Gas Diffusivity and Thermal Properties of Compost-mixed Soils under Variable Water Saturation

Ekanayaka Achchillage Ayesha Dilrukshi, Ken Kawamoto, Takeshi Saito, Iwao Sakaguchi, Per Moldrup, and Toshiko Komatsu

***Abstract*—Gas and heat transport through compost-mixed landfill cover soils affect the emission of toxic gases and methane oxidization processes. In this study, we mixed soils with three different composts in the ratio of either 1:5 or 1:10 (compost:soil) to understand the effect of compost mixing for gas diffusivity and thermal properties. The gas diffusion coefficient (D_p), thermal conductivity (λ), and heat capacity (*HC*) were measured for soils, composts, and compost-mixed soils at different soil-water matric potentials (ψ) starting from nearly saturated to ψ = -10,000 cm H_2O and dry conditions. Data were fitted to the Brooks-Corey soil-water retention curve model to estimate the bubbling pressure (ψ_b). For all materials, D_p increased linearly with increased air content (ε), and the Penman-Call linear $D_p(\varepsilon)$ model with the model slope (*C*) and threshold soil-air content (ε_{th}) fitted the data well. The ε_{th} values increased with increasing compost content, relating non-linearly to the Brooks-Corey ψ_b but highly linearly to the soil macro-porosity. Analogous to the $D_p(\varepsilon)$ model, Penman-Call type linear $\lambda(\theta)$, and $HC(\theta)$ models with slopes (C' and C'') and intercepts (λ_0 and HC_0, thermal conductivity and heat capacity at a volumetric water content of $\theta = 0$) captured reasonably well the data measured from dry to wet conditions. The C' for λ varied depending on the compost ratio and decreased with increasing compost ratio. The C'' for *HC*, on the other hand, had less effect on the compost mix. The thermal properties under the dry condition, λ_0 and HC_0, were well correlated to the volumetric solid content. The results from this study will be helpful towards designing compost-mixed landfill cover soils with optimal heat and gas transport characteristics.**

Keywords*— Landfill cover soil; compost-mixed soils; water retention; gas diffusion coefficient; thermal conductivity; heat capacity

I. INTRODUCTION

Biologically active landfill covers such as biocovers and biofilters mitigate emissions of landfill gases such as methane and volatilized organic compounds from solid waste landfills [1]-[7]. These bio-mitigation systems have a large potential for adoption as a cost-effective sustainable solution in landfills where a landfill gas utilization system cannot be implemented [5], [7].

Compost has been identified as a potential material for biologically active landfill covers due to the retention of adequate moisture for microbial activities and high air-filled porosities, which enhance the deep penetration of oxygen required by methanotropic bacteria [8], [9]. Due to rapid urbanization and increase in population, a significant amount of biodegradable waste such as food waste residue and yard waste is generated in urbanized areas of developing countries [10]. In order to reduce amounts of waste sent to landfills, compost production is frequently used in most developing countries. Thus, reducing methane emissions through biocovers by utilizing compost is attractive as a cost-effective and easily applicable method in developing countries.

Several factors, such as soil texture, soil moisture content, soil organic content, CH_4 and O_2 concentrations, nutrients as well as environmental factors such as temperature and precipitation, control the CH_4 oxidation in natural soils, compost, and biocover materials [1], [11]-[13]. Among them, the most important factors that control CH_4 oxidation in soil have been identified as soil moisture content, temperature, and oxygen supply [12], [14]. Hettiarachchi et al. (2011) [15], for example, investigated the effects of several environmental factors on CH_4 oxidation by using a pilot-scale field methane biofiltration system.They developed a three-dimensional numerical simulation, incorporating advection-diffusive flow of gas, biological reactions and heat and moisture flow to understand the performance of the biofiltration system. They used numerical model simulations of CH_4 oxidation efficiencies under various operating conditions, and results showed that the long-term performance of a methane biofiltration system is highly dependent on

DOI: 10.5176/2335-6774_2.1.23

©The Author(s) 2015. This article is published with open access by the GSTF

environmental factors such as ambient temperature and precipitation.

Despite numerous investigations of CH_4 oxidation and its controlling factors in composts as biocover and biofilter materials, only limited studies have been conducted to measure the water, gas, and heat transport parameters of those materials. The transport parameters control water, gas, and heat movement in the biocovers and directly regulate microbial activities and mitigation of landfill gas emissions. Mostafid et al. (2012) [16] measured gas diffusion coefficients (D_p) of woodchip compost and green waste collected from a landfill biocover and biofilters under variable saturated conditions. In their study, existing predictive D_p models that assumed an inactive pore space (threshold air-filled content) predicted the D_p data well. Pokhrel et al. (2011) [17] measured D_p values for variably saturated compost and soil-compost mixtures based on CH_4 diffusion experiments. They showed that existing D_p models did not predict the measured D_p values well and proposed an empirical model with four fitting parameters. Chandrakanthi et al. (2005) [18] measured thermal conductivities (λ) of leaf compost under variable saturation conditions and showed a linear increase in λ with an increase in volumetric water content.

Previous studies give us a good insight into mass transport parameters for composts; however, they do not provide detail information on the characteristics of mass transport parameters for compost-mixed soils. When we examine the *in situ* mitigation of landfill gas emissions from the existing open dumps of waste landfills that are typical in developing countries, one simple and practical method is to mix composts with a locally available soil to use the compost-mixed soil not only as a biocover but also as a final earthen cover. In order to examine the potential use of compost-mixed soils for the mitigation of landfill gas emissions, it is necessary to evaluate the effects of compost mixed into soil on mass transport parameters such as gas diffusion and thermal conductivity as well as water retention.

Therefore, the objectives of this study were (i) to measure gas and heat transport parameters such as gas diffusion coefficient, thermal conductivity, and heat capacity for compost-mixed soils with different soil moistures starting from nearly saturated to air-dried condition, and (ii) to examine effects of compost mixing on water retention and gas and heat transport parameters based on fitted model parameters.

II. MATERIALS AND METHODS

A. Materials Used

A landfill cover soil was collected from an existing landfill site located in Saitama Prefecture, Japan. The soil was first air dried and then sieved with a 2-mm mesh. The <2-mm fraction of the soil was used in this study. The particle size distribution of the soil was 66% sand, 20% silt, and 14% clay. Three different quality-controlled composts, described as Compost A, B, and C in this study, were used. The compost materials were air-dried and used without sieving to test water retention and gas and heat transport parameters.

Basic physical and chemical properties for the soil and composts are summarized in Table 1. Basically, Test Methods for the Examination of Composting and Compost (TMECC) [19] developed by the US Department of Agriculture (USDA) and the Composting Council Research and Education Foundation (CCREF) were used to characterize chemical properties of the composts in this study. The milled compost materials (10-cm^3 sample aliquots) were ignited in a muffle furnace (FO300, Yamato, Japan) at 550°C for 2 h to determine the loss-on-ignition (LOI). The pH and EC values were determined using a 1:5 (milled compost:deionized water) slurry with 180 rpm and shaking time of 20 min as described by the TMECC standards. The water-soluble P and K were measured from a 1:20 (milled compost:deionized water) slurry after centrifugation. Composts were digested to dry ash for the determination of total phosphorus (P) and potassium (K). The digested samples were filtered and diluted before analysis, and both total and water-soluble elements were analysed using inductively coupled plasma mass spectrometry (ICPE-9000, Shimadzu, Kyoto, Japan). The organic C (OC) and C/N ratios were determined using an automatic CN analyser (CHN corder MT-5, Yanaco, Kyoto, Japan).

