Gas Transport and Thermal properties of Compost-Mixed Landfill Cover Soils under Variable Water Saturation

（不飽和条件下のコンポスト混合処分場覆土のガス移動及び熱特性の評価）

2016 年 3 月

埼玉大学大学院理工学研究科（博士後期課程）

理工学専攻（主指導教員　川本　健）

EKANAYAKA ACHCHILLAGE AYESHA DILRUKSHI

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A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at

Graduate School of Science and Engineering,

SAITAMA UNIVERSITY

by

Ekanayaka Achchillage Ayesha Dilrukshi

Approved by

Prof. Ken Kawamoto, Academic Supervisor and Committee Chairman

Prof. Norio Tanaka, Committee member

Associate Prof. Masahiko Osada, Committee member

Associate Prof. Shingo Asamoto, Committee member

March 2016

ACKNOWLEDGEMENTS

First and foremost, I wish to express my sincere gratitude to my academic supervisor Professor Ken Kawamoto, whose guidance and support from the preliminary to the concluding level enabled me to develop an understanding of the subject. I am very much honored to be his doctoral student.

I owe my sincere gratitude to Professor Toshiko Komatsu, for her continues guidance, encouragement, indispensable support and appropriate suggestions throughout my study.

It is a great honor for me to be supervised by Professor Per Moldrup, whom I really admire for his intelligence and wisdom.

I am heartily grateful to Assistant Professor Takeshi Saito, for his continues guidance, encouragement, kindness and understanding. He played the role of a caring friend instead of his profession, whom I can never forget.

I am deeply grateful to the Japanese Ministry of Education, Culture, Sports, Science, and Technology for providing me the scholarship to carry out my study.

Special note of appreciation must go to Mr. Akiyoshi Yoshida, a former undergraduate student of Saitama University, for his careful and dedicated laboratory work with me.

I am thankful to all my friends in my lab and all our members of the Soil Mechanics Laboratory for their generous support for me.

Finally, to my ever loving husband Isura Nagahage for his dedications, love, understanding and enormous support to continue my higher studies. Without his encouragement, I would not start my higher studies. I always remind my mother and father and their courage. I wish my family good health and God`s blessings. I dedicate this work to my adorable son, Arunalu, whose came with me after 21days of his birth. He was the only controlling factor to decide whether I come to Japan or not. Thanks to Prof. Deepal Weerakon, consultant obstetrician & gynaecologist, Durdans hospital, Colombo and careful investigation of Peadiatrician Dr. Mrs. S. Panditharathne, it was possible with more care.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
GENERAL INTRODUCTION

Landfill gases (LFGs) such as methane (CH_4) and carbon dioxide (CO_2) are produced by microbial degradation of the biodegradable organic materials in the waste under anaerobic conditions. The main components of LFG emissions include 55-60% v/v of CH_4 and 40-45% v/v CO_2 (Scheutz et al., 2009). This process to be continued several decades until the majority of organic materials in the waste sector have been degraded. Both CH_4 and CO_2 are classified as green house gases (GHGs) and CH_4 is considered as a large potential contributor to climate change with a global warming potential of (GWP_{100}) of 25 (IPCC 2007). Chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) known as non-methane organic compounds are also classified as GHGs that are emitted with trace quantities. Further, LFGs contain numerous volatile organic compounds (VOCs) including halogenetaed and aromatic hydrocarbons, sulfur and oxygen (O_2)-containing compounds (Rettenberger and Stegmann, 1996, Allen et al., 1997)

Emission of LFGs increase risk to human health (VOCs), contribute to global warming (GHGs) and depletion of ozone layer (non-methane organic compounds). It has been demonstrated that, properly designed landfill cover materials can mitigate CH_4 emissions as well as degrade wide range of VOCs including halogenated hydrocarbons and aromatics (Kjeldsen et al., 1997, Scheutz and Kjeldsen 2005 and Scheutz et al., 2009)
USEPA reported that, landfills are the third largest source of anthropogenic CH_4 (USEPA 2012) and the world wide contribution as a source of anthropogenic CH_4 emission by the waste sector is about 18% of the global anthropogenic CH_4 emission (Bogner et al., 2007) mainly due to inadequate gas collection systems, uncontrolled emissions from old dumps and unauthorized open dumping. Due to the environmental concern, implementation of LFG extraction system has been became as a mandatory requirement for new waste disposal sites (Scheutz et al., 2009). However, it is not technically and economically feasible for the old or abandoned landfills. Thus, researchers have focused on the low-cost technologies such as landfill cover systems to mitigate emissions of LFGs.

Biocovers and biofilters, which are considered as biologically active landfill covers can mitigate the emissions of landfill gases such as methane and volatilized organic compounds from solid waste landfills (Stein and Hettiaratchi, 2000; Humer and Lechner, 2001a; Barlaz et al., 2004; Stern et al., 2007; Pawlowska and Pawlowski, 2008; Pedersen et al., 2011; Kjeldsene and Scheutz, 2014). Those bio-mitigation systems have a large potential for adopting the landfills where the landfill gas utilization system cannot be implemented as cost-effective sustainable solutions (Pawlowska and Pawlowski, 2008; Kjeldsene and Scheutz, 2014). A group of bacteria known as methanotrophic bacteria available in the biologically active cover soils, can oxidize CH_4 during the transport of LFGs through the porous media. Composts (sewage sludge, garden waste and municipal solid waste (MSW) considered 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 (Humer and Lechner, 2001b; Kettunen et al., 2006). Due to rapid urbanization and increase in population, a significant amount of biodegradable waste such as food waste residue and yard waste is generating in urbanized areas of developing countries (Marmolejo, et al., 2012). In order to reduce waste amount sent to landfills, the compost production is frequently used in most of developing countries. Thus, the bio-mitigation to reduce methane emissions through biocovers by utilizing compost is an attractive as a cost-effective and easy-applicable method in developing countries.

Methane oxidation efficiency of a soil is regulated by the combination of physical and chemical properties of cover material, landfill gas source strength and climate (Gebert et al., 2010). Among of them, the most important factors which control CH_4 oxidation in soil have been identified as soil moisture content, temperature, and oxygen supply (Scheutz and Kjeldsen, 2004; Scheutz et al., 2009). Hence, it is crucial to investigate the material properties and environmental factors which influence the performance of the biocovers. Figure 1.1 shows the main physical, chemical and biological processes inside the landfill biocover.

Soil moisture is a critical parameter for the biocover performance, which regulates the gas movement, thermal conductivity as well as the favorable microclimate to sustain the microorganisms and perform their metabolic activities. When the soil`s degree of saturation (volume of water/volume of voids) reaches a value in the vicinity of 85%, the air-filled voids are no longer interconnected and the gases have to diffuse in the liquid phase (Cabral et al., 2004), limiting the CH_4 and O_2 gas movement and affecting the biocover performances. In contrary, inadequate moisture contents lead for the drying of media and affect the microbial community directly. Thus, it is important to provide optimum moisture content for the efficient performance of biocover by facilitating adequate gas penetration as well as thermal energy transport.

Temperature of the biocover is affect significantly for the biological processes. Thermal energy generated from the microbial activities such as methane oxidation, respiration and complex molecular degradation etc. The generated thermal energy due to the metabolic activities of the microbes as well as weather changes can be detrimental for the biocover performances. The excess of thermal energy may cause for the drying of the media. In contrast, during the wintertime, field biofilters need to be shut down during the due to the low temperatures (Venugopal et al., 2003). Chandrakanthi et al. 2012 pointed out that the importance of simulation of the thermal properties of biocover or biofilter based on the extreme temperature changes during the summer and winter times. They have mentioned that, to design and model heat tracing or insulation system for winter operations and to avoid high temperatures and drying in summer by means of moisture addition, accurate estimation of compost thermal properties is necessary.

Methanotrophic bacteria are obligate aerobes that can achieve optimum CH_4 conversion rates even at very low O_2 concentrations (Scheutz et al., 2009). In landfill cover soils, the O_2 penetration depth will often be the limiting factor for CH4 oxidation process, making soil composition, particle size, and porosity important controlling parameters.

Compost materials has been identified as a potential biomaterial for application as a cover material due to high moisture retention, enhanced porosity, and substrate for microorganisms for their growth and development. The main environmental factors govern the performances of landfill biocovers and compost materials shows specific characteristics, which are favorable for the bio-mitigation process. Moreover, the availability of compost as a low cost material is high in the rapid urbanizing areas where the considerable amount of biodegradable waste generated. Compost mixed with the soil enhances the engineered application of the material and it can be applied as final earthen cover for engineered landfill.

Considerable number of studies has been done to identify the performance of the biomaterial for methane oxidation under variable experimental conditions as batch and column experiments as well as in the field level. But, very limited studies have been done to investigate the material properties for gas, water and heat transport.

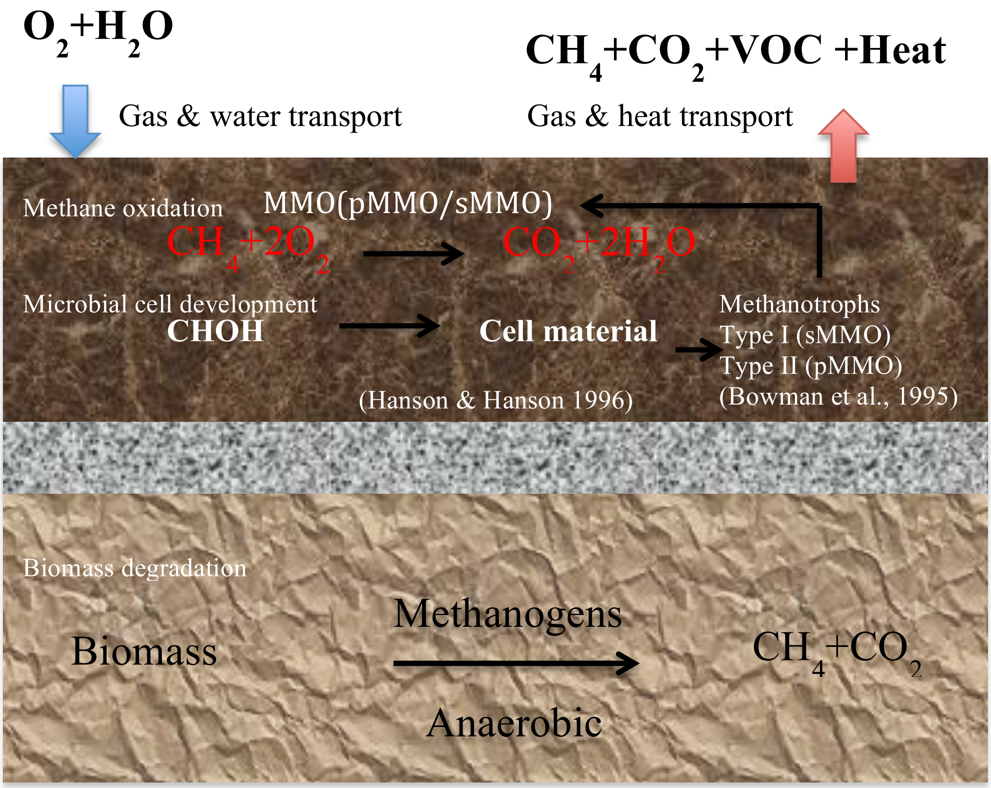

Fig. 1.1 Schematic illustration of main physical, chemical and biological processes inside the biocover

1.1 The scope and the objectives of the study

The general objectives of this study are (1) to investigate the effect of compost mixing with soil for enhancing methane oxidation, (2) to evaluate the gas transport and thermal properties of compost-mixed soils under variable water saturation, and (3) to develop suitable predictive models for assessment of gas transport and thermal properties of compost amended landfill covers.

The general structure of this study is illustrated in Fig. 1.2

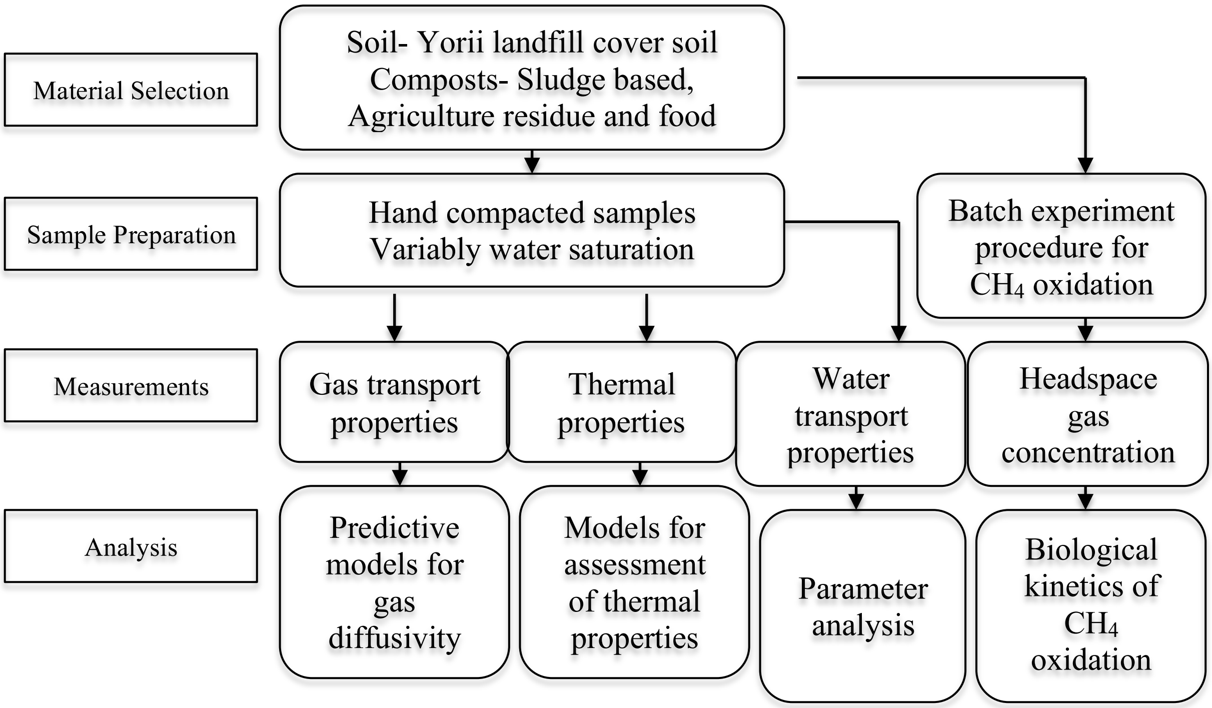

Fig. 1.2 Typical flow diagram of the general structure of this study

The general description of each chapter is as follows,

Chapter 1 (present chapter) gives an introduction about the significance of landfill gas emission, mitigation based on the biocover and potential application of compost-mixed landfill cover including motivation and general objectives of this study.

