Gas and Heat Transport in Variably-Compacted Landfill Cover at Variably-Saturated Condition

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Abstract: *Understandings of gas and heat transport in the landfill covers are essential for enhancing the landfill site stabilization and reducing the greenhouse and toxic gas emissions. Gas diffusion and thermal conduction are main mechanisms for gas and heat transport in soils. Gas diffusion coefficient and thermal conductivity govern gas diffusion and thermal conduction, respectively. In this study, we developed a unified predictive model for gas diffusion coefficient and thermal conductivity considering soil compaction level. Numerical simulations of gas (methane, carbon dioxide, and oxygen) and heat transport in a landfill cover were performed using the developed predictive model. Increase of compaction level enhanced not only heat transport in the landfill cover but also methane gas emissions due to reduced methane gas oxidation nearby soil surface.*

Keywords: *Landfill cover soil, gas diffusivity, thermal conductivity, numerical simulation.*

1. INTRODUCTION

Landfill sites are a significant source of methane (CH_4) which has a high global warming potential, estimated to be more than 20 times that of carbon dioxide. The estimated CH_4 emissions from landfills are 550-635 Mt CO_2-eq. year^{-1} corresponding to about 9% of global anthropogenic methane emissions (Rogner et al., 2007; Bogner et al., 2008). In addition, the emissions of toxic gases such as a hydrogen sulfide and volatile organic chemicals from landfill sites affect surrounding local environments. The exothermal reactions also occur due to the microbiological processes in the waste layer. These gases and heat produced in the waste layer move through landfill covers and emit to the atmosphere. Therefore, the understandings of gas and heat transport in the landfill covers are essential for enhancing the landfill site stabilization and reducing the greenhouse and toxic gas emissions. Gas diffusion and thermal conduction are main mechanisms for gas and heat transport in soils. Gas diffusion coefficient (D_p) and thermal conductivity (λ) govern gas diffusion and thermal conduction, respectively.
Gas diffusion coefficient is controlled by air-filled networks, while thermal conductivity is affected by both solid phase configuration and water-filled pore networks. Since the bulk soil-pore structure is composed of the three phase (air, water, and solid) geometries, gas and heat transport characteristics at different moisture conditions are expected to be interrelated. Such a relation enables to develop a unified predictive model for gas and transport parameters which are promising for simulating simultaneous gas and heat transport in the landfill covers.
In this study, we developed a unified predictive model for gas diffusion coefficient and thermal conductivity considering soil compaction level (i.e., dry bulk density). Numerical simulations of gas (methane, carbon dioxide, and oxygen) and heat transport in a landfill cover were performed using the developed predictive model. The effects of soil compaction level and thickness of the landfill cover on gas and heat transport were investigated.

2. MATERIAL AND METHODS

2.1. Soil Samples and Gas Diffusivity Measurements

A waste landfill site in Saitama Prefecture, Japan, was selected as a sampling location. The final cover soil (size fraction less than 2-mm) was used in this study. The soil texture was a sandy loam. Compaction tests were performed for soil samples at different water content. In the compaction tests, the soil samples were repacked into large soil cores (i.d. 15-cm, length 12-cm) at two different compaction levels (high: 2700 kJ m^{-3} and low: 600 kJ m^{-3}).
After compaction tests, 100-cm^3 core samples were taken inside each repacked large core. The core samples were classified into two different ρ_b ranges (1.80-1.90 g cm^{-3}, labelled as extreme compaction (EC), and 1.70-1.80 g cm^{-3}, labelled as high compaction (HC)). After the core samples were water-saturated, they were drained at different matric suctions and the gas diffusion coefficient (D_p) was measured. For comparison, disturbed soil samples at different water contents were repacked into 100-cm^3 cores at dry density of 1.55 g cm^{-3}, representing normal compacted soils (labelled as normal compaction, NC), and the D_p was measured on the repacked soil samples at different soil-air contents.
The D_p was measured on the repacked 100-cm^3 soil cores with a diffusion chamber method (Rolston and Moldrup, 2002). Oxygen was used as tracer gas and measured as a function of time in the diffusion chamber. The D_p was calculated according to Osozawa (1998). In this study, the gas diffusion coefficient of oxygen in free air (D_0) at 20 °C was taken as 0.20 x 10^{-4} (m^2 s^{-1}).