In Compost A, not only food residue but also sewage and food factory sludges were used. On the other hand, only food and agricultural residues were used for producing Compost B and C (Table 1). Measured physical and chemical properties of our composts were basically similar to previously reported values for organic composts [20]-[22]. The total P of Compost A was 4.8%, which was higher than those for Composts B (2.3%) and C (0.65%). On the other hand, the OC value of Compost A was 25%, which was lower than those of Composts B and C (>30%). These parameters are in accordance with those of Yang (2005) [21]. He reported that the total P for the sludge-based compost (6.6%) was higher than that for the food waste compost (0.76%) and that the OC value for the former compost (24.3%) was lower than that for latter compost (37.1%).

©The Author(s) 2015. This article is published with open access by the GSTF

TABLE 1: BASIC PHYSICAL AND CHEMICAL PROPERTIES FOR USED MATERIALS.

Material	Composition/ particle size fraction*	Particle size range (mm)	Particle density, ρ_s (g cm^{-3})	LOI %	PH	EC mS m^{-1}	Total P† %	Total K‡ %	WSP§ %	WSK≠ %	OC %	ON %	C/N
Soil	Sand: silt: clay = 66% :20% :14%	< 2.0	2.66	2.1	5.6	27	-	-	-	-	0.8	0.2	4
Compost A	Food residue, sewage sludge, food factory sludge	0.075-9.5	1.97	48	6.8	1.2×10^3	4.8	0.98	0.02	0.58	25	4.1	6.2
Compost B	Rice husk, coffee been residue, food residue, wood chip, pork bone	0.075-9.5	1.69	73	6.4	1.7×10^3	2.3	3.7	0.24	2.5	37	3.9	9.5
Compost C	Rice husk, coffee bean residue, soya bean fibers	0.075-4.75	1.70	65	7.2	8×10^2	0.65	1.4	0.14	1.4	34	1.6	21

† Total Phosphorous - elemental Phosphorous as P_2O_5.
‡ Total Potassium - elemental Potassium as K_2O.
§Water Soluble Phosphorous (WSP) as elemental Phosphorous.
≠Water Soluble Potassium (WSK) as elemental Potassium.
*Soil classification by the ASTM: D422-63 [28].

B. *Sample Preparation for Measuring Water Retention, Gas and Heat Transport Parameters*

Compost-mixed soils were prepared by mixing an air-dried compost and soil in the ratios of 1:5 and 1:10 (compost:soil) on a weight basis. The compost-mixed soils were fully mixed and kept in a plastic bag. Then, the samples were packed into 100-cm^3 cores with a diameter of 5.1-cm and a height of 4.1-cm by hand. Packed samples of soil and the three composts were also prepared. Dry bulk densities (ρ_d) of the compost-mixed soils ranged from 0.76 to 1.25 g cm^{-3} for 1:5 mixtures and 1.04 to 1.35 g cm^{-3} for 1:10 mixtures. The ρ_d values of composts varied from 0.17 to 0.61 g cm^{-3}. The ρ_d values for the soil averaged 1.45 g cm^{-3}. Typical particle size distributions for the compost-mixed soils as well as those for tested soil and composts are shown in Fig. 1. Sieve analysis was performed to determine the particle size distribution of soil and three composts (ASTM D 422).

After being packed into 100-cm^3 cores, the packed samples were placed in a tray filled with a 500 ppm NaN_3 solution and saturated for more than 3 days to prevent fungal growth. Then, the saturated samples were transferred to a sand box and subsequently drained to the desired pF [= *log* $|\psi|$ ($-\psi$, soil-water matric potential in cm of H_2O)] values using either a hanging water column method for lower pF = 0.4-2.0 (ψ = -2.5, -5.0, -10, -32, -63, -100 cm H_2O) or a pressure plate apparatus for higher pF = 3 and 4 (ψ = -1,000 and -10,000 cm H_2O). The measured pF values using a water potential meter (WP4-T, Decagon Devices, Pullman, WA, USA) were in the range of 5.5-6.7. The pF controlled samples were used to determine water retention, gas, and heat transport parameters. In addition, oven-dried samples with different ratios of compost and soil, compost:soil = 1:0 (only compost), 1:0.33, 1:1.25, 1:1.7, 1:2.5, 1:5, 1:10, 0:1 (only soil), were prepared by drying the samples at 105°C in an oven to determine heat transport parameters. For each pF, duplicate samples at or under the air- and oven-dried condition were tested in this study.

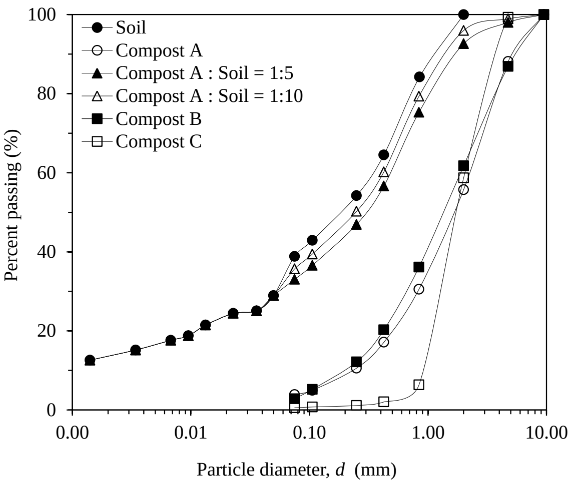

Fig. 1. Particle size distribution of tested materials.

C. Measurement of Gas Diffusion Coefficient and Thermal Properties

The gas diffusion coefficient, D_p ($cm^2 s^{-1}$), of tested samples at different *pF* values were measured under constant temperature at 20°C using a diffusion chamber method [23]. Oxygen was used as a tracer gas, and the change in the oxygen gas concentration was measured as a function of time. Gas diffusion of free air (D_0 =0.20 $cm^2 s^{-1}$ at 20°C) was used to calculate the gas diffusivity (D_p/D_0).

Thermal properties, such as thermal conductivity λ (W $m^{-1} K^{-1}$), and heat capacity *HC* (MJ $m^{-3} K^{-1}$), of tested samples were measured using a portable thermal properties analyser with a dual-needle probe (KD2-Pro and SH-1, Decagon Devices, WA, USA). The KD2-Pro probe determines the λ and *HC* values from a set of temperature measurements taken at 1-s intervals during a 30-s heating period and a 30-s cooling period [24].

III. MODELS FOR WATER RETENTION, GAS AND HEAT TRANPORT PARAMETERS

A. Water Retention Curve

The widely used Brooks-Corey (BC, 1964) [25] model for soil-water retention was applied to characterize measured water retention curves of tested materials. The BC model describes the effective saturation, S_e, as a two-parameter power function of matric potential, ψ (-cm H_2O):

$$S_e = \left(\frac{\psi_b}{\psi}\right)^{\lambda'} \qquad [1a]$$

$$S_e = \frac{(\theta-\theta_r)}{(\theta_s-\theta_r)} \qquad [1b]$$

where θ_s ($cm^3 cm^{-3}$) and θ_r ($cm^3 cm^{-3}$) are the saturated and residual water contents, respectively, ψ_b (-cm H_2O) is the bubbling pressure (air-entry value), and the λ' is a dimensionless parameter that characterizes the pore radius distribution. In this study, θ_s and θ_r were considered fitting parameters. The ψ_b and λ' values were obtained by fitting the BC model to measured plots in the log (S_e) versus log (θ).