Chapter 2 presents the effect of soil-water content and soil-matric potential on the kinetics of methane oxidation for compost-mixed soils.

Chapter 3 evaluates the gas and heat transport properties of compost-mixed soils, where the effect of compost mixing for the gas diffusivity and thermal properties such as thermal conductivity and heat capacity was investigated under variable water saturation.

Chapter 4 presents a study on model performance of the predictive models for gas diffusivity and thermal properties. Based on the empirical relationships of thermal conductivity and heat capacity in chapter 3, predictive models for thermal properties were developed.

Chapter 5 is the summary, conclusions and perspectives of this study.

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CHAPTER 2
EFFECT OF SOIL-WATER CONTENT AND SOIL-MATRIC POTENTIAL ON THE KINETICS OF METHANE OXIDATION FOR COMPOST MIXED FINAL COVER SOILS

ABSTRACT

Compost amended capping geo-materials contribute to the reduction of methane emissions from the landfill sites. This study investigates the effect of soil-water content (WC) and soil-matric potential on kinetics of methane oxidation in compost amended landfill cover soil. Results showed that, the maximum CH_4 oxidation for compost 80(g/g, %) WC was 17.92 μg CH_4 g^{-1} DM h^{-1} while the maximum CH_4 oxidation of compost-soil mixture (1:10) 30 (g/g, %) WC and landfill cover soil 15 (g/g, %) WC) were 9.34 μg CH_4 g^{-1} DM h^{-1} and 2.44 μg CH_4 g^{-1} DM h^{-1} at elevated atmospheric methane concentration of around 8%. The biological reaction of selected samples could be well described by both first and zero order reaction kinetics. On the average, both zero and first order rates of a 1:10 (w/w) compost-soil mixture was around 3 times lower than for pure compost, suggesting that the mixing ratio of compost-soil may be improved for landfill final cover soil application.

2.1 Introduction

Emissions of Green House Gases (GHG) carbon dioxide, methane and nitrous oxide may potentially lead to significant regional and global climate shifts with inherent regional and global environmental problems (Wickramarachchi, et al., 2011). The main components of landfill gases (LFG) are methane (CH_4: 50-60% v/v) and carbon dioxide (CO_2: 40-45% v/v) (Scheutz et al., 2009). Methane in particular is a large potential contributor to climate change. The Global Warming Potential (GWP) of CH_4 is 25 times compared to the GWP of CO_2 over the 100 year horizon (IPCC, 2007). CH_4 has a short atmospheric life time of only 12 years, and therefore the GWP of CH_4 over 20 year time horizon is 72 (Hettiarachchi et al., 2011). Worldwide, the CH_4 emission from the waste sector is about 18% of the global anthropogenic CH_4 emission (Bogner et al., 2007). The estimated landfill CH_4 emission to the atmosphere is ranged between 35 and 69 Tg $year^{-1}$ out of an estimated annual global emission of approximately 600 Tg $year^{-1}$ (Denman et al.; 2007, Bogner et al.; 2007, Scheutz et al., 2009).

Even though, LFG extraction and utilization plants are viable options for new waste disposal sites, most of the researches have been focused increasingly on development of low-cost technologies that limit LFG release from existing landfills where gas collection system has not been implemented and not economically feasible.

Laboratory experimental setups including batch and column experiments are being focused the different fundamental processes, which are controlling CH_4 oxidation in engineered landfill settings. Furthermore, it is evidence that organic-rich materials enhance the methane oxidation. Field and laboratory investigations confirmed that amendment of organic-rich materials into landfill final cover is a reliable low-cost migratory measure for methane oxidation. Properly designed landfill cover materials can degrade a wide range of volatile organic compounds including halogenated hydrocarbons and aromatics. (Scheutz & Kjeldsen 2005, Scheutz et al., 2009) and hydrogen sulfide (Chung et al., 2001).
Numbers of environmental factors affect the CH_4 oxidation: such as soil moisture, temperature, soil texture, CH_4 and O_2 supply, Nutrients etc.

The primary objective of this study was to investigate the effect of gravimetric water content (WC) and soil-matric potential for the kinetics of methanotrophic methane oxidation on final cover soils.

2.2 Materials and Methods

Landfill cover soil was collected from an existing landfill site (Yorii landfill, Saitama prefecture, Japan). Quality controlled compost samples were collected from a local supplier. Air-dried landfill cover soil was sieved through a 2mm mesh and ASTM standards were used for the soil analysis. Compost laboratory sample preparation and analysis done based on the Test Methods for the Examination of Composting and Compost (TMECC) (Thompson et al., 2002), which were developed by US Department of Agriculture (USDA) and the Composting Council Research and Education Foundation (CCREF). Table 1 shows the measured physical and chemical properties of landfill cover soil and selected compost material.

Table 2.1 Basic physical and chemical properties of soil and compost

Materials	Composition	Soil texture	Particle density gcm^{-3}	LOI %	pH	EC $mScm^{-1}$	N %	P %	K %	C/N
Landfill Cover Soil	Gravel (>4.75 mm)[a] = 36% Sand (4.75-0.075 mm)[a] = 42% Silt (0.075-0.005 mm)[a] =13% Clay (<0.005 mm)[a] =9%	Silty sand[b]	2.66	2.1	5.6	0.27	-	-	-	4.0
Compost (Adnis)	Rice Husk, Coffee Residue, Soya been fibers	Particle size (4.75-2.00mm)	1.60	64.6	7.2	8	3.5	1.5	2.4	7.0

[a] Classification by the ASTM: D422-63(2007)

[b] Unified Soil Classification System (USCS)

2.2.1 Batch Experimental Procedure

Yorii landfill cover soil and compost (crop residue compost) were used as the material for preparing three different sample types for batch experimental procedure. The prepared samples were landfill cover soil, compost and compost-soil mixture. Compost-soil mixture was prepared by mixing compost and landfill cover soil by 1:10 mixing ratio based on their dry weight. Samples with different gravimetric water contents WC (g/g, %) which is the ratio of the mass of water and the mass of solids, were obtained by the moisture adjustment using distilled water. Moisture adjusted samples were kept for 24 hours in closed plastic bags to equilibrate and gravimetric water content was verified by testing moisture content of each samples. Batch experiments were performed with 250 mL glass bottles by adding 10g (dry weight) of moisture adjusted samples. The bottle was tightly sealed after adding the sample to make it airtight and rubber septum was used which enabled the gas sampling from headspace by a gas tight syringe (Figure 1).

Gravimetric water contents of water adjusted landfill cover soil samples were 11 and 15 (g/g, %). And gravimetric water contents of compost were 60, 80 and 103 (g/g, %) with 4.67, 4.54 and 4.45 corresponding soil-matric potential values, pF (= log |Ψ|; Ψ in cm H_2O)**.** The measured soil-water potential values for similar samples were -4.52, -3.36 and -2.71 MPa. The measured gravimetric water content of compost-soil mixture was 3, 8,30 and 40 (g/g, %). The corresponding metric potential and water potential values were 5.23, 4.31, 3.68, 3.50 and -16.32, -2.00, -0.46, -0.30 MPa respectively. After adjusting the gravimetric water content, 10g (dry weight basis) of materials were added from each and air tight it. After sealing the batch experimental setup, 20 mL of air from the headspace was withdrawn using a syringe and replace with 20 mL of CH_4 gas (99% purity). It resulted approximately 8% CH_4 (v/v, %) and 18% O_2 (v/v, %) of gas composition of the bottles headspace. The pressure inside the bottle was atmospheric pressure and incubated temperature was 30 °C. Headspace gas concentrations for CH_4, CO_2, O_2 and N_2 were analyzed at regular time intervals. Similar batch experimental setup was prepared without CH_4 injection to analyze the respiration rate of the microbial community. Similarly headspace gas concentration for CO_2 and O_2 was analyzed with regular time intervals.

2.2.2 Headspace Gas Analysis

Headspace gas concentration for CH_4, CO_2, O_2 and N_2 was analyzed by withdrawing 500 μL samples using a gas tight syringe and injected manually into inlet gas chromatograph (Shimadzu GC-2014, equipped with thermal conductivity detector (TCD) and flame ionization detector (FID)). The carrier gas was helium at 20 mL/min, and detector, injector port and the column temperatures were 170, 105 and 80 °C respectively.

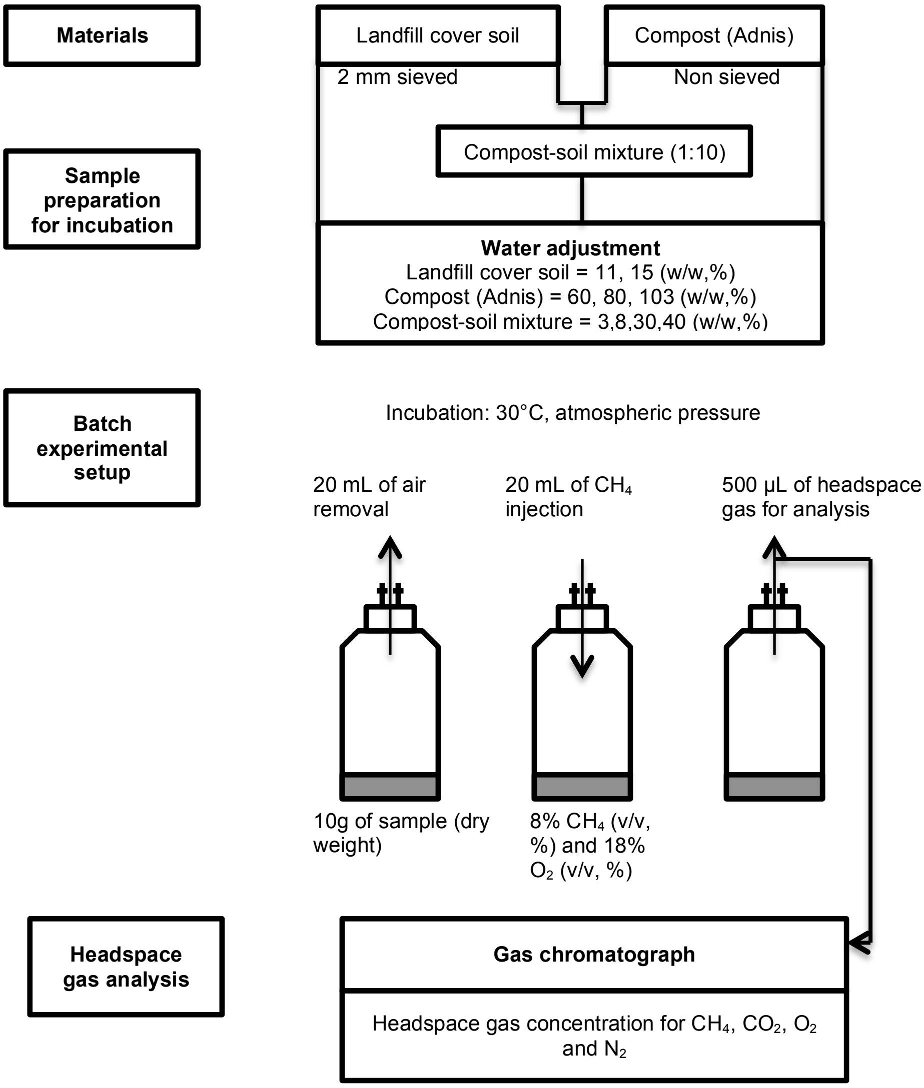

Fig. 2.1 Schematic diagram of batch experimental process

2.3 Results and Discussion

1.1.1 Moisture Effect on Biological Kinetics of Methane Oxidation

Moisture is an essential factor for microorganisms to sustain their activity as it is the transport medium for nutrient supply and also for removal of residual metabolic compounds (Scheutz et al., 2009). When the soil`s degree of saturation (volume of water/ volume of voids) reaches a value in the vicinity of 85%, the air-filled voids are no longer interconnected and gases have to diffuse in the liquid phase (Cabral et al., 2004), drastically reducing the availability of CH_4 and O_2 by limiting CH_4 oxidation. In contrast, decrease in moisture content results low CH_4 oxidation due to water stress of microbes.

