Waste Management 63 (2017) 107–121

Contents lists available at ScienceDirect

Waste Management

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

Unsaturated flow parameters of municipal solid waste

Shi-Jin Feng [a],*, Qi-Teng Zheng [b], H.X. Chen [a]

[a] *Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China*
[b] *Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China*

ARTICLE INFO

Article history:
Received 25 May 2016
Revised 11 January 2017
Accepted 16 January 2017
Available online 24 January 2017

Keywords:
MSW
Unsaturated properties
Porosity
Waste composition
Particle size distribution

ABSTRACT

Leachate pollution/recirculation and landfill gas emission are the major environmental concerns in municipal solid waste (MSW) landfills. A good understanding and prediction of MSW unsaturated properties are critical for the design of piping systems and the control of these problems within landfills. This paper reviews the recent studies of unsaturated properties of MSW, including experimental methods, theoretical models and corresponding model parameters. For experimental methods, the sample size is a common and significant limitation and large test apparatuses (e.g., >80 cm in diameter) are generally required and valuable. The theoretical models for MSW also have some limitations due to the changes in waste composition and particle size distribution caused by biodegradation. Thus, the available data of intrinsic permeabilities, water retention curves, relative permeabilities and anisotropy of MSW were summarized to investigate the influences of porosity, waste composition and particle size distribution. A series of estimation methods were subsequently proposed to determine the parameters of water retention curve like θ_{Lm}, θ_{Lr}, n_{v} and α. The other parameters such as the pore connectivity term (l) and the degree of anisotropy (k) were significantly lacking data, thus only their relationships with porosity were proposed. The results show that it is possible to define the second order effects caused by variations in porosity, waste composition and particle size distribution. However, the estimation methods still need more experimental data for improvement, especially their dependence on waste composition and particle size distribution.

Contents

1. Introduction . . . 108
2. Theoretical models for unsaturated flow . . . 109
  2.1. Models of water retention curve and relative permeability . . . 109
  2.2. Models of intrinsic permeability . . . 109
3. Experimental methods for unsaturated flow . . . 110
  3.1. Measurements of gas permeability . . . 110
  3.2. Measurements of liquid permeability . . . 110
  3.3. Measurements of water retention characteristics . . . 111
  3.4. Discussion of sample size . . . 112
4. Unsaturated flow parameters . . . 112
  4.1. Intrinsic permeability . . . 112
  4.2. Water retention curve . . . 113
    4.2.1. Maximum volumetric moisture content . . . 114
    4.2.2. Residual volumetric moisture content . . . 115
    4.2.3. n_v related to pore size distribution . . . 116
    4.2.4. α related to air entry . . . 116
  4.3. Unsaturated permeability . . . 117
  4.4. MSW anisotropy . . . 118

---

* Corresponding author.
E-mail addresses: fsjgly@tongji.edu.cn (S.-J. Feng), 08qitengzheng@tongji.edu.cn (Q.-T. Zheng).

http://dx.doi.org/10.1016/j.wasman.2017.01.025
0956-053X/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

S_e	effective liquid saturation [1]
S_L	liquid saturation [1]
θ_G, θ_L	volumetric gas and moisture contents [1]
θ_{Ls}, θ_{Lr}	saturated and residual volumetric moisture contents [1]
θ_{Lm}	maximum volumetric moisture content [1]
l	pore connectivity term [1]
α, n_v, m	coefficients in the van Genuchten relationship [$M^{-1}\,L\,T^2$, 1, 1]
p_c	capillary pressure [$M\,L^{-1}\,T^{-2}$]
P_G, P_L	pore-gas and pore-liquid pressures [$M\,L^{-1}\,T^{-2}$]
K_G, K_L	gas and liquid permeabilities [L^2]
n, e	porosity and void ratio [1]
v	specific volume ($v = 1 + e$) [1]
ϕ, ψ	coefficient in the α-v relationship [$M^{-1}\,L\,T^2$, 1]
K_{GV}, K_{GH}	vertical and horizontal gas permeabilities [L^2]
K_{LV}, K_{LH}	vertical and horizontal liquid permeabilities [L^2]
K_{Lsat}, $K_L(\theta_L)$	saturated and unsaturated liquid permeabilities [L^2]
k_i	intrinsic permeability [L^2]
k_i^G, k_i^L	k_i by permeability tests for gas and liquid, respectively [L^2]
k_0	intrinsic permeability coefficient [L^2]
k_{rG}, k_{rL}	relative gas and liquid permeabilities [1]
τ	tortuosity of porous media [1]
A_s	specific surface of porous media [L^{-1}]
d_{10}	effective particle size, corresponding to 10% passing on the particle size distribution curve [L]
D, H, L, W	diameter, height, length or width of samples [L]
d_{max}	maximum particle size [L]
d_{30}, d_{60}	particle sizes corresponding to 30%, 60% passing on the particle size distribution curve, respectively [L, L]
C_U, C_C	coefficients of uniformity and curvature [1, 1]
$\partial P_G/\partial z$	gas pressure gradient in the z direction [$M\,L^{-2}\,T^{-2}$]
μ_G	dynamic viscosity for gas [$M\,L^{-1}\,T^{-1}$]
q_G	Darcy flux [$L\,T^{-1}$]
A, B	Forchheimer coefficients [$M\,L^{-3}\,T^{-1}$, $M\,L^{-4}$]
b, c	fitting parameters [L^2, 1]
A_i^w, A_i^d	percentages of each component i by wet basis and dry basis [%, %]
w_i	gravimetric moisture content for each component i [1]
h_e	air-entry pressure [$M\,L^{-1}\,T^{-2}$]