B. Gas Diffusivity

To characterize the measured D_p/D_0 values as a function of air-filled content, ε ($cm^3 cm^{-3}$), a Penman-Call (PC) linear D_p/D_0 model [26] considering a threshold air-filled content (inactive pore space), ε_{th} ($cm^3 cm^{-3}$), was used in this study. The PC model is:

$$\frac{D_p}{D_0} = C(\varepsilon - \varepsilon_{th}) \quad \text{if } \varepsilon \geq \varepsilon_{th} \qquad [2a]$$

$$\frac{D_p}{D_0} = 0 \quad \text{if } \varepsilon < \varepsilon_{th} \qquad [2b]$$

where *C* is the slope of the linear model that characterizes the ε dependence on D_p/D_0. The gas diffusivity is negligible (= 0) below ε_{th} and ceases due to inactive pore spaces (isolated air spaces) created by interconnected water films [27]. The *C* and ε_{th}, the estimated parameter values were obtained by fitting the PC model directly to measured data.

C. Thermal Conductivity and Heat Capacity

Analogous to the PC linear D_p/D_0 model, simple linear λ and *HC* models were newly introduced to characterize the measured values. Thermal conductivity, λ, as a function of the volumetric water content, θ, can be described by using a linear slope, C', and an intercept:

$$\lambda = C'\theta + \lambda_0 \qquad [3]$$

where λ_0 (W $m^{-1} K^{-1}$) is the thermal conductivity under the dry condition (where $\theta = 0$) and fixed as the intercept of the linear relationship. The C', estimated parameter values of tested materials were obtained by fitting Eq. [3] to measured data.

Heat capacity, *HC*, as a function of the volumetric water content, θ, can be described using a linear slope, C'', and an intercept:

$$HC = C''\theta + HC_0 \qquad [4]$$

where HC_0 (MJ $m^{-3} K^{-1}$) is the heat capacity under the dry condition (where $\theta = 0$). The C'', estimated parameter values were obtained by fitting Eq. [4] to measured data.

IV. RESULTS AND DISCUSSION

A. Water Retention Characteristics

Measured water retention data for tested materials are shown in Fig. 2. In the figures, curves fitted by the Brooks-Corey (BC) water retention model (Eqs. [1a] and [1b]) are also depicted, and fitted BC parameters, λ' and ψ_b, are summarized in Table 2. The mixing of compost into soil normally increases saturated volumetric water contents (θ_s) which was plotted at $pF = -1$ ($\psi = -0.1$ cm H_2O) in Fig. 2. The BC model fitted the measured data reasonably well and captured water retention characteristics of tested materials from nearly saturated to air-dried conditions. The $|\psi_b|$ values for compost materials were very low, close to zero (2.3 cm H_2O for

©The Author(s) 2015. This article is published with open access by the GSTF

Compost A, 0.6 cm H_2O for Compost B, and 0.1 cm H_2O for Compost C), and increased with increasing soil ratio. On the other hand, the λ' values increased with increasing soil ratio, except for Compost C mixtures (Table 2). The mixing of compost into soil increased θ_s (= ϕ) values; however, overall, there were no large differences in measured θ values for soil and compost-soil mixtures at $pF \geq 1.5$ (ψ = -32 cm H_2O). This indicates that the effect of mixing compost with soil on water retention in our test materials can be observed at a nearly water-saturated condition but is not very significant at moderately wet and dry conditions.

B. Soil-gas Diffusivity

Measured gas diffusivities (D_p/D_0) for tested materials were plotted as a function of air-filled contents (ε) in Fig. 3. The Penman-Call (PC) linear model (Eqs. [2a] and [2b]) was fitted to the data and is depicted in the figures. Fitted slope C and the ε_{th} values are tabulated in Table 2. Basically, the measured D_p/D_0 values for all tested materials increased linearly with increasing ε, and the PC model captured the measured data well (r^2 >0.89). For Compost A and its soil mixture (Fig. 3a), there were no significant differences in the measured D_p/D_0 values with similar slope C and the ε_{th} values. For Composts B and C and their soil mixtures (Figs. 3b and 3c), on the other hand, the ε_{th} values increased with decreasing compost ratios, while the slope C values did not vary much among the tested materials (slope C = 0.63-0.84). The linear increases in $D_p(\varepsilon)/D_0$ for compost and compost-mixed soils are in accordance with previous studies. Mostafid et al. (2012) [16] reported linear increases in $D_p(\varepsilon)/D_0$ for variably saturated compost samples in the typical range of $0.3 < \varepsilon < 0.8$ and showed that the PC model performed reasonably well for capturing $D_p(\varepsilon)/D_0$. Pokhrel et al. (2011) [17] also showed linear increases in $D_p(\varepsilon)/D_0$ for variably saturated compost and soil-compost mixtures in the range of $0.35 < \varepsilon < 0.55$.

The ratio of ε_{th} to total porosity (ϕ), ε_{th}/ϕ, was calculated and is tabulated in Table 2. The ε_{th}/ϕ values for Composts B and C and their soil mixtures were 0.37-0.54 that are higher than those for Compost A and its soil mixtures (0.19-0.31). The higher ε_{th}/ϕ values for Composts B and C and their soil mixtures might be correlated to compost compositions of Composts B and C. These compost materials are rich in rice husks (Table 1). During the water draining (drying) from saturation, water drained first from water-filled rice husks and then relatively large numbers of isolated and disconnected air spaces. The created air spaces inside the structure, did not contribute to internal gas diffusion, resulting in apparently zero values of D_p/D_0 below ε_{th} despite of water drainage. On the other hand, Compost A was made from food residues and sludge materials (Table 1). The addition of sludge might cause less formation of isolated and disconnected air spaces during the water drainage process and result in lower ε_{th}/ϕ values for Compost A and its soil mixtures.

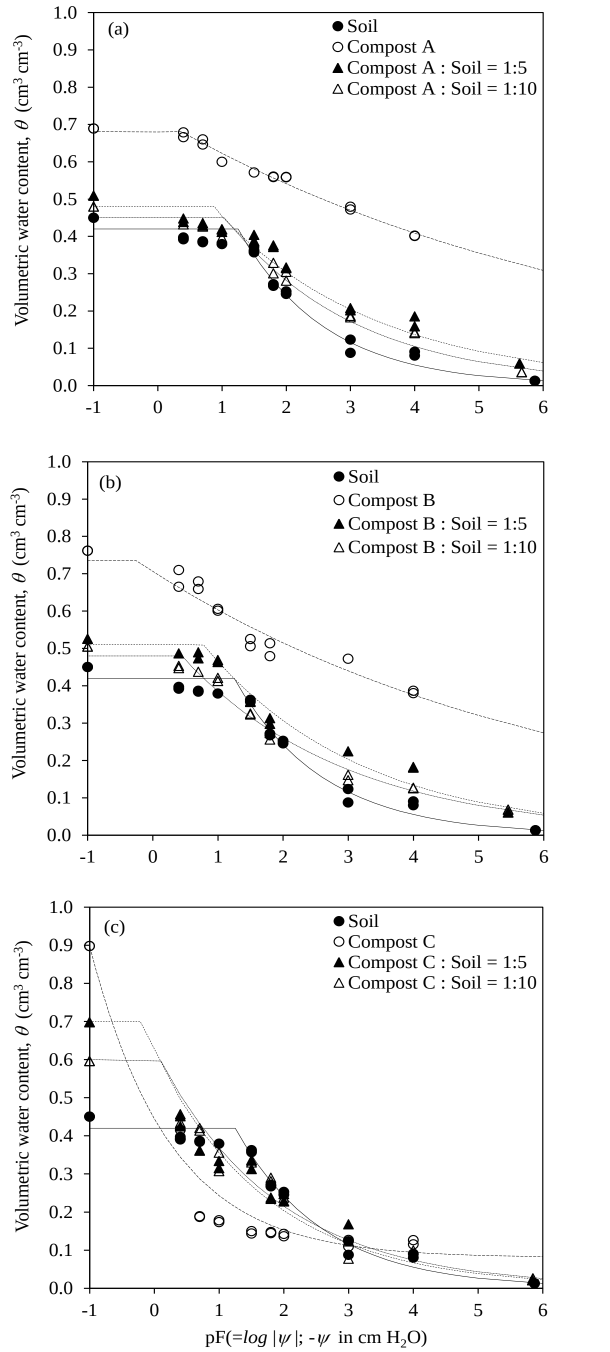

Fig. 2. Measured water retention curves for tested materials. Fitted curves of the Brooks-Corey (BC) water retention model are also depicted. Saturated volumetric water contents (θ_s) are plotted at pF = -1 (ψ = -0.1 cm H_2O).