Figure 2 shows the available moisture retain on selected materials for the utilization of microbial community at different gravimetric water content. Pure compost shows comparatively high moisture retention at higher gravimetric water contents.

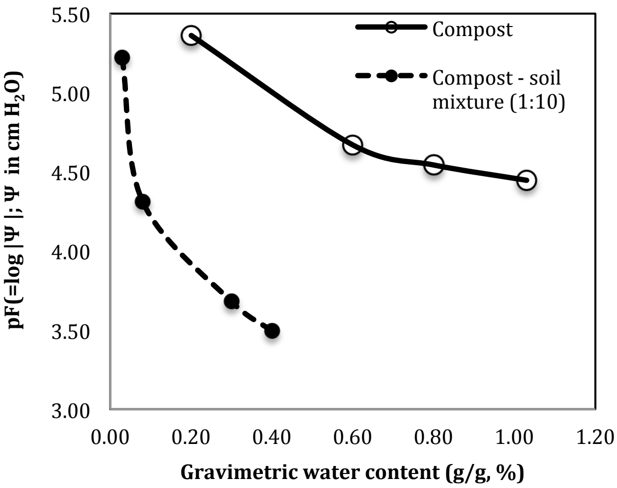

Fig. 2.2 Soil-water retention curves of the selected materials

2.3.1 Biological Kinetics Of Methane Oxidation

Biological kinetics of methane oxidation can be explained by the zero order and first order reaction kinetics. The changes of the CH_4 concentration over the incubation time period can be explained by the zero order kinetics reaction (Equation 2.1). The linear relationship of the first order kinetics can be explained by the equation 2.2.

$$[CH_4]_0 - [CH_4] = -k_0 t \quad [2.1]$$

$$ln \frac{[CH_4]}{[CH_4]_0} = -k_1 t \quad [2.2]$$

Where, $[CH_4]_0$ is the initial CH_4 concentration ($\%CH_4$), $[CH_4]$ is the final CH_4 concentration ($\%CH_4$) of a particular incubation period, t is the incubated time period (h), k_0 and k_1 are the zero-order reaction rate constant ($\%CH_4h^{-1}$) and first-order reaction rate constant (h^{-1}).

Batch experimental results suggested that, biological kinetics of methane oxidation of pure compost, compost-soil mixture and landfill cover soil can be explained by the zero order and first order kinetics (Table 2). The zero order and first order reaction constants of pure compost are approximately 3 times higher than the compost-soil mixture (1:10) and both reaction kinetics constants of landfill cover soil are similar as the very dry sample [WC=3 (g/g,%)] of compost –soil mixture.

Moreover, when considering the landfill cover soil with 15 (g/g, %) WC and compost-soil mixture (1:10) with 8 (g/g, %) WC, it confirmed that the water holding capacity by the small fraction of compost has improved the CH_4 oxidation ability.

2.3.2 CH_4 Oxidation Rate of Pure Compost, Compost-Soil Mixture and Landfill Cover Soil

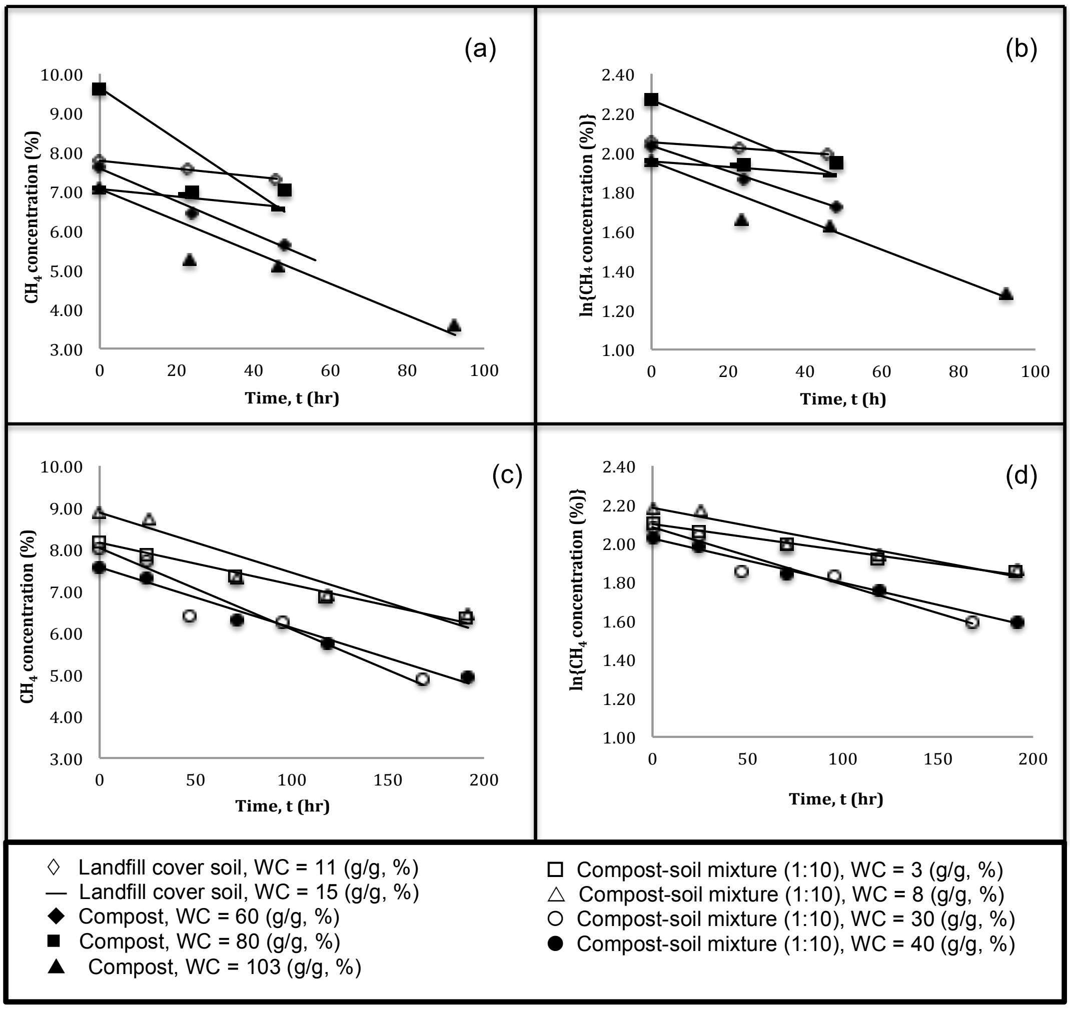

Fig. 2.3 Measured CH_4 concentrations as a function of time for different moisture adjusted samples; (a) CH_4 and (b) ln(CH_4)concentration of landfill cover soil and compost. (c) CH_4 and (d) ln(CH_4) concentration of compost-soil mixture (1:10)

Table 2.2 Zero order and first order rate constant values for landfill cover soil, compost and compost-soil mixture with corresponding R^2 values

Material	Water content, WC (g/g, %)	Soil-water potential, Ψ (MPa)	pF (= log |Ψ|; Ψ in cm H_2O)	k_0 ($\%CH_4h^{-1}$)	k_1 (h^{-1})	Incubated time interval (h)
Landfill	11	-	-	0.0100 (0.99)[a]	0.0013(0.99)[a]	0-50
cover soil	15	-	-	0.0096 (0.92)[a]	0.0014(0.92)[a]	0-50
Compost	60	-4.52	4.67	0.0432 (0.99)[a]	0.0065(0.99)[a]	0-50
(Adnis)	80	-3.36	4.54	0.0657 (0.68)[a]	0.0080 (0.68)[a]	0-50
	103	-2.71	4.45	0.0402(0.86)[a]	0.0075(0.93)[a]	0-95
Compost-	3	-16.32	5.23	0.0101 (0.98)[a]	0.0014 (0.99)[a]	0-190
soil	8	-2.00	4.31	0.0144 (0.90)[a]	0.0019 (0.92)[a]	0-190
Mixture	30	-0.46	3.68	0.0195(0.91)[a]	0.0030 (0.92)[a]	0-170
(1:10)	40	-0.30	3.50	0.0145(0.98)[a]	0.0023 (0.99)[a]	0-190

[a] R^2 values

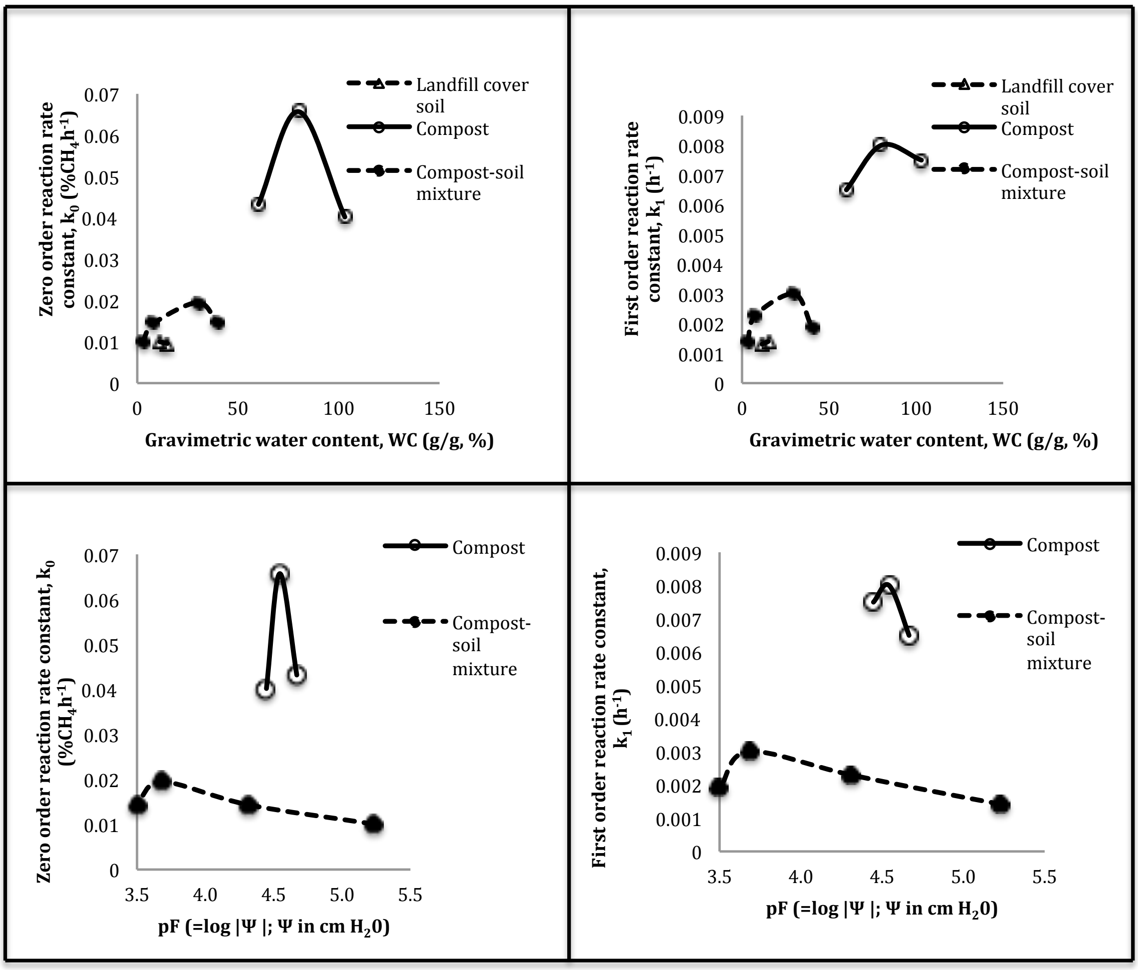

Fig. 2.4 Zero order and first order reaction constant of pure compost, compost-soil mixture and landfill cover soil with gravimetric water content

The maximum CH_4 oxidation was calculated using the ideal gas law (PV=nRT; P= pressure of the gas (Nm^{-2}), V is the volume of the gas (m^3), n is the amount of substance of gas/ number of moles (mol), R is the ideal or universal gas constant (8.314$Jmol^{-1}K^{-1}$), T is the temperature of gas). The biological kinetics of CH_4 was investigated at 30 °C temperature and the pressure of the batch experimental setup was maintained at atmospheric pressure.

Crop residue compost (64.63% organic matter) showed 17.92 µg CH_4 g^{-1} DM h^{-1} maximum CH_4 oxidation at 80 (g/g,%) WC while compost-soil mixture had 9.34 µg CH_4 g^{-1} DM h^{-1} of oxidation at 30 (g/g, %) WC and maximum CH_4 oxidation of landfill cover soil showed 2.44 µg CH_4 g^{-1} DM h^{-1} at 15 (g/g, %) WC at elevated atmospheric CH_4 concentration of around 8%.