3. DEVELOPMETNS OF UNIFIED PREDICTIVE MODEL FOR GAS DIFFUSIVITY AND THERMAL CONDUCTIVITY CONSIDERING COMPACTION LEVEL

3.1. Gas Diffusivity (Dp) Measurements and Development of Compaction-Dependent Predictive Dp Model

Figure 1a shows the measured gas diffusivity. At the same soil-air content (ε, m^3 m^{-3}), higher D_p for soils at higher ρ_b were observed. It is because the soil samples at higher ρ_b have lower volumetric water content as compared to those at lower ρ_b. This effect is more significant for soils under wet conditions (i.e., lower ε). The following power-law function was fitted against the measured data.

$$\frac{D_p}{D_0} = \alpha_p \varepsilon^{X_p} \qquad (1)$$

where α_p, X_p are fitting parameters to represent air-filled pore connectivity. Figure 1b shows the fitted α_p and X_p values as a function of ρ_b. Both α_p and X_p linearly decreased with increasing ρ_b, suggesting that larger pore-networks for loosely-compacted soils more dramatica

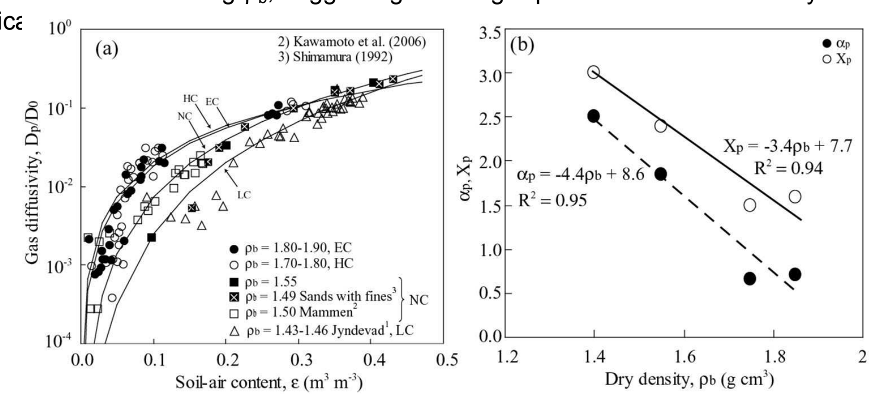

Figure 1 (a) Gas diffusivity as a function of soil-air content, (b) fitted α_p, X_p as a function of dry bulk density. Redrawn from Hamamoto et al. (2011).

3.2. Unified Predictive Model for Gas Diffusivity and Thermal Conductivity

In addition to the measured D_p data for landfill cover soils, D_p and thermal conductivity data (λ, W m^{-1} K^{-1}) were collected from literature (e.g., Lu et al., 2007). Figure 2 shows transport parameter (P: D_p or λ) normalized by P at fluid saturation (D_p: air saturation, λ: water saturation), P_{sat}, as a function of fluid saturation (ϕ/ϕ_{sat}). ϕ is the fluid content (m^3 m^{-3}) and ϕ_{sat} is the total porosity (m^3 m^{-3}). The ϕ for D_p and λ represents soil-air content (ε) and volumetric water content (θ), respectively. As shown in Fig. 2, the D_p rapidly increased at higher fluid saturation since at dry condition (higher ϕ/ϕ_{sat}), gas diffusion is enhanced due to well-connected larger pore-networks. On the other hand, more marked increase in the λ was observed under lower fluid saturation. Since thermal conduction process is mainly governed by thermal conduction through solid phase, at dry condition, water bridges begin to form between soil particles, and the λ starts to increase rapidly because of the improved thermal contact between particles.