©The Author(s) 2015. This article is published with open access by the GSTF

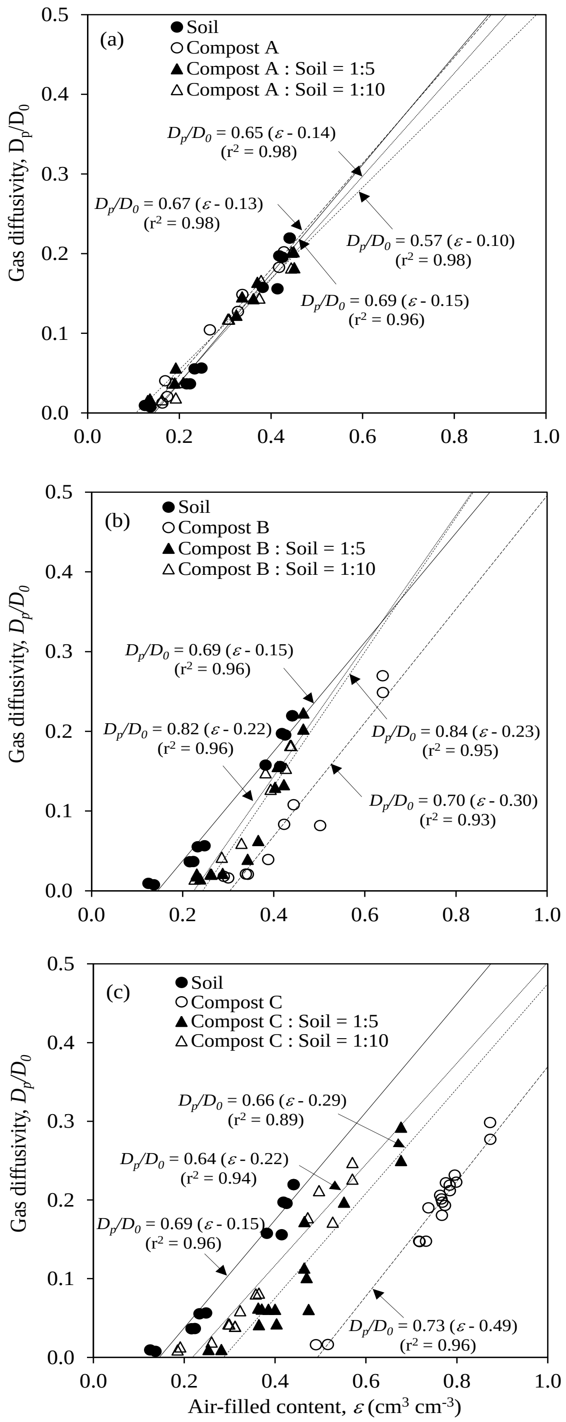

Fig. 3. Gas diffusivities (D_p/D_0) as a function of air-filled content (ε) for tested materials. Fitted lines of the Penman-Call (PC) model are also depicted.

In addition, correlations between the ε_{th} values from gas diffusivities and the ψ_b values from water retention curves were plotted in Fig. 4a, and correlation between the ε_{th} and air-filled content at pF 2 (ψ = -100 cm H_2O), ε_{100} were plotted in Fig. 4b. The ε_{th} values increased with increasing compost content, relating non-linearly to the Brooks-Corey bubbling pressure (r^2 = 0.78) and highly linearly (r^2 = 0.96) to the soil macro-porosity. It is noted that easily-drained test materials, such as Composts B and C and their soil mixtures with relatively lower $|\psi_b|$, gave larger ε_{th} values (> 0.2). Again, this indicates that such easily-drained pores which were given by lower $|\psi_b|$ values did not contribute to create inter-connected air-filled pore networks that caused internal gas diffusion inside test materials such as Composts B and C, which are rich in rice husks. The ε_{100} represents soil macro-porosity and equals to the volume of soil pores with an equivalent pore diameter > 30 μm [drained at pF 2 (ψ = -100 cm H_2O)] [29]. As shown in Fig. 4b, there is a good linear relation between ε_{th} and ε_{100} [$\varepsilon_{th} = 0.64\varepsilon_{100}$, ($r^2$ = 0.96)], which might be useful to predict and design ε intervals of adequate O_2 diffusion in soil-compost mixtures

C. *Thermal Conductivity and Heat Capacity*

Measured thermal conductivities (λ) and heat capacities (*HC*) for tested materials were plotted as a function of volumetric water content (θ) in Fig. 5. A linear λ model (Eq. [3]) was fitted to the measured λ data and depicted in Figs. 5a, 5b, and 5c. A linear *HC* model (Eq. [4]) was fitted to the measured *HC* data and depicted in Figs. 5d, 5e, and 5f. The values of fitted parameters for the models, C', λ_0, C'', HC_0, are tabulated in Table 2.

The measured λ and *HC* values for all test materials increased linearly with increasing θ, and the linear λ and *HC* models captured the measured data (r^2 >0.81 for λ, r^2 >0.72 for *HC*) reasonably well. The measured λ values for tested composts were much lower than those for soil and compost-soil mixtures (Figs. 5a, 5b, and 5c) and both C' and λ_0 values for compost-soil mixtures decreased with increasing compost mixing ratio (Table 2). In addition, the C' values for composts and compost-soil mixtures did not affect by the type of compost (i. e. Compost A, B, and C), with the range of 0.57-0.59 for compost, 1.93-2.17 for compost:soil = 1:5, and 2.25-2.57 for compost:soil = 1:10. On the other hand, measured *HC* values for tested materials did not vary except for Compost C (Fig. 5f). The fitted C'' values ranged from 3.18 to 4.72, which is narrower compared to the C' values.

©The Author(s) 2015. This article is published with open access by the GSTF

TABLE 2. FITTED PARAMETERS OF BROOKS AND COREY (BC) MODEL [λ', PORE RADIUS DISTRIBUTION, AND ψ_B, BUBBLING PRESSURE (EQ. 1)], PENMAN-CALL (PC) LINEAR D_P/D_0 MODEL [C, SLOPE OF THE LINEAR MODEL, AND ε_{TH}, THRESHOLD AIR-FILLED CONTENT (EQ. 2)], AND NEW λ AND HC LINEAR MODELS [C', SLOPE OF THE λ LINEAR MODEL (EQ. 3), AND C'', SLOPE OF THE HC LINEAR MODEL (EQ. 4)].