Table 2.3 Summary of maximum methane oxidation rates for landfill cover soils obtained from batch studies

Reference	Soil texture/ material	Content of organic matter (% w/dw)	Maximum oxidation rate ($\mu g\ CH_4\ DM\ g^{-1}\ h^{-1}$)	Initial CH_4 concentration (% v/v)	Investigated temperature range (°C)	Optimum temperature (°C)	Investigated soil moisture range (% w/dw)	Optimum soil moisture content (% w/dw)
Hilger et al. (2000)	Sandy loam	1.5	2.4	8	22		15	
Figueroa (1993)	Humic soil	7.2	86.4	10	20		0-50	21
	Till	4.4	40	10	10-40	30	0-23	12
	Biowaste compost	31.6	128	10	20			
Bender & Conrad (1994)	Loamy clay		0.0096	5		25		22
Börjesson et al. (2004)	Sandy loam[a]	25.3	18.8	5	3-20	≥20	66.1	n.m.
Börjesson et al. (2004)	Sandy loam[a]	7.5	25.2	5	3-20	≥20	33.5	n.m.
Börjesson et al. (1997)	Silty loam[a]	22-30	173	5	2-37	31	22-108	61
Einola et al. (2007)	5-year-old compost cover	7.3	2.5	8-9	1-19	19	7-34	21-28

Mor et al., 2006	Kitchen & garden waste (GFT1 & GFT2)	39.1 42.9		5	7-40	22		
	Garden waste compost (G1, G2 & G3)	31.1 38.2 52.1	135.72 104.54				29-110 34-110	85 110
This study	Landfill cover soil (silty	2.1	2.44	8	30		11-15	15
	sand)	64.63	17.92	8	30		60-103	80
	Crop residue compost		9.34	8	30		3-40	30
	Crop residue compost-silty sand							

The maximum CH_4 oxidation is highly heterogeneous based on the different factors, which governs the oxidation process. It is a combination of optimum condition of all above considered factors (Table 3). In this study, even though the organic matter content of the used compost material was very high, it had low CH_4 oxidation rate. The effect of inorganic nitrogen on CH_4 oxidation is very complex and can be both stimulatory and inhibitive (De Visscher and Van Cleemput, 2003, Mor et al., 2006). Influence of ammonium and chloride on CH_4 oxidation by soils is time dependent. Time dependence of the influence of temperature and moisture on CH_4 oxidation has never been studied systematically (Mor et al., 2006). However, Scheutz et al., 2008, was suggested that the best CH_4 uptake belongs to well decomposed (mature), fairly uniform and coarsely structured compost materials, which has low C/N ratios and low ammonium concentrations.

2.4 Conclusion

The biological reaction of methane oxidation in compost, compost-soil mixture, and landfill cover soil at elevated atmospheric methane concentrations of 8% CH_4 could be well described by both first and zero order reaction kinetics. Maximum methane oxidation rates were obtained at around 80 (g/g,%) WC for pure compost and at around 30 (g/g, %) WC for a soil-compost mixture, in both cases showing a significant influence of water status and thus of the diffusion processes in the water and gas phases. The maximum oxidation rate of pure compost was around twice that of a compost-soil mixture. On the average, both zero and first order rates of a 1:10 (w/w) compost-soil mixture was around 3 times lower than for pure compost, suggesting that the mixing ratio of compost-soil may be improved for landfill final cover soil application.

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CHAPTER 3
GAS AND HEAT TRANSPORT PROPERTIES OF COMPOST-MIXED SOILS

ABSTRACT

Gas and heat transport through compost-mixed landfill cover soils affect the fate and 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). 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 ($\varepsilon_{\mathrm{th}}$) 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.

3.1 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 (Stein and Hettiaratchi, 2000; Humer and Lechner, 2001a; Barlaz et al., 2004; Stern et al., 2007; Pawlowska and Pawlowski, 2008; Pedersen et al., 2011; Scheutz et al., 2014). 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 (Pawlowska and Pawlowski, 2008; Scheutz et al., 2014).

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 (Humer and Lechner, 2001b; Kettunen et al., 2006). 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 (Marmolejo, et al., 2012). 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 (Stein and Hettiaratchi, 2000; Börjesson et al., 2001; Scheutz et al., 2009; Sadasivam and Reddy, 2014). Among them, the most important factors that control CH_4 oxidation in soil have been identified as soil moisture content, temperature, and oxygen supply (Scheutz and Kjeldsen, 2004; Scheutz et al., 2009). Hettiarachchi et al. (2011), for example, investigated the effects of several environmental factors on CH_4 oxidation by using a pilot-scale field methane biofiltration system, and a three-dimensional numerical simulation incorporating advection-diffusive flow of gas, biological reactions and heat and moisture flow was developed to understand the performance of the biofiltration system. They used numerical model simulations of CH_4 oxidation efficiencies under various operating conditions, and indicated that the long-term performance of a methane biofiltration system is highly dependent on 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) 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) 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) 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 full 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.

3.2 Materials and Methods

3.1.1 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) (Thompson et al., 2001) 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).

Table 3.1 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

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 (Hernàndez-Apaolaza et al., 2005; Yang, 2005; Bajawa, 2012). 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). 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%).

3.1.2 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 compacted into 100-cm^3 cores with a diameter of 5.1-cm and a height of 4.1-cm by hand. Compacted 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. 3.1.

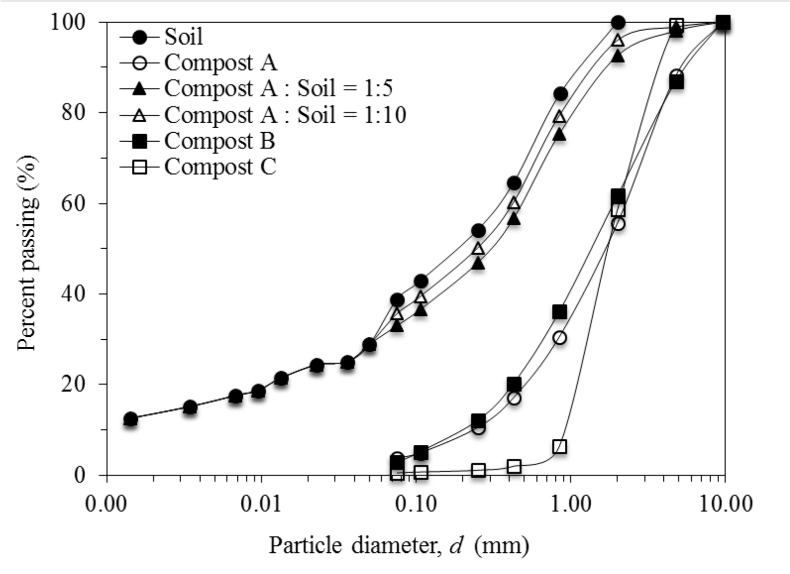

Fig. 3.1Particle size distribution of tested materials.

After being compacted into 100-cm^3 cores, the compacted 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* |ψ| (-ψ, 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 and 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.

3.1.3 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 (Rolston and Moldrup, 2002). 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 (Decagon Devices, 2012).

3.1.4 Models for Water Retention, Gas and Heat Tranport Parameters

Water Retention Curve

The widely used Brooks-Corey (BC, 1964) 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):

$$S_e = \left(\frac{\psi_b}{\psi}\right)^{\lambda'} \qquad [3.1a]$$

$$S_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \qquad [3.1b]$$

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).

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 (Moldrup et al., 2005) considering a threshold air-filled content (inactive pore space), ε_{th} (cm^3 cm^{-3}), was used in this study. The PC model is:

$$\frac{D_p}{D_0} = C(\varepsilon - \varepsilon_{th}) \qquad \text{if } \varepsilon \geq \varepsilon_{th} \qquad [3.2a]$$

$$\frac{D_p}{D_0} = 0 \qquad \text{if } \varepsilon < \varepsilon_{th} \qquad [3.2b]$$

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 (Troeh et al., 1982). The C and ε_{th} values were obtained by fitting the PC model directly to measured data.

Thermal Conductivity and Heat Capacity

Analogous with 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:

$$\lambda = C'\theta + \lambda_0 \qquad [3.3]$$

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' values were obtained by fitting Eq. [3.3] to measured data.

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

$$HC = C''\theta + HC_0 \qquad [3.4]$$

where HC_0 (MJ m^{-3} K^{-1}) is the heat capacity under the dry condition (where $\theta = 0$). The C'' values were obtained by fitting Eq. [3.4] to measured data.

3.2 Results and Discussion

3.2.1 Water Retention Characteristics

Measured water retention data for tested materials are shown in Fig. 3.2. In the figures, curves fitted by the Brooks-Corey (BC) water retention model (Eqs. [3.1a] and [3.1b]) were also depicted, and fitted BC parameters, λ' and ψ_b, are summarized in Table 3.2. The mixing of compost into soil normally increases saturated volumetric water contents (θ_s) which was plotted at pF = -1 (ψ = -0.1 cm H_2O) in Fig. 3.2. 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 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 3.2). 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.

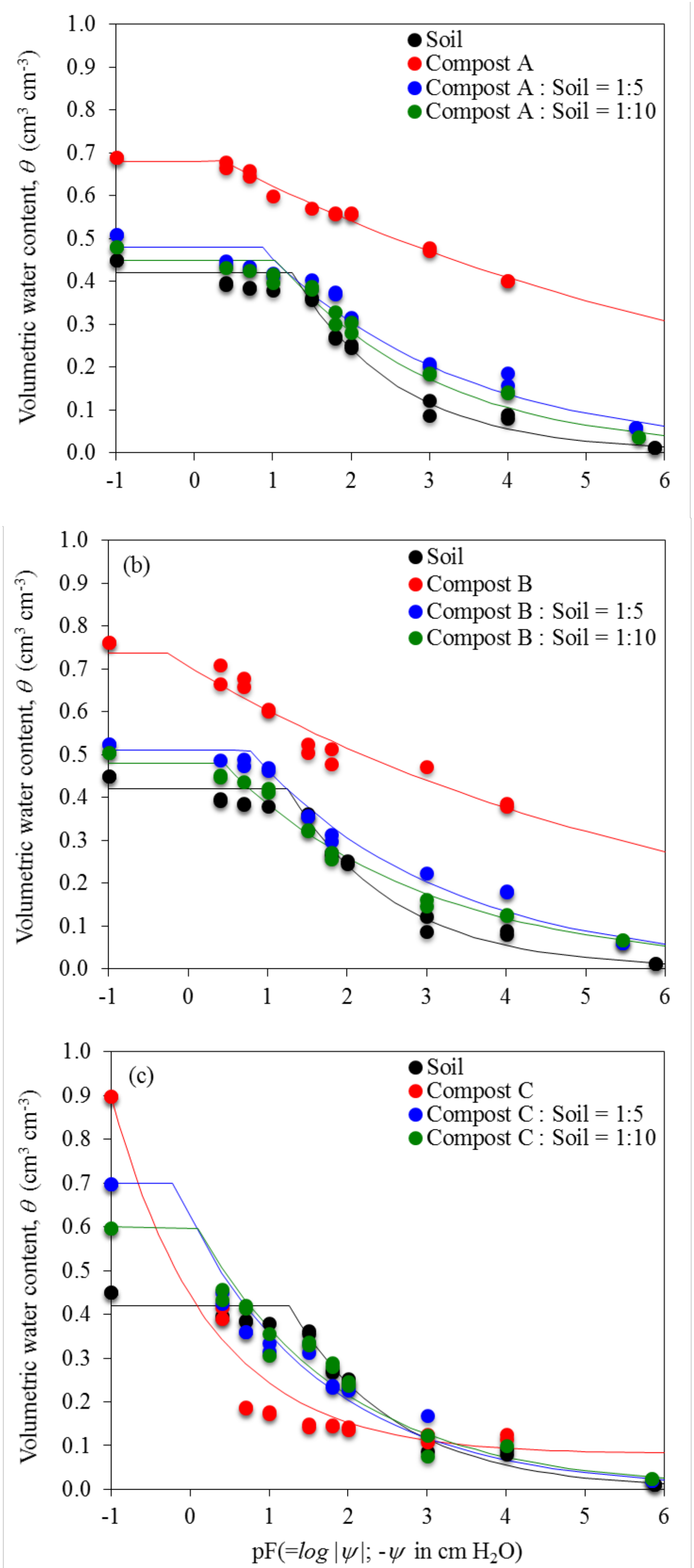

Fig. 3.2 Measured water retention curves for tested materials. Fitted curves of the Brooks-Corey (BC) water retention model were also depicted. Saturated volumetric water contents (θ_s) were plotted at pF = -1 (ψ = -0.1 cm H_2O).

3.2.2 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. 3.3. The Penman-Call (PC) linear model (Eqs. [3.2a] and [3.2b]) was fitted to the data and is depicted in the figures. Fitted slope C and the ε_{th} values are tabulated in Table 3.2. 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. 3.3a), 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. 3.3b and 3.3c), 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) 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) 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 3.2. 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 3.1). 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 that did not contribute to internal gas diffusion were created inside, 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 3.1). 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.

