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論文の内容の要旨

When municipal solid wastes (MSWs) are buried in landfills, biodegradable fractions decompose via a complex series of microbial and abiotic reactions. The anaerobic degradation of organic waste in landfills results in the production of a gas mixture that contains methane (CH_4), carbon dioxide (CO_2), and potentially also numerous toxic compounds. The greenhouse gases and toxic gases are mainly produced under oxygen-limited (anaerobic) conditions and can subsequently be emitted to the atmosphere through the landfill final cover soil. Therefore, the landfill final cover should be designed to promote oxygen exchange between the atmosphere and waste layer to maintain aerobic conditions and high methane oxidation in the final cover soil layer and at the same time to secure a good hydraulic performance. Numerous studies have focused on characterizing and controlling the hydraulic performance of differently textured landfill final cover soils to prevent water infiltration during precipitation. However, only few measurements and limited knowledge of the gas transport characteristics (gas diffusion coefficient, D_p and air permeability, k_a) and their relationships to soil physical properties in landfill cover soils are available at present. Soil physical properties such as bulk density (ρ_b) and particle size fraction and soil pore structure parameters including soil-air content (ε), total porosity (Φ), and pore connectivity-tortuosity as inferred from gas diffusivity all strongly affect the gas transport parameters. The recent soil-gas transport studies imply that soil compaction and particle size fraction are key parameters to understand gaseous phase performance of landfill cover soils. Basically, this study was carried out a) to measure the gas diffusion coefficients as function of soil-air contents for differently compacted and variably saturated landfill final cover soils, b) to test/modify recent predictive models against measured data, and c) to apply the relationship between soil physical properties and gas transport parameters in a systematic flow chart for landfill cover performance in relation to gas exchange.

In chapter 2.1, the gas transport parameters were measured on variably saturated and differently compacted reddish brown cover soil in Sri Lanka. Further, model performance was also done for the measured data and effects of moisture content and compaction on gas transport parameters were investigated. Finally, based on the measured gas transport parameters, the soil-pore characteristics and preferential gas transport properties were evaluated. The samples were prepared by either standard proctor compaction or hand compaction to dry bulk densities between 1.60 to 1.94 g cm^{-3}. The simple, single-parameter Buckingham (1904) model equally well or better predicted measured D_p/D_o values across compaction levels, as compared with multi-parameter models including a dry bulk density (DBD) dependent model and soil-water retention (SWR) dependent model. For air permeability, a single-parameter Buckingham type k_a model showed to be superior but only reasonable accurate (order of magnitude estimate) for predicting ka in across compaction levels and moisture contents.

The calculated equivalent pore diameter (d_{eq}) was markedly increasing with compaction level, suggesting that a very high compaction level may create well-connected macropores in the reduced total pore space of the cover soil. In chapter 2.2, gas transport parameters were measured in extremely compacted landfill final cover soil in Japan and based on measured data, model performance was evaluated. Based on measured data, the highly-and extremely-compacted landfill cover soils (ρ_b = 1.70-1.80 and 1.80-1.90) showed negligible threshold values for soil air content (ε_{th}) for both D_p/D_0 and k_a and an almost linear increase of D_p/D_0 with soil-air content (ε). Soil compaction also caused the reduction of larger-pore networks, hereby markedly reducing the increase in k_a with ε under dry conditions.

In Chapter 3, the effects of soil compaction and particle size fraction on gas diffusion coefficient (D_p) and air permeability, (k_a) in variably saturated and differently compacted landfill final cover soils were investigated. In addition, the recent models were modified for D_p/D_o and k_a by considering the model parameters as a function of dry bulk density, (ρ_b). The measurements showed higher D_p and k_a values for the coarser fraction (< 35 mm) as compared with the finer fraction (< 2 mm) at similar air-filled porosity. We suggest this is caused by compaction creating well-aligned large-pore networks that are readily available for gas transport through the porous material. The compaction effect was found more evident for air permeability as compared to gas diffusivity, and more pronounced for coarser than for finer soil size fractions. The WLR model for D_p and the RPL model for k_a were modified with reference point measurements and model parameters (with power-law exponents M for the D_p model and P for the k_a model) were correlated linearly to ρ_b values for both fraction of landfill final cover soil. Finally, based on the developed predictive equations, a systematic flowchart was introduced and it may be a useful tool during design and management of landfills, regarding optimizing gas exchange for minimizing greenhouse gas emission from landfill sites.

In chapter 4, gas transport parameters were investigated to examine the effects of structure formation on moderately compacted (HAC- hand compacted) landfill final cover soils. The study revealed that moisture adjustment method together with dry bulk density caused to change the pore structure formation in final cover soils. The difference of D_p/D_o was not much significant but k_a showed significant variation with altering pore structure changes. Moisture adjustment before compaction samples (HAC-A) showed greater variation on k_a, compared with samples in which moisture adjusted after compaction, suggesting higher potential for structure forming. The region of structure formation occurred at intermediate to field water content. Soil pore indices also varied considerably in HAC-A samples, especially d_{eq}, highlighting structure forming may affect gas transport parameters in landfill final cover soils. Overall, these two indices were good indicators to exhibit the effects of structure forming potential on gas transport parameters in differently compacted landfill final cover soils.