Material	θ_s $cm^3\ cm^{-3}$	λ'	ψ_b -cm H_2O	C	ε_{th} $cm^3\ cm^{-3}$	ε_{th}/ϕ	C' $W\ m^{-1}\ K^{-1}$	λ_0 $W\ m^{-1}\ K^{-1}$	C'' $MJ\ m^{-3}\ K^{-1}$	HC_0 $MJ\ m^{-3}\ K^{-1}$
Soil	0.42	0.32	17.8	0.69	0.15	0.36	2.75	0.19	3.27	1.29
Compost A	0.68	0.06	2.3	0.67	0.13	0.19	0.59	0.11	4.43	1.02
Compost A:Soil =1:5	0.48	0.17	7.6	0.57	0.10	0.21	2.17	0.15	3.81	1.16
Compost A:Soil =1:10	0.45	0.21	10.7	0.65	0.14	0.31	2.57	0.17	3.57	1.15
Compost B	0.74	0.07	0.6	0.70	0.30	0.41	0.57	0.08	4.11	0.73
Compost B:Soil =1:5	0.51	0.18	6.0	0.84	0.23	0.45	1.93	0.14	3.51	1.02
Compost B:Soil =1:10	0.48	0.17	2.9	0.82	0.22	0.46	2.25	0.16	3.18	1.11
Compost C	0.90	0.35	0.1	0.73	0.49	0.54	0.57	0.06	3.81	0.43
Compost C:Soil =1:5	0.70	0.24	0.6	0.66	0.29	0.41	2.15	0.12	4.72	0.95
Compost C:Soil =1:10	0.60	0.23	1.3	0.64	0.22	0.37	2.42	0.13	4.30	0.99

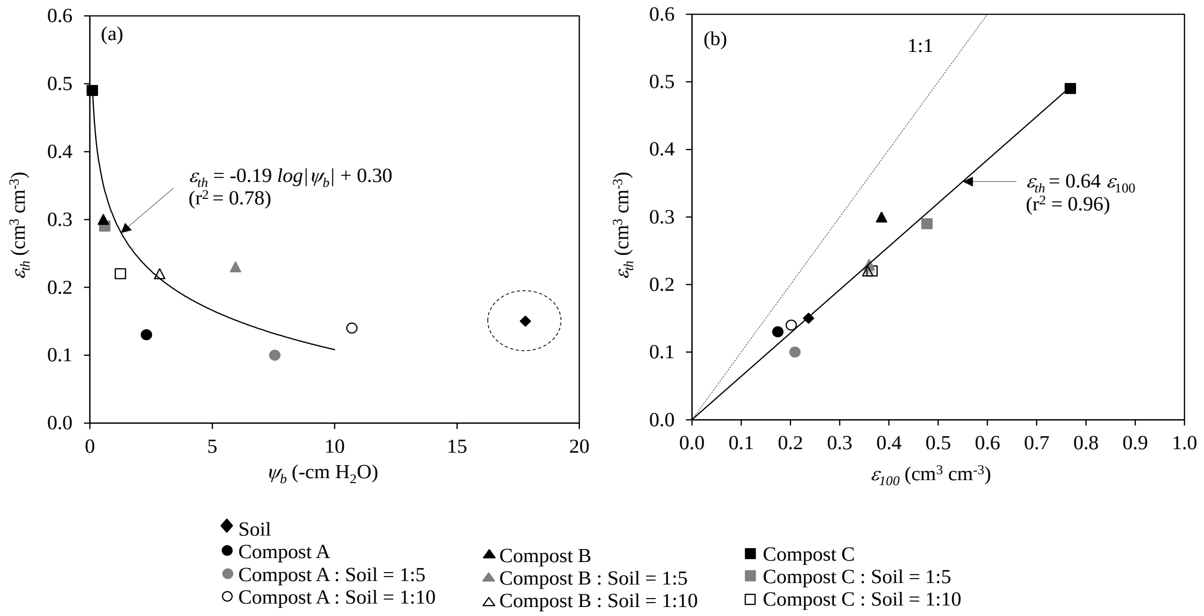

Fig. 4. (a) Correlation between the threshold air-filled content (ε_{th}) values from gas diffusivities and the bubbling pressure (ψ_b) values from water retention curves. A fitted curve for the plots except for soil is given in the figure. (b) Correlation between the ε_{th} and air-filled content at pF 2, ε_{100}.

Chandrakanthi et al. (2005) [18] measured λ for leaf compost with around 20% organic carbon (OC) under variable saturation conditions and showed a linear increase in λ with increasing θ. Based on the regression line shown in their figure (Fig. 5 in the literature), the C' value can be estimated to be around 1.4, which was a little higher than those for our test composts (C' = 0.57-0.59). This might be attributed to the difference in OC among composts used. The OC contents for our test composts were 25-37% (Table 1), which are higher than their compost using leaves. Dissanayaka et al. (2012) [30] measured λ and HC values of variably saturated peaty soils with 33.3-89.7% OC and obtained C' = 0.51 and C'' = 3.66 (Eqs. [9] and [10] in the literature). Those values are similar to our obtained C' and C'' for tested composts (Table 2).

©The Author(s) 2015. This article is published with open access by the GSTF

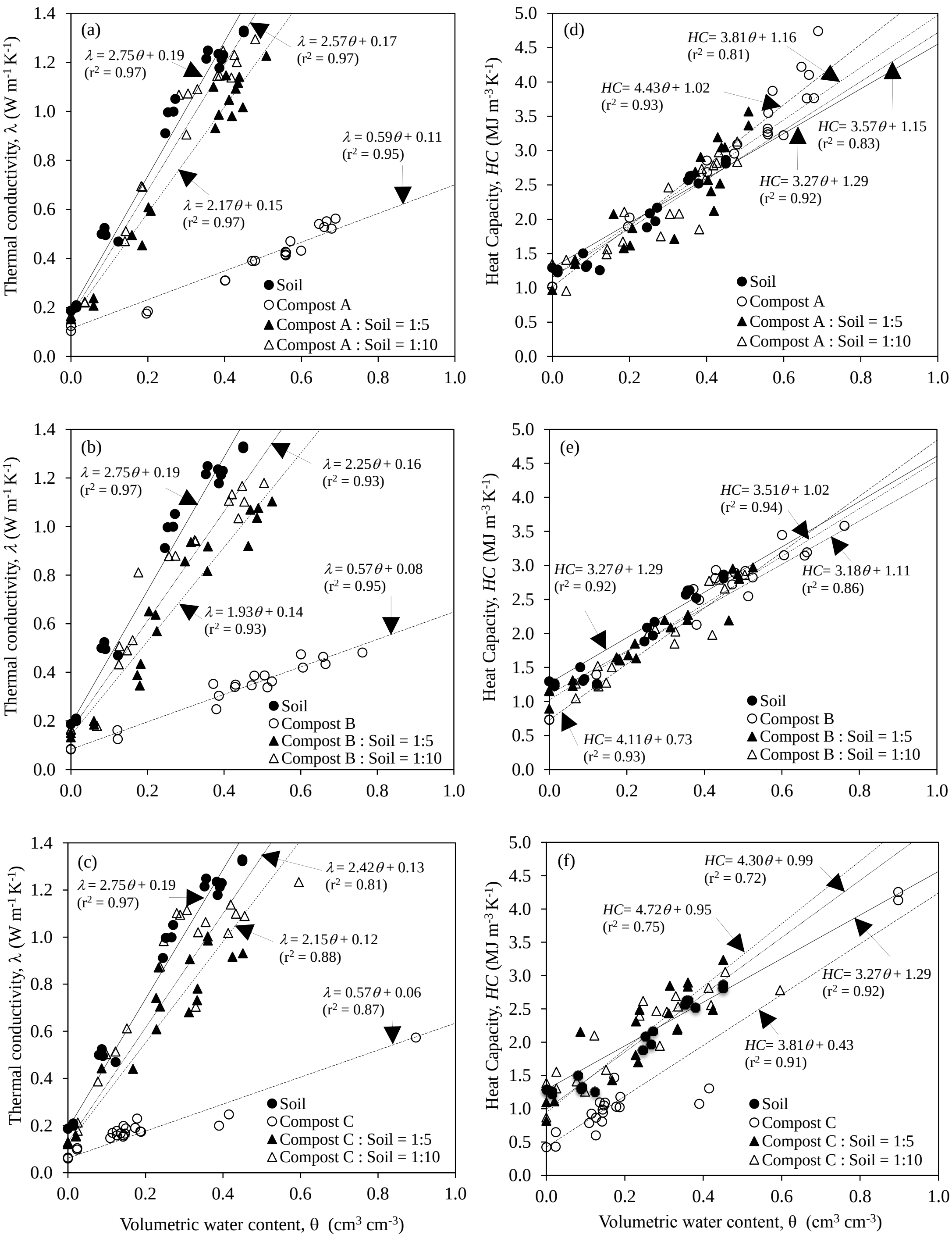

Fig. 5. (a, b, and c) Thermal conductivities (λ) and (d, e, and f) heat capacities (*HC*) as a function of volumetric water content (θ) for tested materials. Fitted lines of the Penman-Call (PC) type models (Eqs.[3] and [4]) are also depicted.