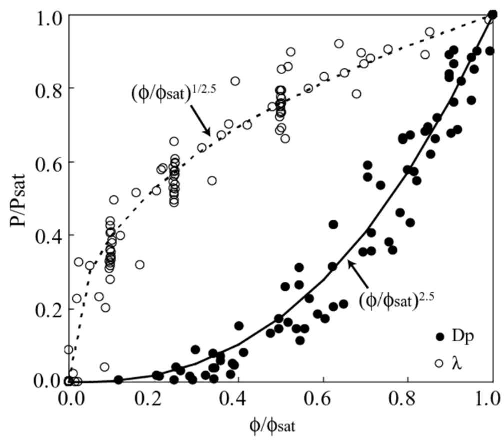

Figure 2 Normalized transport parameter as a function of fluid saturation. Redrawn from Hamamoto et al. (2010).

As shown in solid and dotted lines in Fig. 2, the normalized D_p and λ values could be well expressed by $(\phi/\phi_{sat})^{2.5}$ and $(\phi/\phi_{sat})^{1/2.5}$, respectively. Thus, the clear mirror image was obtained for D_p and λ behaviours as a function of fluid content. By combining the obtained relation between D_p and λ, and predictive D_p model as a function of ρ_b (Fig. 2), the following unified predictive model for D_p and λ considering compaction level (ρ_b) can be derived.

$$\frac{P}{P_{sat}} = \left(\frac{\phi}{\phi_{sat}}\right)^{X_p} \qquad (2)$$

where the X_p in Eq. (2) can be expressed as a function of ρ_b shown in Fig. 1b, and for λ, inverse of X_p ($1/X_p$) instead of X_p. In this study, P_{sat} values for D_p and λ were estimated by Eq. (1) and predictive model from literature (Lu et al., 2007), respectively.

4. NUMERICAL SIMULATIONS ON GAS AND HEAT TRANSPORT IN LANDFILL COVER

4.1. Governing Equations for Gas and Heat Transport

In this study, CH_4, CO_2, and O_2 movements in the landfill cover were simulated. By assuming Fickian diffusion process and methane oxidation as main gas transport mechanisms, the governing equation for gas transport for each gas species can be expressed as,

$$\varepsilon\frac{\partial C_i}{t} = D_p\frac{\partial^2 C_i}{\partial z^2} - \chi_i R_{CH4} \qquad (3)$$

where C_i is the gas concentration (mol m^{-3}) of species i (i.e,. i = CH_4, CO_2, or O_2), R_{CH4} is the methane oxidation rate (mol m^{-3} s^{-1}), and x_i is the stoichiometric factors (χ_{CH4} = 1.0, χ_{02} = 1.5, χ_{CO2} = -0.5), t is the time (s), z is the length (m). Following Michaelis-Menten equation, the R_{CH4} can be expressed as,

$$R_{CH4} = \rho_b V_{\max} / \left\{ \left(1 + \frac{K_{m,CH4}}{C_{CH4}}\right)\left(1 + \frac{K_{m,O2}}{C_{O2}}\right) \right\} \quad (4)$$

where V_{max} is the maximum methane oxidation rate (mol g^{-1} s^{-1}), $K_{m,CH4}$ and $K_{m,O2}$ are the half-saturation constants of CH_4 and O_2 (mol m^{-3}), respectively. In this study, V_{max} = 750x10^{-12}、$K_{m,CH4}$ = 0.29、$K_{m,O2}$ = 0.49 were used based on de Visscher and van Cleepmut (2003).

When thermal conduction process is considered as a heat transport mechanism, the governing equation for heat transport can be expressed as,

$$C_v \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2} \quad (5)$$

where C_v is the volumetric heat capacity (J m^{-3}, K^{-1}) and T is the soil temperature (K). The C_v value can be estimated from specific heat and volumetric ratio of each solid, liquid, and air phase. The temperature dependency on D_p is considered as $D_{0,T(K)}/D_{0,293(K)} = (T/293)^{1.67}$ ($D_{0,T(K)}$, m^2 s^{-1}: gas diffusion coefficient in free air at T (K), $D_{0,293(K)}$, m^2 s^{-1}: gas diffusion coefficient in free air at 293 (K)).

