samples were then recovered by using a 13-cm hollow stem auger. The waste samples (~10.0 kg each) taken out at depths of 1–4, 11–14, and 22–25 m represented landfilled MSW in the shallow, middle, and deep layers, respectively. The excavated MSW samples were weighed, and the measured weights of the samples were divided by the estimated volume of the cavity to obtain the *in situ* bulk unit weight of MSW. The landfill age of the samples was determined according to the borehole logs and a record of landfill operations.

2.2. Pressure plate tests

Prior to analysis, the raw samples were manually homogenized and quartered to obtain representative samples. Large size rocks (>4.0 cm in diameter) were taken out during quartering.

Pressure plate tests were performed using a modified Tempe cell (Fig. 1). After treatment with a bactericide (sodium orthophenylphenate, SOPP) to inhibit biodegradation, a certain amount of the representative samples was packed into the column and compressed to obtain specific-unit weight specimens. The necessary weight of samples was determined according to the *in situ* bulk unit weight measured during borehole sampling. The specimen (15.6 cm in diameter, 12.0 cm in height) was placed between two porous plates. A porous ceramic plate (1 bar high air-entry ceramic plate, 15.558 cm in diameter, 0.714 cm in thickness, Soilmoisture Equipment Corp., Santa Barbara, CA, USA) was placed at the bottom of the column, supporting the compressed samples and only permitting the flow of water. A porous steel plate with thickness of 1.3 cm was placed at the top of the column to allow even distribution of air.

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