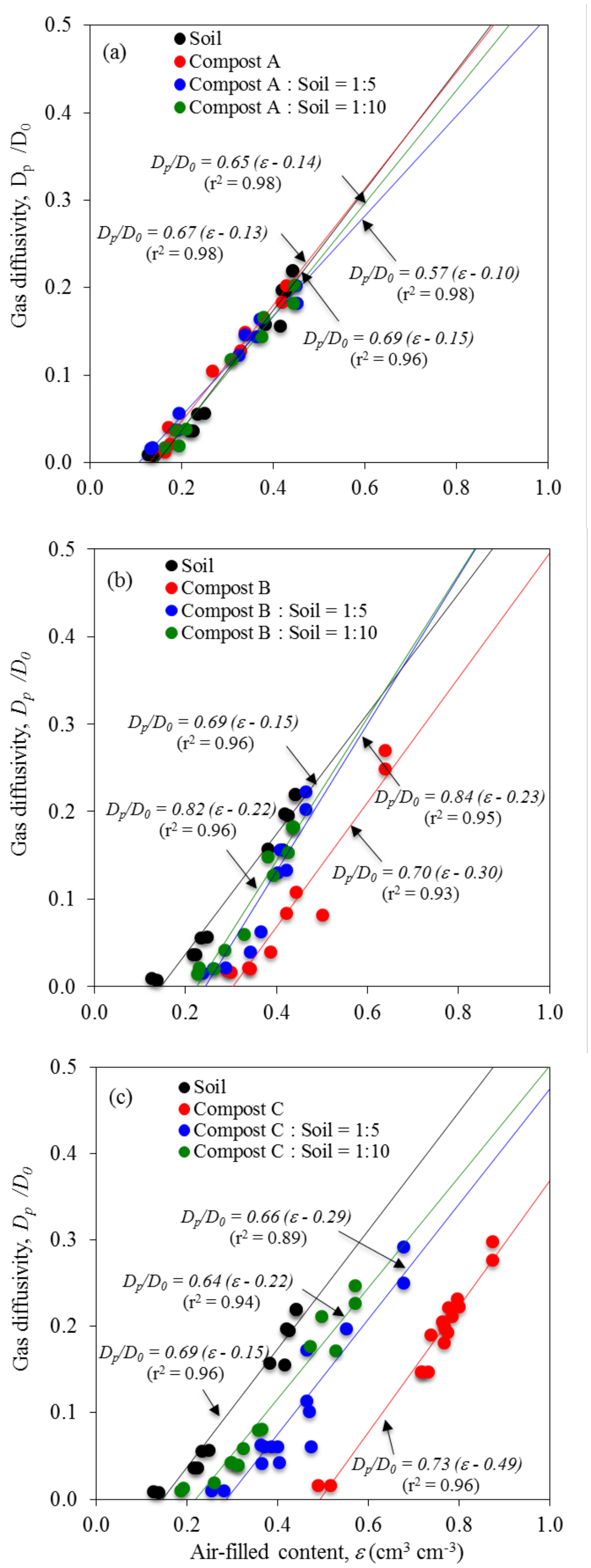

Fig. 3.3 Gas diffusivities (D_p/D_0) as a function of air-filled content (ε) for tested materials. Fitted lines of the Penman-Call (PC) model (Eq. [3.2]) were also depicted.

Table 3.2 Fitted parameters of Brooks and Corey (BC) model [λ', pore radius distribution, and ψ_b, bubbling pressure (Eq. 3.1)], Penman-Call (PC) linear D_p/D_0 model [C, slope of the linear model, and ε_{th}, threshold air-filled content (Eq. 3.2)], and new λ and HC linear models [C', slope of the λ linear model (Eq. 3.3), and C'', slope of the HC linear model (Eq. 3.4)].

Material	θ_s	λ'	ψ_b	C	ε_{th}	ε_{th}/f	C'	λ_0	C''	HC_0
	$cm^3\ cm^{-3}$		-cm H_2O		$cm^3\ cm^{-3}$		$W\ m^{-1}\ K^{-1}$	$W\ m^{-1}\ K^{-1}$	$MJ\ m^{-3}\ K^{-1}$	$MJ\ m^{-3}\ K^{-1}$
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

In addition, correlations between the ε_{th} values from gas diffusiviti values from water retention curves were plotted in Fig. 3.4a, and correlation b and air-filled content at pF 2 (ψ = -100 cm H_2O), ε_{100} were plotted in Fig values increased with increasing compost content, relating non-linearly to the bubbling pressure (r^2 = 0.78) and highly linearly (r^2 = 0.96) to the soil macro noted that easily-drained test materials, such as Composts B and C and thei with relatively lower $|\psi_b|$, gave larger ε_{th} values (> 0.2). Again, this indic easily-drained pores which were given by lower $|\psi_b|$ values did not contribute of connected air-filled pore networks that caused internal gas diffusion inside such as Composts B and C, which are rich in rice husks. The ε_{100} represen porosity and equals to the volume of soil pores with an equivalent pore diar [drained at pF 2 (ψ = -100 cm H_2O)] (Moldrup et al., 2000). As shown in Fig a good linear relation between ε_{th} and ε_{100} [$\varepsilon_{th} = 0.64\varepsilon_{100}$, ($r^2$ = 0.96)], which n to predict and design ε intervals of adequate O_2 diffusion in soil-compost mixt

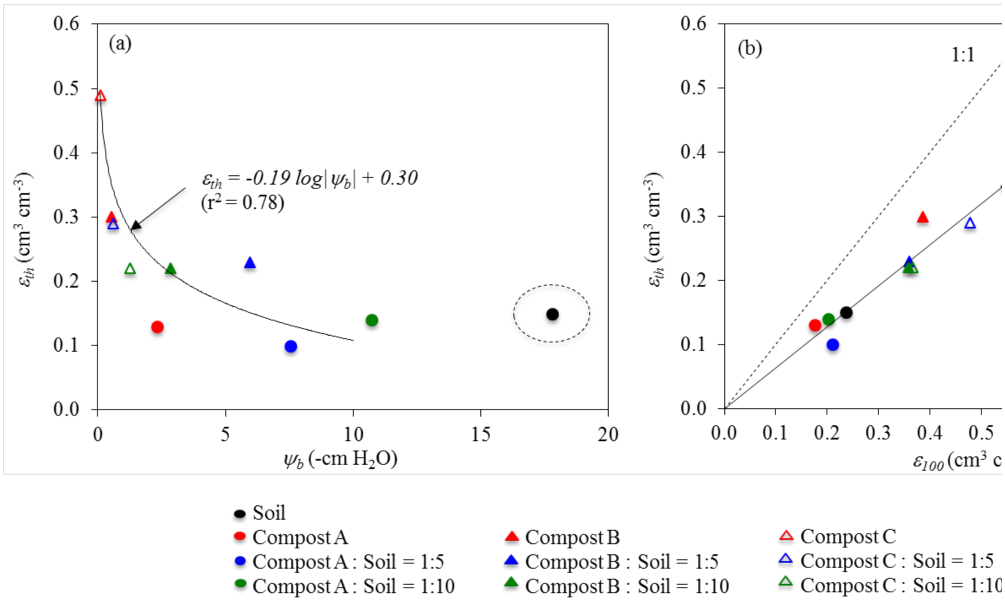

Fig. 3.4 (a) Correlation between the ε_{th} values from gas diffusivities and t from water retention curves. A fitted curve for the plots except for soil is figure. (b) Correlation between the ε_{th} and air-filled content at pF 2, ε_{100}.

3.2.3 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. 3.5. A linear λ model (Eq. [3.3]) was fitted to the measured λ data and depicted in Figs. 3.5a, 3.5b, and 3.5c. A linear *HC* model (Eq. [3.4]) was fitted to the measured *HC* data and depicted in Figs. 3.5d, 3.5e, and 3.5f. The values of fitted parameters for the models, C', λ_0, C'', HC_0, are tabulated in Table 3.2.

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. 3.5a, 3.5b, and 3.5c) and both C' and λ_0 values for compost-soil mixtures decreased with increasing compost mixing ratio (Table 3.2). In addition, the C' values for composts and compost-soil mixtures did not vary regardless of the compost type (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. 3.5f). The fitted C'' values ranged from 3.18 to 4.72, which is narrower compared to the C' values.

Chandrakanthi et al. (2005) 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 3.1), which are higher than their compost using leaves. Dissanayaka et al. (2012) 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 3.2).

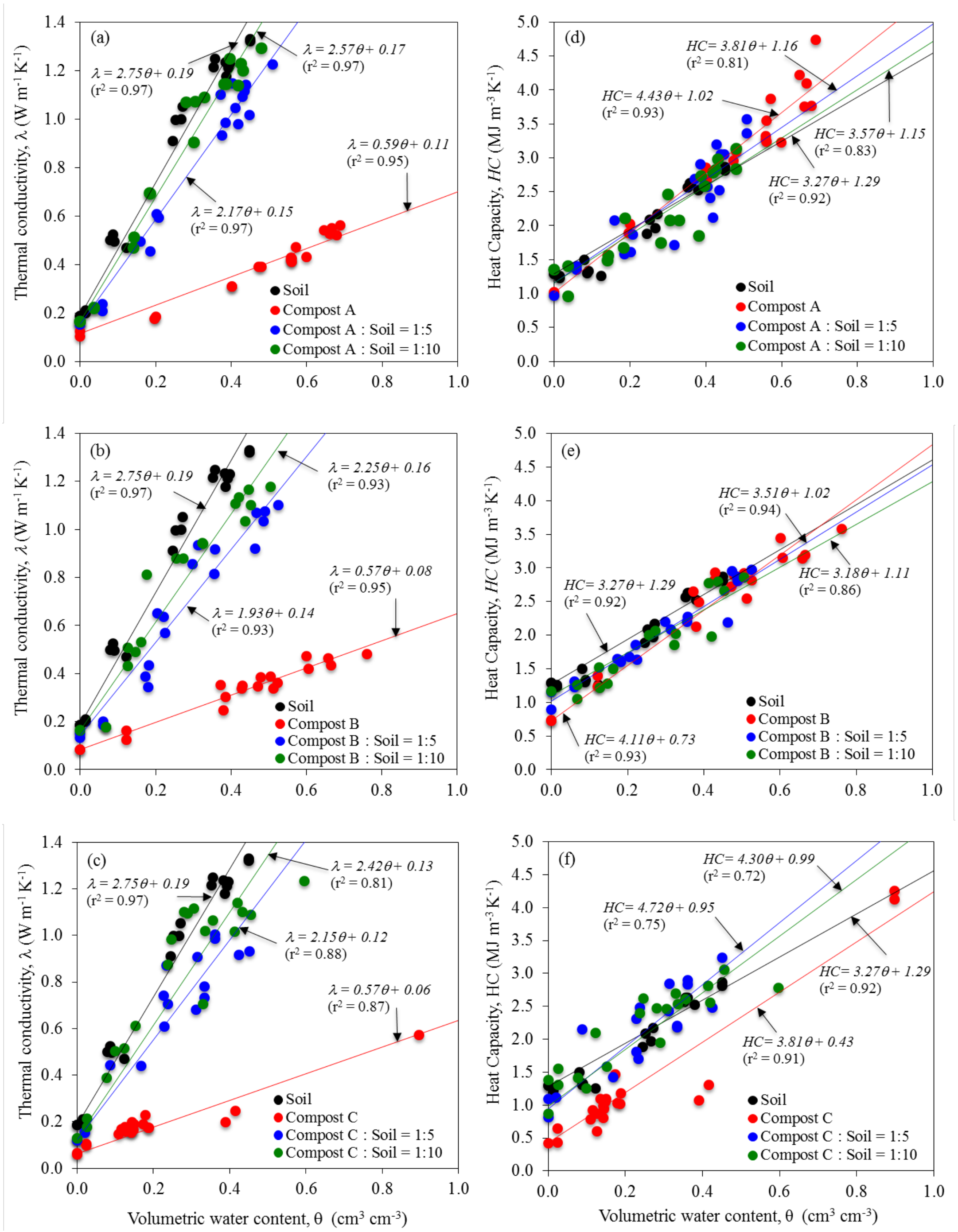

Fig. 3.5 Thermal conductivities (λ) and heat capacities (*HC*) as a function of volumetric water content (θ) for tested materials. Fitted lines of the Penman-Call (PC) type models (Eqs.[3.3] and [3.4]) were also depicted.

For dry conditions (where $\theta = 0$), the volumetric solid content, σ, controls the λ and *HC* in porous media (de Vries, 1963; Johansen, 1975). 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. 3.6 and a fitted line for $\lambda_0(\sigma)$ and a fitted curve for $HC_0(\sigma)$ were given (see the equations in the figure):

$$\lambda_0 = 0.25\sigma + 0.025 \qquad [3.5]$$

$$HC_0 = 1.55\sigma^{0.48} \qquad [3.6]$$

In Figure 3.6, previously proposed linear relationships based on the data measured for organic peaty soils by Dissanayaka et al. (2012) were 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) (Fig. 3.6a). The HC_0, on the other hand, increased nonlinearly with increasing σ. Both Eqs. [3.5] and [3.6] 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.