4.2. Model Domain and Parameters for Numerical Simulations

Figure 3 shows the model domain for the numerical simulations. The thickness of the landfill final cover was set as 1 m. For CH_4 movement, a constant flux boundary of 1.2x10^{-5} (mol m^{-2} s^{-1}) was applied at the bottom boundary based on the field measurements of methane emission flux at the landfill site where the soil samples were taken in this study. In addition, to express the exothermal reactions in the waste layer, the heat rate, P(t) (W m^{-2}), was applied as P(t) = 200exp(-t/10^6) based on Klein et al. (2003).

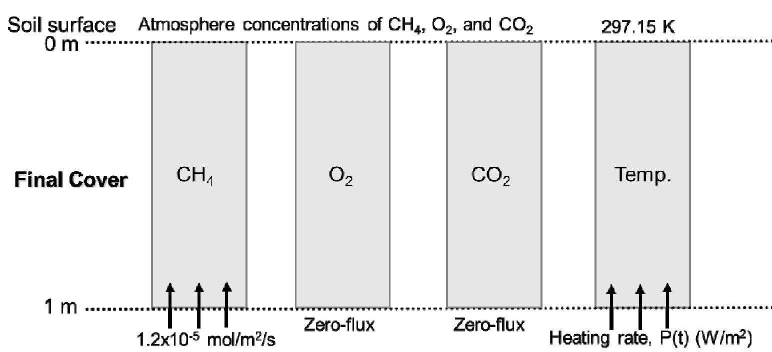

Figure 3 Model domain and boundary conditions for numerical simulations.

Numerical simulations were performed against two model cases: landfill cover soils at extreme compaction (ρ_b = 1.85) and loose compaction (ρ_b = 1.44) levels. The moisture condition for each model case was assumed as a field moisture condition represented by θ at soil-water matric potential of -100 cm H_2O. The total porosity, soil-air content, volumetric water content at field moisture condition for each model case were obtained by separate measurements using repacked soil cores in a laboratory. In addition, based on the obtained soil physical properties, volumetric heat capacity (C_v) and D_p and λ were estimated by Eqs. (1) and (2), respectively. Table 1 shows the parameter values used in the numerical simulations. The COMSOL Multiphysics Ver. 3.5a was used for solving gas and heat transport in the landfill cover soils.

Table 1 Parameter values used in the numerical simulations.

Bulk density	Total porosity	Soil-air content	Soil-water content	Soil heat capacity	Gas diffusivity	Thermal conductivity
ρ_b	ϕ_{sat}	ε	θ	C_v	D_p/D_0	λ
g/cm^3	m^3/m^3	m^3/m^3	m^3/m^3	$J/m^3/K$		$W\ m^{-1}\ K^{-1}$
1.44	0.46	0.363	0.10	2.27E+06	1.35E-02	1.46
1.85	0.30	0.041	0.26	3.51E+06	5.91E-04	3.24

4.3. Numerical Simulation Results

Figure 4a shows changes of soil temperature with time in the landfill cover soils at ρ_b = 1.85 and 1.44. For the extremely-compacted cover soil, soil temperature increased up to 60 ^oC after 5 days at bottom boundary (at the interface between waste layer and cover soil), while for loosely-compacted cover soil, increased up to 90 ^oC. Furthermore, soil temperature reach equilibrium with atmospheric temperature after 60 days for the extremely-compacted cover soil but longer time period was needed for the loosely-compacted cover soil. The finding suggests that the extremely-compacted cover soil has higher heat exchange ability since the extreme soil compaction increases contact number of soil particles, giving higher λ value (Table 1). Figure 4b shows changes of methane concentration profile with time in the landfill cover soils at ρ_b = 1.85 and 1.44. After 120 days, extremely-compacted cover soil exhibited around 90% of CH_4 at the bottom boundary, while CH_4 concentration rapidly decreased nearby soil surface due to a methane oxidation effect. The CH_4 concentration for the loosely-compacted cover soil increased up to only 30% and more marked effect of methane oxidation was observed. Since at field moisture condition, the extremely-compacted cover soil has higher water retention, soil-air content is lower as compared to loosely-compacted cover soil, giving lower D_p (Table 1). Hence, lower gas diffusion characteristics for extremely-compacted soil caused higher CH_4 concentration and lower methane oxidation effect as compared to the loosely-compacted soil.