©The Author(s) 2015. This article is published with open access by the GSTF

For dry conditions (where $\theta = 0$), the volumetric solid content, σ, controls the λ and HC in porous media [31], [32]. The measured λ_0 and HC_0 values for dry samples with different mixing ratios of compost and soil, compost:soil = 1:0 (only compost), 1:0.33, 1:1.25, 1:1.7, 1:2.5, 1:5, 1:10, and 0:1 (only soil) were plotted as a function of σ in Fig. 6 and a fitted line for $\lambda_0(\sigma)$ and a fitted curve for $HC_0(\sigma)$ were given (see the equations in the figure):

$$\lambda_0 = 0.25\sigma + 0.025 \quad [5]$$

$$HC_0 = 1.55\sigma^{0.48} \quad [6]$$

In Figure 6, previously proposed linear relationships based on the data measured for organic peaty soils by Dissanayaka et al. (2012) [30] are also depicted. For $\lambda_0(\sigma)$, there was a good linear relationship and the solid content mainly controlled that thermal conductivity for dried materials. The fitted line was similar to the one proposed by Dissanayaka et al. (2012) [30] (Fig. 6a). The HC_0, on the other hand, increased nonlinearly with increasing σ. Both Eqs. [5] and [6] are simple but give good regressions ($r^2 = 0.81$ and 0.90, respectively); thus, it seems useful to have a quick assessment of thermal properties for dried compost-mixed soils.

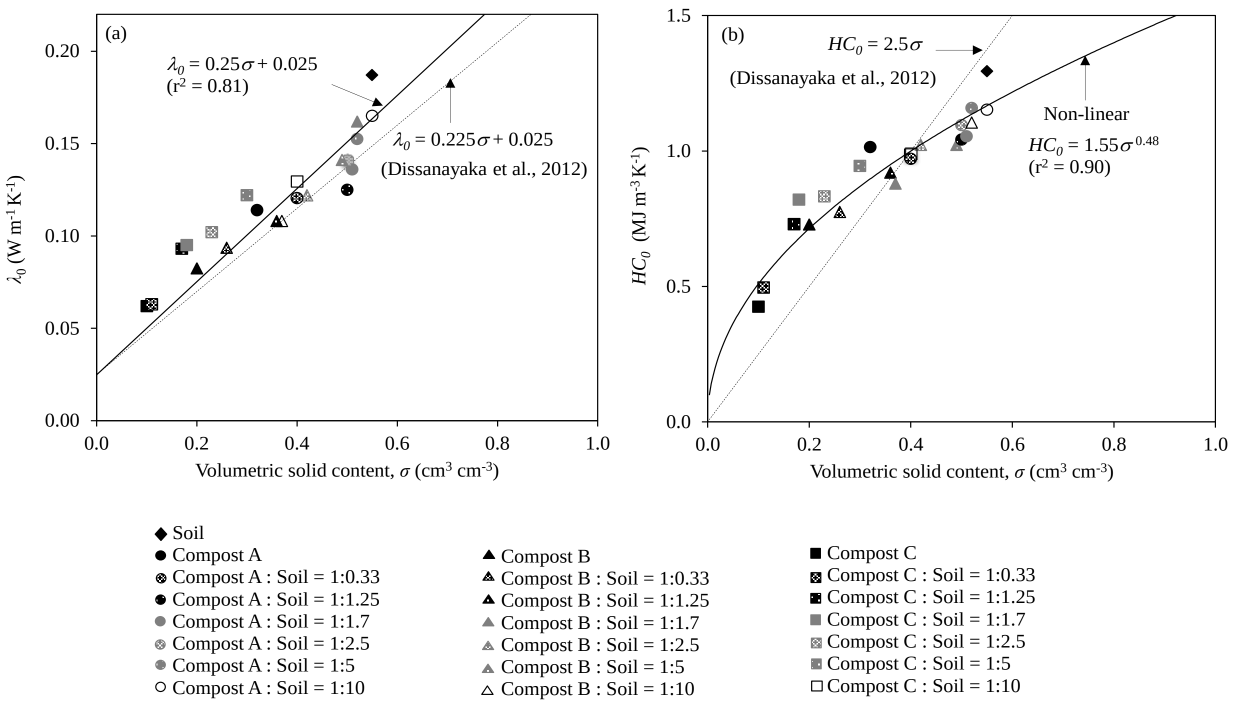

Fig. 6. (a) Thermal conductivities and (b) heat capacity under dry conditions, (λ_0) and (HC_0), respectively as a function of volumetric solid content (σ). Fitted line (Eq. [5]) and curve (Eq. [6]) are also shown. It is noted that intercept values at $\sigma = 0$ for the fitted line and curve were fixed to be those values for air (0.025 for λ_0 and 0 for HC_0).

Furthermore, in order to clarify the effect of compost mixing on the thermal properties of dried compost-mixed soils, the measured λ_0 and HC_0 values were plotted as a function of the ratio of volumetric compost content ($\sigma_{compost}$) to volumetric solid content (σ), $\sigma_{compost}/\sigma$, and are shown in Fig. 7. The $\sigma_{compost}$ can be calculated by using the dry mass weight of mixed compost and particle density (ρ_s) of compost. In the figure, fitted curves with a parameter, n, which fixes both ends of $\sigma_{compost}/\sigma = 0$ and 1 are given:

$$\lambda_0 = \left(\lambda_{0,soil} - \lambda_{0,compost}\right)\left(1 - \sigma_{compost}/\sigma\right)^n + \lambda_{0,compost} \quad [7]$$

$$HC_0 = \left(HC_{0,soil} - HC_{0,compost}\right)\left(1 - \sigma_{compost}/\sigma\right)^n + HC_{0,compost} \quad [8]$$

where $\lambda_{0,soil}$ and $\lambda_{0,compost}$ (W m^{-1} K^{-1}) are the thermal conductivities of soil and compost under the dried condition (where $\theta = 0$), respectively, and $HC_{0,soil}$ and $HC_{0,compost}$ (MJ m^{-3} K^{-1}) are the heat capacities of soil and compost under the dry condition, respectively. Eqs. [7] and [8] described the data ($r^2 > 0.95$) well and both λ_0 and HC_0 nonlinearly decreased with increasing $\sigma_{compost}/\sigma$. It is noted that fitted n values for both λ_0 and HC_0 did not much vary irrespective of compost type with different λ_0 values.