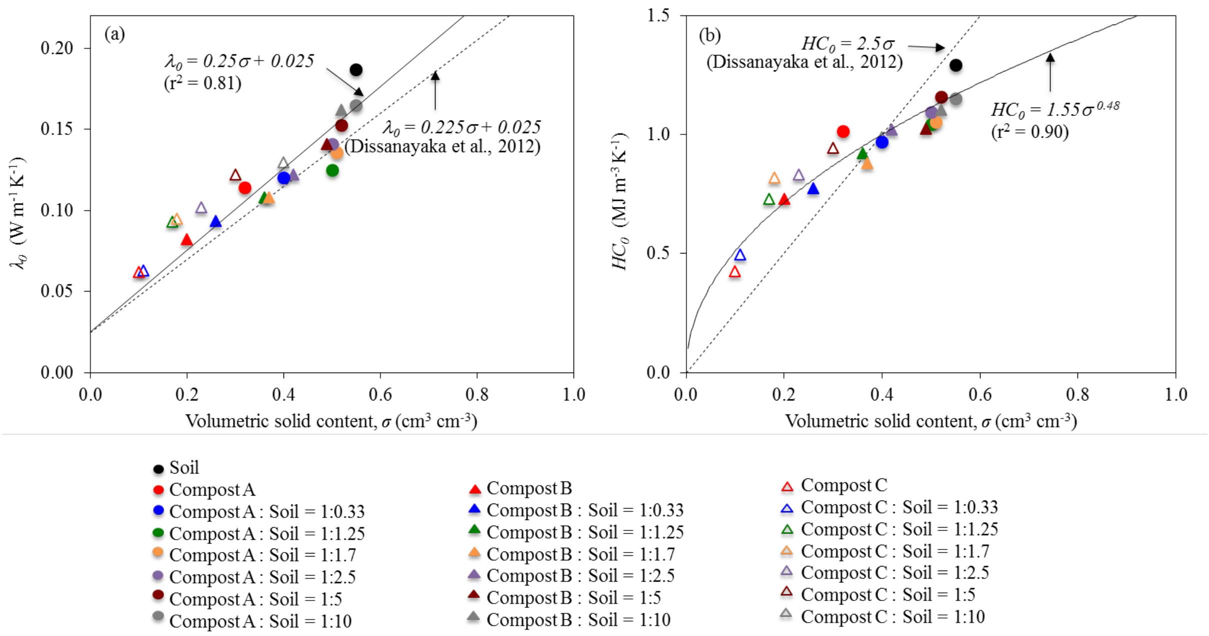

Fig. 3.6 The λ_0 and HC_0 as a function of volumetric solid content, σ (cm^3 cm^{-3}). Fitted line (Eq. [3.5]) and curve (Eq. [3.6]) were also shown. It is noted that intercept values at σ = 0 for the fitted line and curve were fixed to be those values for air (0.025 for λ_0 and 0 for HC_0).

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. 3.7. 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:

$$\lambda_0 = (\lambda_{0,soil} - \lambda_{0,compost})(1 - \sigma_{compost}/\sigma)^n + \lambda_{0,compost} \quad [3.7]$$

$$HC_0 = (HC_{0,soil} - HC_{0,compost})(1 - \sigma_{compost}/\sigma)^n + HC_{0,compost} \quad [3.8]$$

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. [3.7] and [3.8] 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.

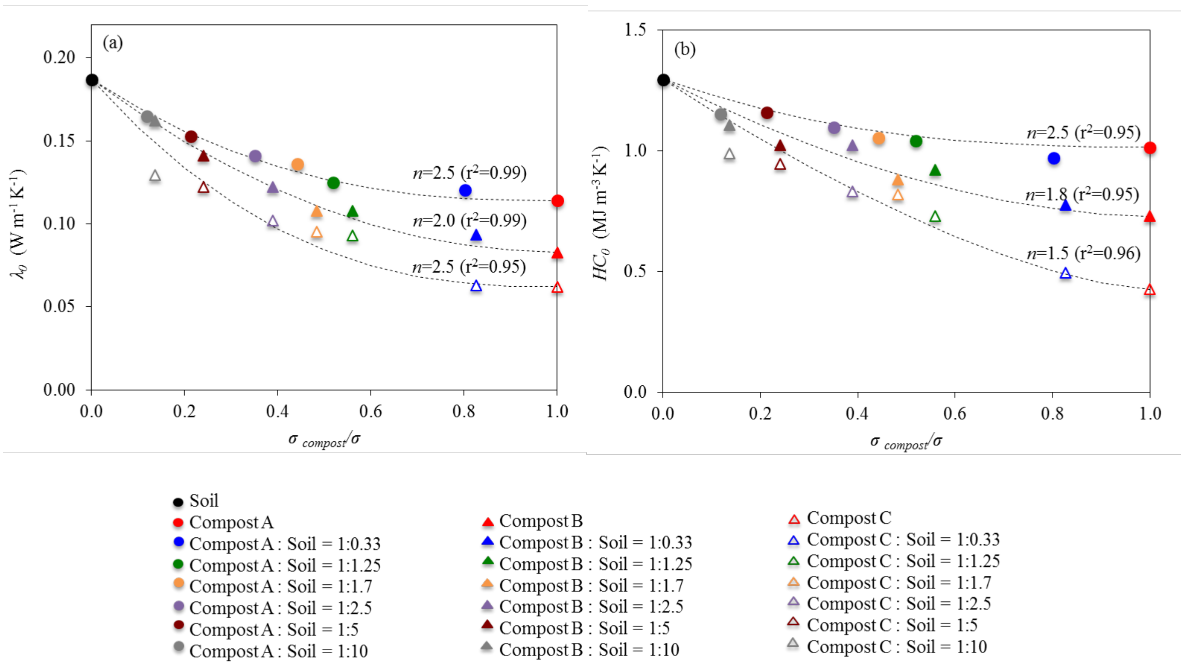

Fig. 3.7 λ_0 and HC_0 as a function of $\sigma_{compost}/\sigma$. Fitted curves (Eqs.[3.7] and [3.8]) were also depicted.

3.3 Conclusions

This study investigated the effects of mixed composts on water retention and 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 vary much among the tested materials (slope $C = 0.57\text{-}0.84$). 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 test results from this study, gas and heat transport parameters (D_p/D_0, λ, and *HC*) measured for compost materials and compost-mixed soils gave clear 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.

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CHAPTER 4
PREDICTIVE MODELS FOR GAS DIFFUSIVITY AND THERMAL PROPERTIES OF COMPOST-MIXED SOILS

ABSTRACT

Accurate prediction of gas transport parameters and thermal properties are important for assessing the landfill gas emission, methane oxidation and finally the performance of the biocover. The data obtained from the previous study were used to test the model performance for the gas diffusivity and the thermal properties. Predictive models for gas diffusivity were tested based on the sensitivity analysis. The tested model predictions were highly deviated from the wet region and well predicted in the dry regions (ψ > -1,000 cm H_2O) for soil. Predictive models for the quick assessment of the thermal properties at dry conditions (λ_0 and HC_0) were developed based on their dry bulk densities (ρ_d). Three-phase mixing model was applied by incorporating the impedance factors for thermal conductivity f_λ and heat capacity f_{HC} and based on the λ_0-σ and HC_0-σ relations. The modified mixing model is represented by $\lambda=\lambda_0+f\lambda\theta\lambda_w$ and $HC=HC_0+f_{HC}\theta HC_w$. The modified mixing model and existing predicting models were compared. Similarly, predictive models for gas diffusivity were tested based on the sensitivity analysis. The newly developed and modified model for thermal properties might be useful for the assessment of the thermal properties of compost mixed biocovers towards optimal performances.

4.1 Introduction

Mitigation of landfill gas emission through a biologically active landfill covers such as biocovers and biofilters (Stein and Hettiaratchi, 2000; Humer and Lechner, 2001a; Barlaz et al., 2004; Stern et al., 2007; Pawlowska and Pawlowski, 2008; Pedersen et al., 2011; Kjeldsene and Scheutz, 2014) become as an economical and technically feasible solution for the landfills where the landfill gas utilization system cannot be implemented (Pawlowska and Pawlowski, 2008; Kjeldsene and Scheutz, 2014).

Compost as a granular media can be used to control the most important influencing factors on CH_4 oxidation such as temperature and moisture content by the unique physical properties of compost. For instance, compost materials have high water retention capacity due to their high organic content and high specific surface area which is favorable for micro organisms and detrimental for gas transport through the cover due to the blockage effect by excess water and CH_4 production in extreme cases (Scheutz et al., 2009). Further, physical and chemical properties of compost such as moisture content (volumetric water content), air content (volumetric air content) and dry bulk density controls the thermal properties of compost (Chandrakanthi et al., 2009). Hence, moderate moisture content, which facilitate improved porosity with deep penetration of atmospheric O_2 for CH_4 oxidation and create a favorable environment for methanotropic bacteria (Humer and Lechner, 2001b; Kettunen et al., 2006).

Mainly, microbial respiration, organic matter degradation and environmental factors produce the thermal energy inside the biocover and become detrimental by drying of the medium due to increased temperature (Mysliwiec et al., 2001). Further, seasonal temperature changes are highly affected for the biocover performances (Venugopal et al., 2003).

In addition, applicability of compost materials based on the biodegradable food waste residue and yard waste in urbanized areas of developing countries shows clear sign of reduction, recycling and reuse of waste materials.

It is necessary to estimate the thermal properties to avoid the detrimental conditions and optimize the performances.

4.2 Materials and Methods

Similar to the previous chapters used materials, air-dried 2-mm fraction of landfill cover soil and same compost materials used for the study (Table 3.1).

The measured data for gas diffusivity and thermal conductivity and heat capacity were used for the further analysis in this chapter.

4.2.1 Predictive models for gas diffusivity in repacked soils

Several predictive gas diffusivity (D_p/D_0) models were tested against the measured data. Widely used and applicable models with the tested materials were considered. Penman-Call model (Eq. 4.1) was applied considering the linear increase of the gas diffusivity for soil, composts and compost-mixed soils by considering the threshold air content.

$$\frac{D_p}{D_0} = 0.66(\varepsilon - \varepsilon_{th}) \qquad [4.1]$$

where ε is the air-filled content ($cm^3\ cm^{-3}$) , ε_{th} is the threshold soil-air content, D_p is the gas diffusion coefficient, ($cm^2\ s^{-1}$) and D_0 is the gas diffusion of free air (D_0 =0.20 $cm^2\ s^{-1}$ at 20°C).

Further, three types of water induced liner reduction (WLR) models; WLR (Penman) Eq. 4.2, WLR (Marshall) Eq. 4.3 and WLR (Millington) Eq.4.4 models were tested with the measured data.

It has been identified that the gas diffusivity in wet media is lower than gas diffusivity in dry media at the same air-filled porosity (Papendick and Runkles 1965).

Moldrup et al. (2000) suggested that, in wet media, a change of the pore shape and configuration of air-filled pores cause increased tortuosity for gas transport (i. e., reduced diffusive gas flux)

They have introduced an additional, water-induced linear reduction (WLR) of diffusivity with air-filled porosity for the wet media, which increased tortuosity at the same air-filled porosity as dry soil. In dry soil $\varepsilon = \phi$, hence, WLR term was identified as ε/ϕ. The modified classical models of Penman, Marshall and Millington, with additional WLR term as follows;

The WLR (Penman) model:

$$\frac{D_p}{D_0} = 0.66\varepsilon\left(\frac{\varepsilon}{\phi}\right) \qquad [4.2]$$

where ϕ is the total porosity.

WLR (Marshall) model:

$$\frac{D_p}{D_0} = \varepsilon^{3/2} \left(\frac{\varepsilon}{\phi}\right) \quad [4.3]$$

WLR (Millington) model:

$$\frac{D_p}{D_0} = \varepsilon^{4/3} \left(\frac{\varepsilon}{\phi}\right) \quad [4.4]$$

Mostafid et al. 2012 tested the Variable Inactive Pore Space (VIPS) predictive model, Eq. 4.6 for gas diffusivity to compare the measured gas diffusivity data of undisturbed compost-woodchip and green waste samples from an existing landfill biocovers and biofilters and obtained reasonable best-fit model parameters, RMSE and bias for both undisturbed compost-woodchip and green waste samples among the tested models; Millington-Quirk, Penman-Call, VIPS and Troeh models.

In this study, the VIPS model was tested to obtain the accurate predictions based on the threshold air-filled content.

$$\frac{D_p}{D_0} = \left(\varepsilon - \left[\frac{\phi-\varepsilon}{\phi-\varepsilon_{th}}\right] \varepsilon_{th}\right)^V \quad [4.5]$$

where V is the fitting parameter

4.2.2 Predictive models for thermal properties

Impedance factors for each material for different mixing ratios were calculate by taking the ratio of C'(slope of λ-θ relation) or C''(slope of HC-θ relation) (Eq. 3 and 4) to λ_w (0.57; de Vries, 1963) and HC_w (4.18; de Vries, 1963).

Existing models for thermal conductivity

A widely used de Vries (1963) model for estimating thermal conductivity based on volumetric fractions of each constituent (water, solid-organic matter, silt and clay, sand, and air) and weighting factors which is associated with geometric shapes of solid and air fractions was tested to identify the applicability of existing models for predicting thermal conductivity. The general form of the model can be expressed as follows;

$$\lambda = \frac{\sum_{i=1}^{N} k_i V_i \lambda_i}{\sum_{i=1}^{N} k_i V_i} \quad [4.6]$$

where V_i is the volumetric fraction, and k_i is the weighting factor determined by the thermal conductivities and geometric shapes of solid and air fractions. The k_i of liquid fraction is considered as 1.0. Solid and air filled fractions. The subscript *i* represent the different constituents of the sample (i. e., water, solid-organic matter, silt and clay, sand, and air)

$$k_i = \frac{1}{3} \sum_{j=a,b,c} \left[1 + \left(\frac{\lambda_i}{\lambda_0} - 1\right) g_{ij}\right]^{-1} \quad [4.7]$$

where g_{ij} is the geometric shape factor of solid or air-filled phase and the subscript *j* represent the ratios of the axes a, b, and c for the solid particles, satisfying $g_{ia} + g_{ib} + g_{ic} = 1$.