In perspective, the introduced predictive equations need to be tested for more independent measurements with different size fractions and soil textures. The actual greenhouse gas emission (i.e., methane) measurements are highly helpful to link the main gas transport parameters and also methane emission rates and their dependence on soil physical and chemical properties are highly recommended.

論文の審査結果の要旨

当学位論文審査委員会は，平成 23 年 7 月 14 日に論文発表会を開催し，論文内容の発表に続いて質疑と論文内容の審査を行なった。以下に審査結果を要約する。

一般廃棄物処分場の最終覆土は，通常雨水等の浸入を防ぐために，極度に締固めが行われている。しかし，このような場合，一旦内部に雨水が貯留されると，最終覆土層を通したガス交換（酸素供給）が制限され，内部廃棄物層には嫌気的環境が形成され，それが長期にわたり維持される。このような嫌気的環境下では，メタンなどの温室効果ガスや硫化水素などの有害ガスの生成が盛んになり，これらが地球環境や廃棄物処分場周辺に及ぼす影響が懸念されている。このような嫌気的環境を軽減する方法の一つとして，最終覆土層のガス交換機能の改善が考えられる。そのためには，最終覆土での締固めの度合いや土壌水分量が，ガス交換機能を決定する土壌ガス拡散係数や通気係数といったガス移動パラメータに及ぼす影響を明らかにする必要があるが，そうした影響因子がガス移動にどのような影響を及ぼすのか十分な知見が得られているとは言い難く，これらの因子の影響を組み込み，定量的にガス移動パラメータを記述できる予測モデルはこれまで提案されていないのが現状である。本学位論文では，我が国とスリランカにおける廃棄物処分場の最終覆土から土試料を採取し，室内実験によってガス移動パラメータに締固め度合いや土壌水分量の影響を調べ，これらの実験結果に基づき，乾燥密度を指標にした新たなガス移動パラメータ予測モデルの提案・検証，ガス交換機能改善のための意思決定フローチャートの提案を行っている。

第 1 章では，研究の背景や目的，関連する既往の研究について記述している。既往の研究については，特に本研究で主要な内容となる，ガス移動パラメータ（土壌ガス拡散係数と通気係数）と基本土壌物理性（気相率や土性）との関係性や，各種パラメータ予測モデルについてのこれまでの研究のレヴューを詳細に行っている。

第 2 章では，スリランカの典型的な土壌である赤褐色土を用いて，ガス移動パラメータに土壌水分量や締固めの度合いが及ぼす影響を実験的に明らかにした。そして，既存のガス拡散係数予測モデルの測定データへの適用性を検討したところ，古典的な Buckingham (1904) モデルが，他の予測モデル（DBD model，SWR　model）よりも適合性が高く，測定データを上手く表現することを明らかにした。さらに，Buckingham (1904) モデルを拡張し，修正通気係数予測モデルを提案し，その有効性を検討した。

第 3 章では，我が国の廃棄物処分場の最終覆土より採取した土試料について，室内実験によって締固め度合いや土壌水分量，さらには粒度がガス移動パラメータに及ぼす影響を明らかにした。そして，土壌ガス拡散係数と通気係数について，乾燥密度を指標とした新たな予測モデルを提案した。新たなモデルは，土壌水分量による係数低減効果を示す指標（Water blockage parameter）と乾燥密度との関係性に基づいて構築されたものである。乾燥密度は原位置において比較的測定や管理が容易であることから，本予測モデルの工学的適用性は高いものと判断できる。さらに，本予測モデルを活用した，ガス交換機能改善のための意思決定フローチャートの提案も本章で行っている。

第 4 章では，第 2 章と第 3 章で得られたガス移動パラメータの実測データに基づいて，締固めや土壌水分量，粒度が，ガス拡散や通気に寄与する土壌内間隙の間隙構造についての議論を行っている。成果としては，土

試料は締固めを受けることにより，内部に選択的ガス経路（preferential gas paths）が形成され，このガス経路が試料の脱水・乾燥に伴い，ガス移動に大きく寄与することが明らかになった。また，第5章は結論と今後の研究展開の方向性を示している。

以上のように，本研究は，室内実験や土壌物理特性に基づいた予測モデルの構築をもとに，ガス移動パラメータに締固め度合いや土壌水分量の影響を定量的に解析することが可能となるなど，その成果は今後，廃棄物処分場の最終覆土層におけるガス交換能の評価や機能改善に効果的に活用されるものである。このことから，当学位論文審査委員会は，本論文が工学博士の学位に相応しい内容であると判断した。

なお，本論文の内容は，第2章がJ. Hazardous, Toxic and Radioactive Waste, ASCE（米国土木学会），第3章がWaste Management（IF 2.358, 2010）に掲載が受理され，現在印刷中である。