©The Author(s) 2015. This article is published with open access by the GSTF

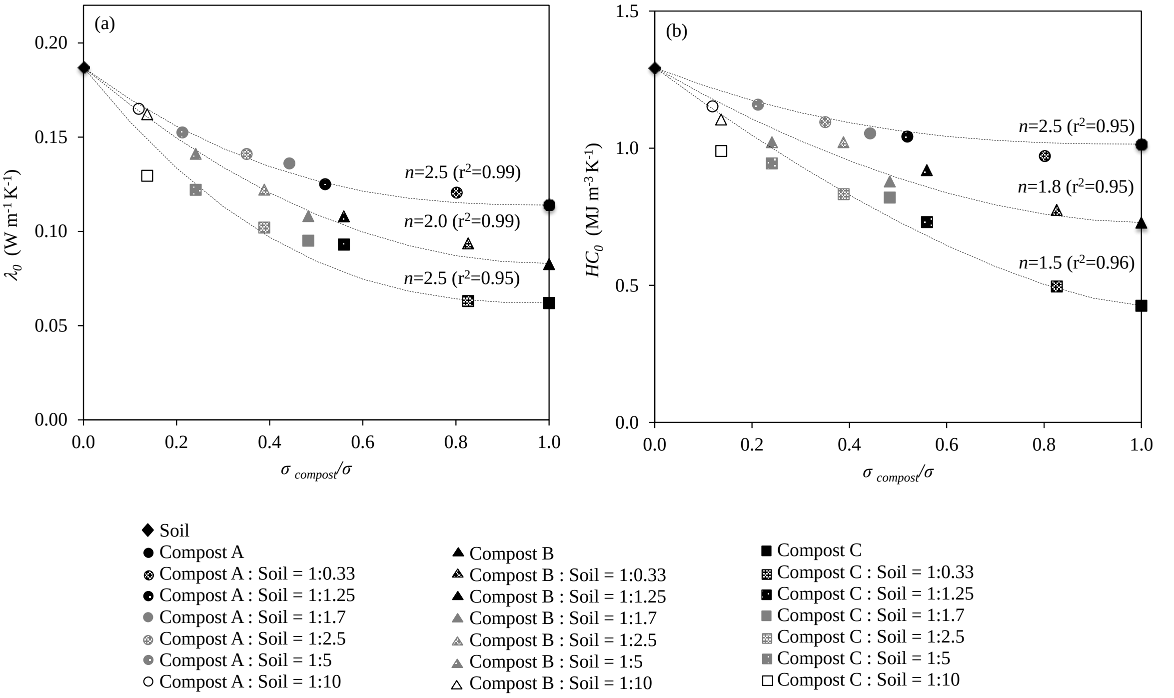

Fig. 7. Thermal conductivity and heat capacity under dry conditions, (λ_0) and (HC_0), respectively as a function of the ratio of volumetric compost content ($\sigma_{compost}$) to volumetric solid content (σ), $\sigma_{compost}/\sigma$. Fitted curves (Eqs.[7] and [8]) are also depicted.

V. CONCLUSIONS

This study investigated the effects of mixed composts on water retention, gas, and heat transport parameters based on fitted model parameters. Measured water retention data were fitted well by the BC water retention model. The effect of compost in soil on water retention appeared at the near water-saturated condition but was not significant at moderately wet and dry conditions. The PC linear model captured D_p/D_0 data well for both compost and compost-soil mixtures. The fitted slope, C, in the PC model did not show significant difference among the tested materials (slope C = 0.57-0.84). On the other hand, the ε_{th} values increased with increasing compost content, relating non-linearly to the Brooks-Corey bubbling pressure but highly linearly to macro-porosity. Analogous to the PC model for gas diffusivity, linear λ and HC models were used to fit the measured data. The models captured reasonably well the measured λ and HC data from dry to wet conditions. The model slope C' for λ varied depending on the compost ratio and became lower with increasing compost ratio. The model slope C'' for HC, on the other hand, showed less effect of the compost ratio. The thermal properties under the dry condition, λ_0 and HC_0, were well correlated to the volumetric solid content, and unique nonlinear relationships between λ_0 and HC_0 and volumetric compost content were seen.

Based on the results from this study, gas and heat transport parameters (D_p/D_0, λ, and HC) of compost materials and compost-mixed soils gave significant linear relationships to their fluid contents (ε for D_p/D_0 and θ for λ and HC). The number of measurements is still limited, and correlations among model parameters (C, C', and C'') for compost-mixed soils have not been fully discussed yet. However, the PC type simple linear models used in this study would be useful for a quick assessment of gas and heat transport through compost-mixed landfill cover soils.

ACTKNOWLEDGEMENTS

This work is partially supported by the JST-JICA Science and Technology Research Partnership for Sustainable Development (SATREPS) project. We especially acknowledge Mr. Akiyoshi Yoshida, a former undergraduate student of Saitama University, for his careful and dedicated laboratory work. We would like to thank companies, I'll Clean-tech Inc.

©The Author(s) 2015. This article is published with open access by the GSTF

(Saitama, Japan) and Yorii Compost Corp. (Saitama, Japan), for providing us compost materials.

REFERENCES

[1] B. Stein, and J. P. A. Hettiaratchi. 2000. Methane oxidation in three Alberta soils: influence of soil parameters and methane flux rates. Environ. Technol. 22:101-111.

[2] M. Humer, and P. Lechner. 2001a. Microbial methane oxidation for the reduction of landfill gas emissions. J. Solid Waste Technol. and Manag. 27(3&4):146-151.

[3] M. A. Barlaz, R. B. Green, J. P. Chanton, C. D. Goldsmith and G. R. Hater. 2004. Evaluation of a biologically active cover for mitigation of landfill gas emissions. Environ. Sci. Technol. 38(18): 4891-4899.

[4] J. C. Stern, J. Chanton, T. Abichou, D. Powelson, L. Yuan, S. Escoriza, and J. Bogner. 2007. Use of a biologically active cover to reduce landfill methane emissions and enhance methane oxidation. Waste Manage. 27(9): 1248-1258.

[5] M. Pawlowska, and L. Pawlowski. (2008). Management of Pollutant Emission from Landfills and Sludge. Taylor and Francis/Balkema, AK Leiden, The Netherlands. ISBN 13: 978-0-203-93218-6 (e book).

[6] G. B Pedersen, C. Scheutz, and P. Kjeldsen. 2011. Availability and properties of materials for the Fakse Landfill biocover. Waste Manag. 31(5):884-894.

[7] C. Scheutz, R. B. Pedersen, P. H. Petersen, J. H. B. Jorgensen, I. M. B. Ucendo, J. G. Monster, J. Samuelsson, and P. Kjeldsen. 2014. Mitigation of methane emission from an old unlined landfill in Klintholm, Denmark using a passive biocover system. Waste Manag. 34:1179-1190.

[8] M. Humer, and P. Lechner. 2001b. Design of a landfill cover layer to enhance methane oxidation-results of a two year field investigation. Proceedings Sardinia 2001, Eighth international Waste Manag. and Landfill Symp., S. Margherita di Pula, Cagliari, Italy.

[9] R. H. Kettunen, J.M Einola, and J.A Rintala. 2006. Landfill methane oxidation in engineered soil columns at low temperature. Water, Air, and Soil Pollu. 177:313-334.

[10] L. F. Marmolejo, L. F. Diaz, P. Torres, and M. Garcia. 2012. Perspectives for sustainable resource recovery from municipal solid waste in developing countries: Application and alternatives. Waste Manag. – An integrated vision, Edition:1, Chapter 7, InTech, Rijeka, Croatia. pp. 153-166.

[11] G. Börjesson, J. Chanton, and B.H. Svensson. 2001. Methane oxidation in two Swedish landfill covers measured with carbon-13 and carbon-12 isotope ratios. J. Environ. Qual., 30(2):369-376.