The thermal conductivities of water (λ_{water}), sand (λ_{sand}), silt-clay ($\lambda_{silt\text{-}clay}$), organic matter ($\lambda_{om}$), and air ($\lambda_{app}$) were considered as 0.57, 3.0, 2.93, 0.25 and 0.05 W m^{-1} K^{-1} (de Vries, 1963), respectively. The λ_{app} is the apparent thermal conductivity of the air-filled pore space, made up partly of normal heat conduction (λ_a) and partly of vapor movement (λ_v).

4.2.3 Sensitivity Analysis of the models

The performances of the considered prediction models for gas diffusivity, thermal conductivity was evaluated based on two different statistical indices, root mean square error (RMSE) and bias (Hamamoto et al., 2011; Dissanayaka et al., 2012; Saito et al., 2014). The RMSE was used to evaluate the overall performance or best-fit of the models:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (d_i)^2} \quad [4.8]$$

where N is the number of measurements, d_i is the difference between the model-predicted and measured values.

The bias was used to evaluate the overestimation (positive bias) or underestimation (negative bias) of the models as compared to the measured data:

$$bias = \sqrt{\frac{1}{N}\sum_{i=1}^{N} d_i} \qquad [4.9]$$

4.3 Results and Discussions

4.3.1 Model performance of the predictive models for gas diffusivity

Several predictive gas diffusivity (D_p/D_0) models were tested against the measured data. Widely used and applicable models with the tested materials were considered. Penman-Call (Eq. 4.1), Millington-Call (Eq. 4.2) models, the modified classical models of Penman, Marshall and Millington, with additional WLR term (Eq. 4.3, 4.4 and 4.5, respectively), POE model (Eq. 4.7) considering the high porosity of the tested materials and VIPS model (Eq. 4.8) considering the threshold air-filled content were tested and obtained reasonable best-fit model parameters, RMSE and bias for all models.

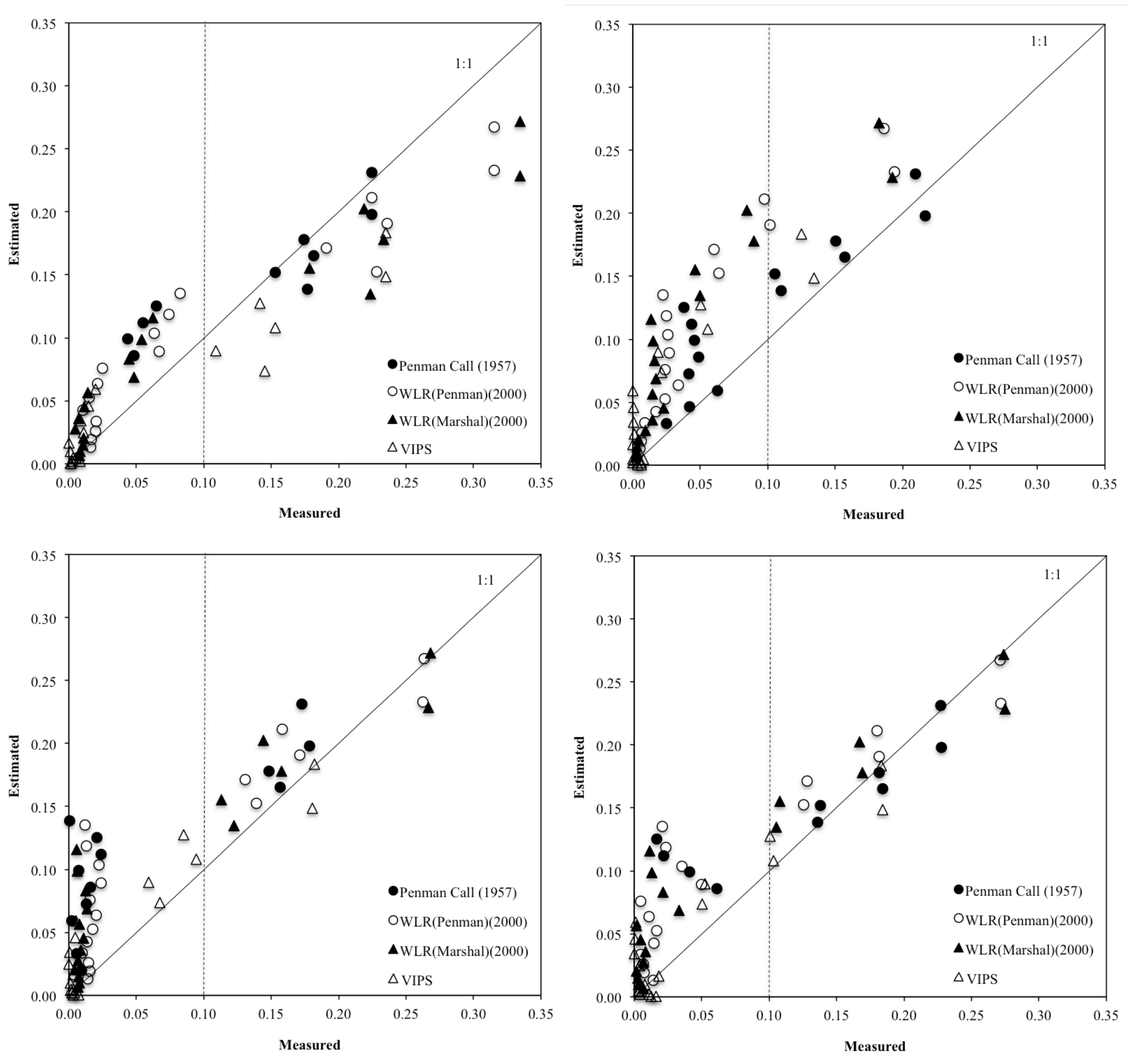

Fig. 4.1 Scatter-plot comparison of predicted and measured gas diffusivity (D_p/D_0) of soil.

Table 4.1 Test of predictive gas diffusivity against the data. Calculated RMSE and bias are given

Model	Soil		Compost A		Compost A:Soil = 1:5		Compost A:Soil = 1:10	
	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias
PC (1957)	0.024	-0.013	0.024	0.013	0.019	0.007	0.027	0.004
MC (1957)	0.110	-0.077	0.088	-0.061	0.095	-0.064	0.093	-0.063
POE (2005)	0.090	-0.065	0.092	-0.066	0.085	-0.059	0.079	-0.056
WLR (Penman)(2000)	0.041	0.030	0.019	-0.007	0.025	0.013	0.031	0.017
WLR (Marshal)(2000)	0.044	0.022	0.025	-0.015	0.027	0.004	0.030	0.008
WLR (Millington)(2000)	0.064	0.039	0.025	-0.006	0.040	0.017	0.045	0.022
VIPS	0.026	-0.017	0.045	-0.034	0.033	-0.022	0.030	-0.018

4.3.2 Prediction of thermal properties

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 ρ_d 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):

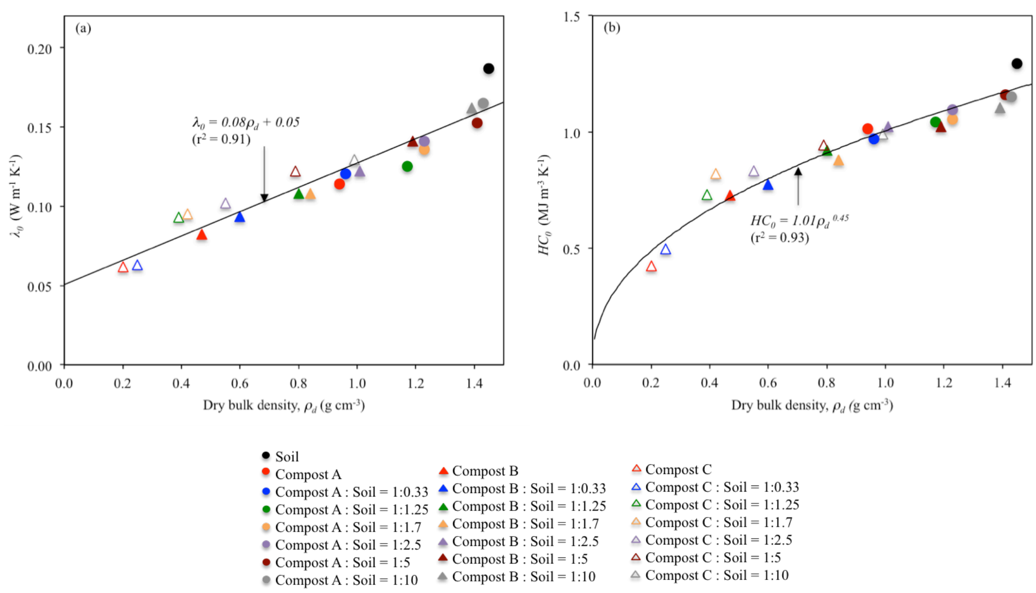

Fig. 4.2 The λ_0 and HC_0 as a function of dry bulk density, ρ_d (cm^3 cm^{-3}). Fitted line (Eq. [4.10]) and curve (Eq. [4.11]) were also shown.

$$\lambda_0 = 0.08\rho_d + 0.05 \quad [10]$$

$$HC_0 = 1.01{\rho_d}^{0.48} \quad [11]$$

The λ_0 increased linearly with increasing ρ_d and nonlinearly for HC_0. The developed empirical relationships might be useful for the assessment of the thermal properties for dried compost-mixed soils.

Based on the findings of previous study, $\lambda\text{–}\theta$ and $HC\text{–}\theta$ relations were incorporated and modified the three-phase mixing model. the λ and HC can be predicted for different θ values based on the λ_0 and HC_0 values and liquid-phase impedance factor, of each material. Based on the three-phase mixing model concept, λ and HC can be predicted based on following equations;

$$\lambda = \lambda_0 + f_\lambda \theta \lambda_w \quad (4.12a)$$

$$HC = HC_0 + f_{HC} \theta HC_w \quad (4.12b)$$

Similarly, Dissanayaka et al., 2011, modified mixing model to develop the prediction models considering the impedance factors representing liquid-phase tortuosity for thermal conductivity and heat capacity (λ and C) using the peat soils. The calculated f_λ and f_C values for peat soil were 0.89 and 0.88 respectively. The developed predictive models for thermal properties based on the f_λ / f_C and λ_{dry} / C_{dry} were well predicted the λ –θ data on peaty and highly organic soils under variable saturation.

Additionally, classical predictive model, de Vries (1975) model and modified mixing models were tested for sensitivity analysis. The scatter-plot comparison of predicted and measured thermal conductivity of de Vries model (Eqs. 4.8 and 4.9) illustrated in Figure 4.3 and 4.4.

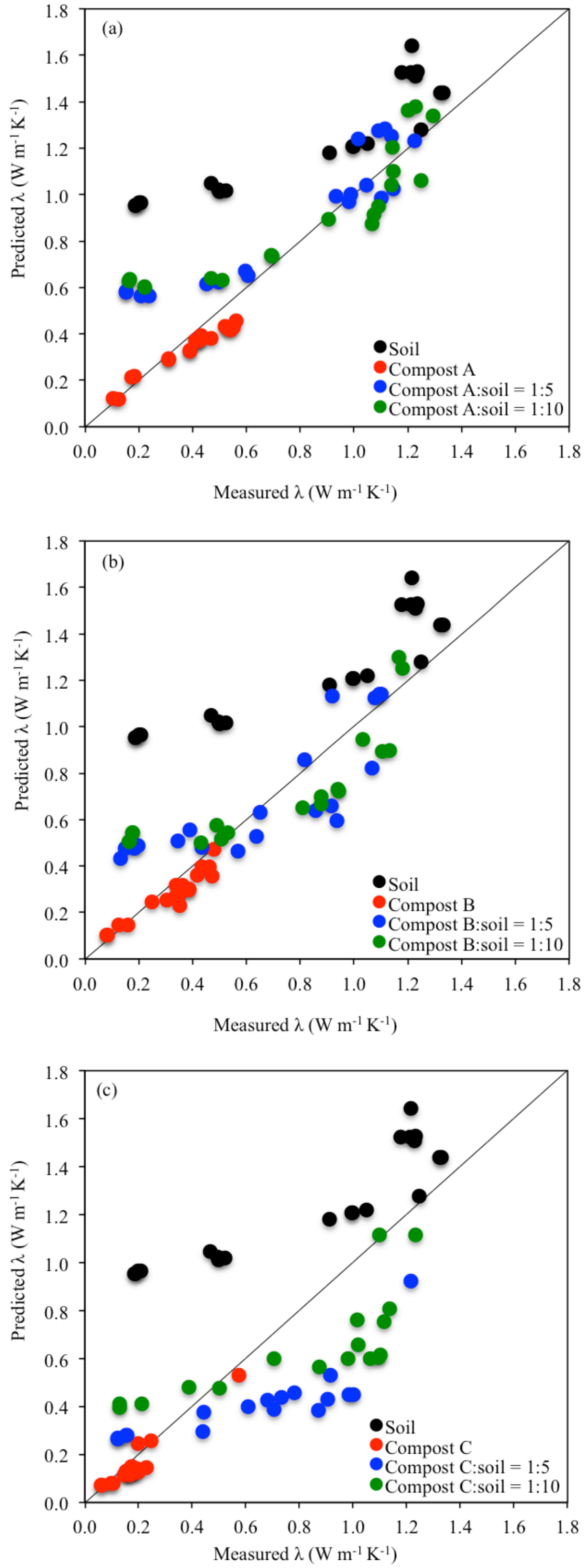

Fig. 4.3 Scatter-plot comparison of predicted and measured thermal conductivity (λ) of soil, composts and compost-mixed soils.