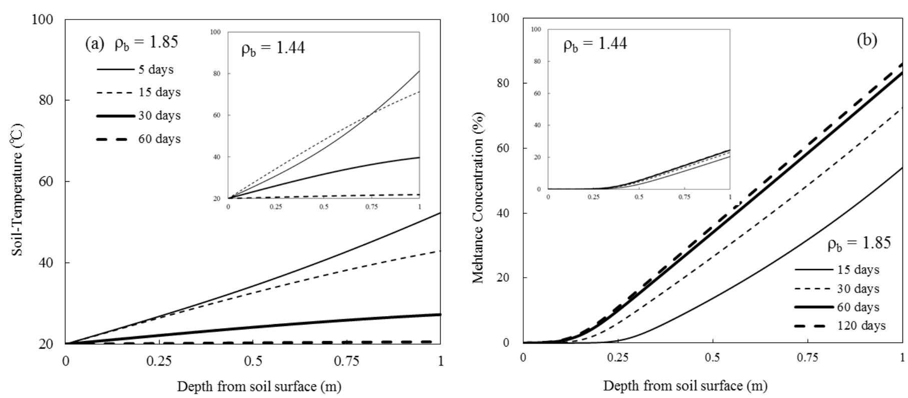

Figure 4 (a) Soil temperature profile and (b) methane concentration in the landfill cover soils at two different compaction levels.

CH_4 and CO_2 emission fluxes to the atmosphere were calculated for cover soils with different thickness and compaction levels shown in Fig. 5. The CO_2 emission flux was higher as compared to the CH_4 emission flux due to methane oxidation near soil surface. In addition, with increasing thickness of the cover soil, CO_2 and CH_4 emission fluxes increased and decreased, respectively. Higher methane oxidation ability for the loosely-compacted soil (Fig. 4b) caused higher CO_2 and lower CH_4 emission fluxes as compared to those for extremely-compacted cover soil. The numerical simulation results suggest that landfill cover soils with extreme compaction may contribute to global warming due to its high CH_4 emission ability since CH_4 has 20 times higher global warming potential than CO_2. In addition, when the thickness of the landfill cover is less than 50 cm, the CH_4 emission flux rapidly increased, indicating methane oxidation is not effective for cover soils with very thin thickness, enhancing the CH_4 emission.

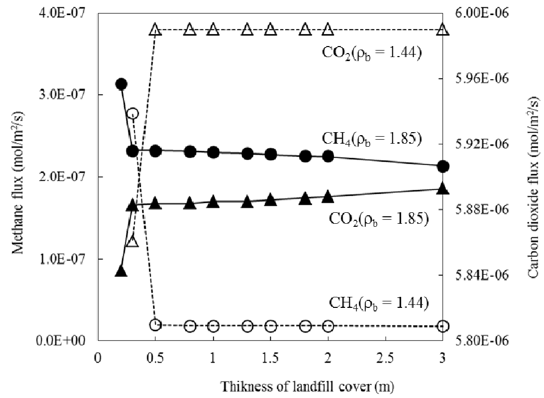

Figure 5 Methane and carbon dioxide flux to the atmosphere from the landfill cover soils at two different compaction levels and different thickness.

5. CONCLUSIONS

Using a developed unified predictive model for gas diffusivity and thermal conductivity, gas and heat transport in landfill cover soils at different compaction levels were simulated. Higher compaction enhances heat exchange through landfill cover soil, possibly contributing rapid site stabilization in the landfill site. On the other hand, lower gas diffusion characteristic in the highly-compacted cover soils decreased gas diffusivity, hereunder causing enhancement of CH_4 emission flux to the atmosphere due to ineffective methane oxidation ability. The methane oxidation ability is also highly affected by the thickness of the landfill cover. In perspective, more accurate simulations to represent more complex gas and heat transport such as heat-induced density-driven gas flow and further model developments for biological kinetic parameters to evaluate methane oxidation rate are needed to reduce and control greenhouse and toxic gas emissions from the landfill site and more rapid site stabilization.

6. ACKNOWLEDGMENTS

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