[12] C. Scheutz, P. Kjeldsen, J. E. Bogner, A. De Visscher, J. Gebert, H. A. Hilger, M. Huber-Humer, and K. Spokas. 2009. Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions. J. Waste Management Res. 27:409-455.

[13] B. Y Sadasivam, and K. R. Reddy. 2014. Landfill methane oxidation in soil and bio-based cover systems: a review. Rev. Environ. Sci. Biotechnol. 13:79-107.

[14] C. Scheutz, and P. Kjeldsen. 2004. Environmental factors influencing attenuation of methane and hydrochlorofluorocarbons in landfill cover soils. J. Environ. Qual. 33:72-79.

[15] V. C. Hettiarachchi, P. J. Hettiarachchi, A. K. Mehrotra, and S. Kumar. 2011. Fiels-scale operation of methane biofiltration systems to mitigate point source methane emissions. Environ. Pollu. 159:1715-1720.

[16] M. E. Mostafid, C. Shank, P. T. Imhoff, and R. Yazdani 2012. Gas transport properties of compost-woodchip and green waste for landfill biocovers and biofilters. Chem. Eng. J. 191:314-325.

[17] D. Pokhrel, P. Hettiaratchi, and S. Kumar. 2011. Methane diffusion coefficient in compost and soil-compost mixtures in gas phase biofilter. Chem. Eng. J. 169:200-206.

[18] M. Chandrakanthi, A. K. Mehrotra, and J. P. A. Hettiaratchi. 2005. Thermal conductivity of leaf compost used in biofilters: an experimental and theoretical investigation, Environ. Pollu. 136:167-174.

[19] W. H. Thompson, P. B. Leege, P. D. Millner, and M. E. Watson (Eds.) 2001. Test methods for the examination of composting and compost. Joint Project of the U. S. Department of Agriculture and the U. S. Composting Council.

[20] L. Herna´ndez-Apaolaza, A. M. Gasco´, J. M. Gasco´, F., Guerrero. 2005. Reuse of waste materials as growing media for ornamental plants. Bioresource Technol. 96: 125–131.

[21] S. S. Yang, 2005. Management of composting. Report for food and fertilizer technology center for the Asian and pacific region. Wenchow st. Taipei 10648, Taiwan.

[22] T. M. Bajawa, 2012. Experimental characterization of the thermal, hydraulic and mechanical (THM) properties of compost based landfill covers. Thesis for master of applied science in civil engineering, university of Ottawa, Ottawa, Canada.

[23] D. E. Rolston, and P. Moldrup. 2002. Gas diffusivity. In: Dane, J. H., Topp, G.C. (Eds.), Methods of soil Analysis, Part 4, SSSA Book Ser. 5. ASA and SSSA, Madison, WI, pp. 1113-1139.

[24] Decagon Devices. 2012. KD2 Pro thermal properties analyzer operator`s manual version 12. Decagon Devices Inc., Pullman, USA.

[25] R. H. Brooks, and A. T. Corey. 1964. Hydraulic properties of porous media. Hydrol. Pap. 3, Civil Eng. Dep., Colo. State Univ., Fort Collins.

[26] P. Moldrup, T. Olesen, S. Yoshikawa, T. Komatsu, A. M. McDonald, and Rolston, D. E. 2005. Predictive-descriptive models for gas and solute diffusion coefficients in variably saturated porous media coupled to pore-size distribution: III, Inactive pore space interpretations of gas diffusivity. Soil Sci. 170:867-880.

[27] F. R. Troeh, J. D. Jabro, and D. Kirkham. 1982. Gas diffusion equations for porous materials. Geoderma 27:239-253.

[28] ASTM. 2007. Standard test method for particle-size analysis of soils, ASTM D422-63 (2007): Philadelphia.

[29] P. Moldrup, T. Olesen, P. Schjønning, T. Yamaguchi, and D. E. Rolston. 2000. Predicting the gas diffusion coefficient in undisturbed soil from soil water characteristics. Soil Sci. Am. J. 64:94-100.

[30] S. H. Dissanayaka, S. Hamamoto, K. Kawamoto, T. Komatsu, and P. Moldrup. 2012. Thermal properties of peaty soils: effects of liquid-phase impedance factor and shrinkage. Vadose Zone J. 11(1): doi:10.2136/vzj2011.0092

©The Author(s) 2015. This article is published with open access by the GSTF

[31] D. A. de Vries, 1963. Thermal properties of soils. In: van Wijk, W.R. (Ed.). Physics of Plant Environment. North Holland Publishing Company, Amsterdam, Netherlands, pp. 210-235.

[32] O. Johansen, 1975. Thermal conductivity of soils. Ph.D. diss. Univ. of Trondheim, Norway. CRREL Draft Engl. Transl. 637. U.S. Army Corps of Eng., Cold Regions Res. Eng. Lab., Hanover, NH.

AUTHORS' PROFILE

E. A. Ayesha Dilrukshi holds a BSc in Agriculture from Wayamba University Sri Lanka and MPhil in Integrated water resources management from Post Graduate Institute of Agriculture, University of Peradeniya, Sri Lanka. Currently she is doing her PhD in soil mechanics in Saitama University Japan from 2012 October.

Dr. Ken Kawamoto, Ph.D. University of Tokyo (2002) is Professor at the Graduate School of Science and Engineering, Saitama University. His majors are Geoenvironmental Engineering, Soil Physics, and Vadose Zone Hydrology. Research interests are pollution control and environmental risk assessment at waste disposal sites, measurements and models for mass transport parameters in soils, and soil-water repellency and its impacts on hydraulic properties. He supervised more than 20 MSc and 5 PhD students for their dissertation work. He is the Principal Investigator for the Japan Science and Technology Agency (JST) - the Japan International Cooperation Agency (JICA) Science and Technology Research Partnership for Sustainable Development (SATREPS) Project entitled "Development of pollution control and environmental restoration technologies of waste landfill sites in Sri Lanka (2011-2016)" and a member of the Soil Infrastructure, Interfaces, and Translocation Processes in Inner Space ("Soil-it-is") project from the Danish Research Council for Technology and Production Sciences.

Dr. Takeshi Saito received Ph. D from University of Tsukuba (2011). He worked at Saitama University as postdoctoral researcher (2011-2014), and has been an assistant professor at Saitama University since 2014. His research fields are Hydrogeochemistry and Geoenvironmental Engineering, and his present research interests are to understand the effects of subsurface thermal disturbance (subsurface thermal pollution) on the behavior of chemical pollutants and greenhouse effect gases in groundwater, soil and sediment.

Dr. P. Moldrup received the PhD degree in environmental engineering (1990) from Aalborg University, Denmark. He has worked as assistant and associate professor and since 2007 been professor in environmental soil physics and engineering at Aalborg University. His research focuses on soil ecosystem functions with emphasis on measuring and modeling transport processes and parameters in the gaseous and liquid phases of soil and other porous media. He has authored/co-authored >200 peer-reviewed papers, is Fellow of the Soil Science Society of America, and in 2006 received the Don and Betty Kirkham Reward for Excellence in Soil Physics.

Dr. T. Komatsu received Ph.D in engineering from Hiroshima University (1987). She worked at Department of Civil and Environmental Engineering in Hiroshima University as assistant and associate professor (1992-2002), and has been a professor at Graduate School of Science and Engineering, Saitama University since 2002. Her main research area is environmental soil science and her research interests cover mass and heat transport in soils. She has been Team Leader (PI) for Core Research for Evolutionary Science and Technology (CREST), "Sustainable Groundwater Management Systems under Enhanced Geo-Thermal Energy Usage" since 2010 (5 year project by JST; Japan Science and Technology).

©The Author(s) 2015. This article is published with open access by the GSTF