5. Conclusions 119
Acknowledgements 119
References 119

1. Introduction

Leachate pollution/recirculation and landfill gas emission are the major environmental concerns in municipal solid waste (MSW) landfills. The control of these problems is related to the understanding of liquid and gas flows within landfills. Numerous researchers (Chen, 2014; Feng et al., 2015; Hettiarachchi et al., 2009; Jain et al., 2010; Reddy et al., 2014; White et al., 2014) have established analytical and numerical models to design the leachate collection/recirculation and gas collection systems. In these models, MSW was generally assumed as a continuum medium consisting of a solid phase and two fluid phases: leachate and landfill gas. The migration equations can then be formulated using a representative elementary volume (REV) as the smallest homogeneous model unit (Kindlein et al., 2006). However, because of the multidisciplinary nature of this problem, there is no unique REV value for MSWs (Staub et al., 2013). The unsaturated flow theory for soils is widely applied to study the migration of leachate and landfill gas. However, this kind of application is sometimes inappropriate due to the difference between MSWs and soils (Hossain et al., 2009). Therefore, it is very essential to have a better understanding of unsaturated flow theory, especially flow parameters of MSW.

MSW consists of everyday items such as kitchen waste, yard trimmings, plastics, metals, glass, paper/cardboard, textiles, wood and miscellaneous materials (EPA, 2010; Stoltz et al., 2012). The miscellaneous materials mainly include inert elements like soil particles and fine components that may be other components like paper, textiles or organic matrix. As a result, the size of MSW particles spans a wide range from about 0.1 mm to >100 mm (Hudson, 2007; Powrie et al., 2008; Reddy et al., 2011). The maximum particle size can reach 120 mm for aged MSW samples and a much higher value for fresh ones (Hudson, 2007). As for sands, soil particles are generally smaller than 2.0 mm, beyond which particles are defined as gravels (Gee and Or, 2002). Moreover, different from generally incompressible soil particles, MSW particles are much thinner and flatter (Hossain et al., 2009) and are regarded as compressible (Beaven et al., 2011). The organic matter in wastes can also be biodegraded. The biodegradation reduces solid components and produces large amounts of gas and leachate. The waste composition and particle size distribution will then change significantly. Thus, the mechanisms in MSWs are more complex than those described by traditional soil mechanical theory (Chen et al., 2006).

The water phase of MSW can be classified into four sub phases: capillary water, gravitational water, hygroscopic water and cell plasma water (Jayakody et al., 2014). The hygroscopic water refers to the water molecules adsorbed by solid particles from the air by means of surface forces. The cell plasma water can be gradually released to the pore space during biodegradation (Liu et al., 2014). Before the release, it was often assumed to be stagnant. The unsaturated properties of porous media are significantly affected by the water content, combined with effective stress, organic matter and particle size distribution (Kutilek, 2004; Richard et al., 2001; Vereecken, 1995; Walczak et al., 2006). These properties of MSW, including water retention and permeability characteristics, have been studied experimentally by some researchers (Breitmeyer and Benson, 2011; Breitmeyer and Benson, 2014; Kazimoglu, 2007; Stoltz et al., 2010, 2012; Wei et al., 2007a, 2007b; Wu et al., 2012a; Xu et al., 2014b). The results can be regressed using theoretical models developed by some researchers such as Brooks and Corey (1966) and van Genuchten (1980). However, model parameters exhibit considerable variability with MSW properties such as porosity and waste composition, making it difficult to establish a quantitative evaluation system. White et al. (2015) proposed functional relationships between the van Genuchten parameters and saturated moisture content, and concluded that this second order effect would have no