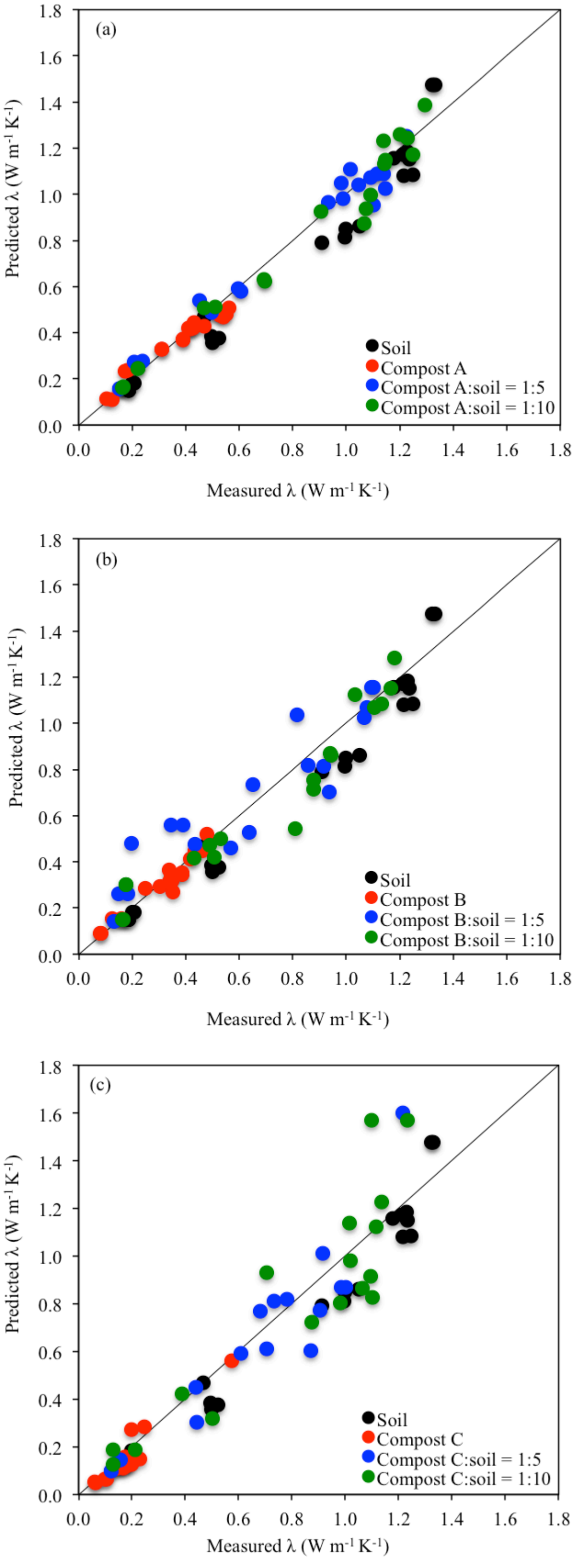

Fig. 4.4 Scatter-plot comparison of predicted and measured thermal conductivity (λ) of soil, composts and compost-mixed soils using modified mixing model.

4.4 Conclusions

The tested classical and modified classical models for gas diffusivity model predictions were highly deviated from the wet region and well predicted in the dry regions (ψ > -1,000 cm H_2O) for soil. The Penman-Call type linear model well describe the data of soil, composts and compost-mixing soil, suggesting that the other models are not applicable for predicting gas diffusivities in saturated and moderate saturated condition.

Further, predictive models for design criteria of compost : soil mixing ratios were developed based on the λ-σ and HC-σ linear relationship. The three-phase mixing model concept was used to develop the predictive models for λ and HC incorporating λ_o and HC_0. The developed model can be used to predict λ and HC values based on two variables; oven dry λ and HC and θ of prepared thermal property.

Predicted thermal property models testing will be conducted by a model performance based on the literature of the related studies. Since the number of related studies are limited and studies related to the different mixing ratios are not available, this study will be investigate further based on the composting material composition to validate the developed models for thermal properties.

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CHAPTER 5
SUMMARY, CONCLUSIONS AND PERSPECTIVES

5.1 Summary and conclusions

Gas and heat transport properties of compost-mixed landfill cover soils control the fate and emission of toxic gases from the landfill and the rate of methane oxidization in the cover.

In this study we measured methane oxidation rates of compost-mixed soils and evaluate the gas transport parameters (gas diffusion coefficient, D_p) and thermal properties (thermal conductivity, λ and heat capacity, *HC*) of compost-mixed soils in order to understand the potential application of compost-mixed soils as a biological active cover for the mitigation of landfill gas emission.

In chapter 2, the biological reaction of methane oxidation in compost, compost-soil mixture, and landfill cover soil at elevated atmospheric methane concentrations of 8% CH_4 were described using first and zero order reaction kinetics. Results of this study showed that WC for a soil-compost mixture, in both cases showing a significant influence of water status and thus of the diffusion processes in the water and gas phases. According to the results of the methane oxidation batch experimental procedure, the maximum oxidation rate of pure compost higher than that of a compost-soil mixture. Besides, the biological kinetics of methane oxidation based on both zero and first order rates of a 1:10 (w/w) compost-soil mixture was lower than for pure compost, suggesting that the mixing ratio of compost-soil may be improved for landfill final cover soil application.

In chapter 3, we measured gas diffusivity D_p/D_0 and thermal properties such as thermal conductivity (λ) and heat capacity (*HC*) of soil, composts and compost-mixed soils using the hand compacted samples under variably water saturation. Model parameters for gas diffusion (slope *C* of Penman-Call model), thermal properties (C' and C'' slopes of λ-θ and HC-θ relationships, respectively) were obtained by fitting the measured data to the PC

type gas diffusivity, thermal conductivity and heat capacity linear models. The effects of mixed composts on water retention and gas and heat transport parameters were investigated based on fitted model parameters. Measured water retention data were fitted well by the BC water retention model. The effect of compost mixing and composting material composition for soil water retention, gas diffusion and thermal properties were evaluated based on the measured parameters of BC, PC type gas diffusivity and thermal property models.
Model parameter of gas diffusivity (ε_{th}) related with the BC model parameter (ψ_b) and macro-porosity (ε_{100}). Empirical relationships were developed for the ε_{th}-ψ_b non linear relationship and

Results of the parameter analysis showed that, the ε_{th} values increased with increasing compost content, relating non-linearly to the Brooks-Corey bubbling pressure but highly linearly to macro-porosity. The obtained results of this study might be useful for predicting aeration and gas emission in landfill cover soils.

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.

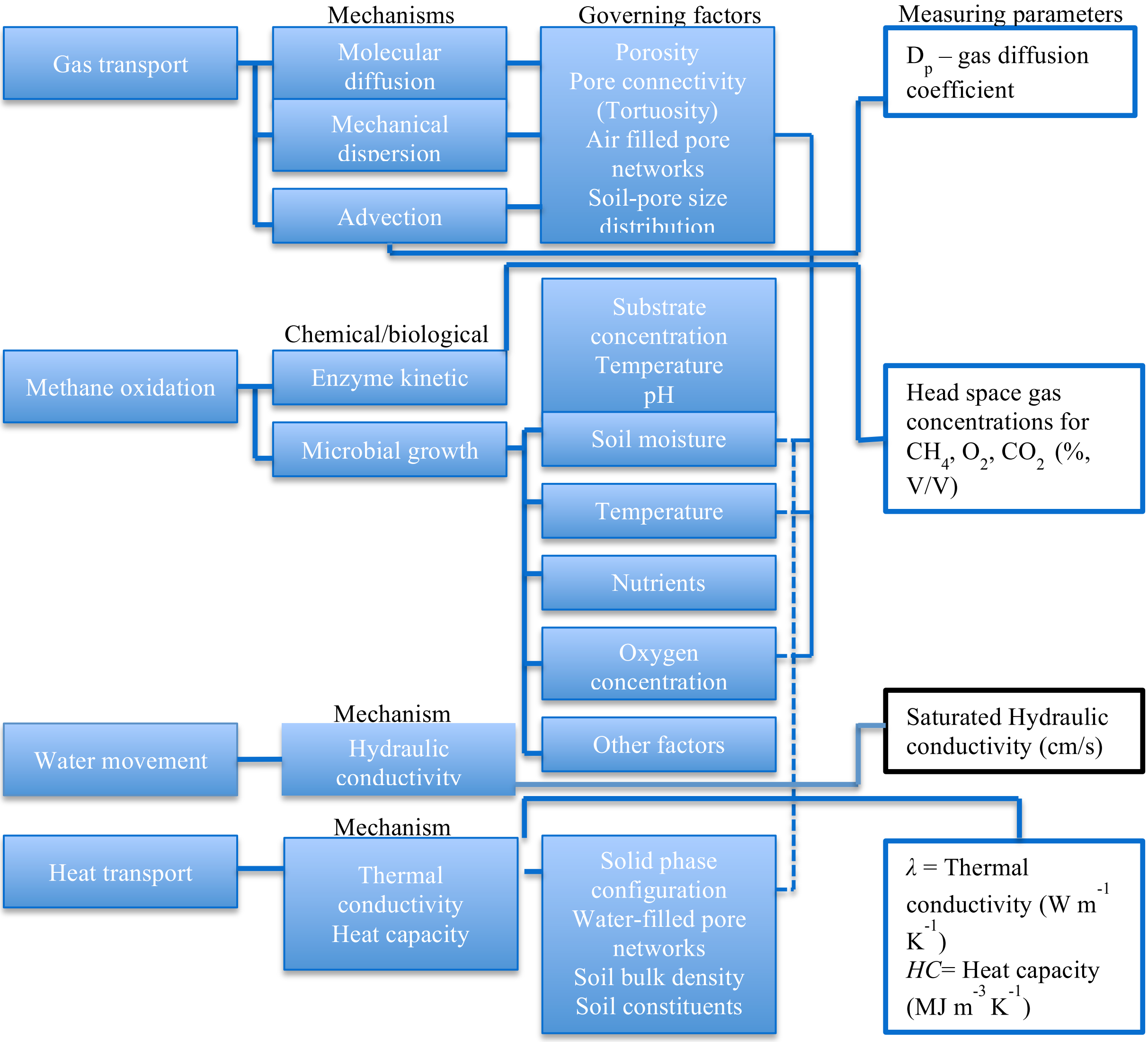
Based on test results from this study, gas and heat transport parameters (D_p/D_0, λ, and *HC*) measured for compost materials and compost-mixed soils gave clear linear relationships to their fluid contents (ε for D_p/D_0 and θ for λ and HC). However, the PC type simple linear models used in this study would be useful for a quick assessment of gas and heat transport through compost-mixed landfill cover soils.

In chapter 4, the Penman-Call type linear model well describe the data of soil, composts and compost-mixing soil, suggesting that the other models are not applicable for predicting gas diffusivities in saturated and moderate saturated condition. The modified mixing model for thermal properties might be useful for the assessment of the thermal properties of compost mixed biocovers.

Considering the overall study, we can come to a final conclusion based on the critical findings of the study as follows;

- The higher methane oxidation is given by the higher mixing ratio of compost (i.e Oxidation of pure compost > Oxidation of compost-soil mixture 1:5 >1:10)
- ε_{th} does not change much for the tested materials which contain sludge based compost (compost A, compost A-soil 1:5 and 1:10 mixtures) and they show lower ε_{th} values among other tested compost materials.
- The mixing ratios of compost into soil and composting material composition do not show any significant effect for thermal properties (but lower thermal conductivities in pure compost and λ decrease with increasing compost mixing ratio).
- It is necessary to penetrate the O_2 gas into deeper layers for methane oxidation process. And landfill gases move towards the bio cover from the waste layer. Thus, gas diffusion plays a vital role to optimize these processes.
- To achieve optimum performance, among the tested materials, compost A mixed soils (with lower mixing ratioes, e.g compost A-soil=1:5), might be applicable for optimal heat and gas transport characteristics as well as higher methane oxidation rates at moderate wet conditions.

5.2 Perspectives



This schematic diagram shows, there are ccontinuous indirect interactions between physical, chemical and biological processes inside the engineered landfill cover. These processes have been identified to understand the performances inside the landfill cover. The measuring parameters of these main processes were investigated in this study. The parameter analysis was performed in order to correlate these main processes. It will be useful for the estimate one parameter based on rapid and easy measurable parameter.

The model parameters of gas, heat and water transport were compared. The available data for the model parameter analysis is still limited. It is necessary to expand the tested data for parameter analysis to suggest strong recommendations for field applications.

Several predictive models for thermal properties were developed in this study. Further investigations are required to test the models. Predicted thermal property models testing will be conducted by a model performance based on the literature of the related studies. Since the number of related studies are limited and studies related to the different mixing ratios are not available, this study will be investigate further based on the composting material composition to validate the developed models for thermal properties.