Effect of Compaction, Particle Size Distribution and Moisture Content on Gas Emission in Landfill Final Cover

M.H. Samarakoon1, E.B.S. Madushan1, N.H.Priyankara1 and A.M.N. Alagiyawanna1

1Department of Civil and Environmental Engineering
Faculty of Engineering
University of Ruhuna
Hapugala, Galle
SRI LANKA
E-mail: mhsamarakoon@gmail.com

Abstract: Landfill sites have become main cause for climate change scenarios as one of significant sources of greenhouse gasses. Solid waste inside the landfill undergoes complex sequence of biological and chemical reactions. These reactions can be categorized mainly into two, aerobic and anaerobic. In both these two reactions, Carbon Dioxide generates. But in anaerobic condition methane produces, which emits through final soil cover. Hence final cover of landfill plays a vital role for gas emission which causes severe environmental problem. Hence it is important to create aerobic condition by ventilation inside the landfill. Hence there should be a clear idea about the gas emission through soil in order to take necessary precautions. Gas exchange through final cover soil is governed by two gas transport mechanisms, advection and diffusion. Based on series of laboratory experiments, it was found that gas transport parameters are significantly vary with moisture content of soil, compaction energy applied to soil layers and particle size distribution of soil present in final cover. Obtained results were compared with existing gas diffusion and advection relationships. Finally optimum ranges of those soil parameters were found in order to enhance the gas transport parameters of cover material.

Keywords: Landfill final cover, gas transport parameters, moisture content, compaction energy, grain size distribution

1. INTRODUCTION

Municipal solid waste inside the landfill undergoes complex sequence of biological and chemical reactions under anaerobic conditions which cause to generate hazardous gasses. Inadequate waste management and disposal practices combined with the climatic changes result in increasing environmental problems (Visvanathan et al., 2004). Hence it is necessary given special attention on controlling the emission of landfill gasses, since it causes global warming. Methane is 25 times critical than CO2 for greenhouse effect (Wickramarachchi et al., 2010). The major controlling environmental and physical factors governing the CH4 oxidation process in landfill cover soils are soil texture, porosity, air content, bulk density, organic content, moisture content, soil temperature, pH, nutrients, and O2 and CH4 concentrations (Abushammala et al., 2014). Since most of the gasses emit through the final cover of a landfill, studying the affecting parameters for gas transportation is an important fact.

The design of cover systems to accommodate landfill gas control requires an understanding of the physical, chemical and biological processes governing gas migration. (Hettiaratchi et. al, 1998). Advection and the diffusion are the two mechanisms of gas transportation through the final cover soil. Diffusion is a process of movement of particles from high concentration to low concentration. Therefore, molecules of methane and carbon dioxide diffuse from the landfill gas to the air. Simultaneously, atmospheric air, mainly oxygen diffuse to waste body and it helps to increase the aerobic decomposition of organic matter (Kumari and Sanjaya, 2013). The gas diffusion coefficient in soil (Dp) and its dependency on soil physical characteristics, governs the diffusive transport of oxygen, greenhouse gasses through landfill final cover. Fick’s law is used to calculate the gas diffusion coefficient (Dp). Soil gas diffusivity (Dp/D0) is defined as the normalized ratio between soil gas diffusion coefficient (Dp) and gas diffusion coefficient in free air (D0). There exist developed models for soil gas diffusivity as a function of soil type and air content (ε). Buckingham suggested that soil gas diffusivity follows power law function of soil air content such that,
\[ \frac{dP}{dO} = \varepsilon^x \]  

Where \( \varepsilon \) is the soil air content and \( x \) is an exponent characterizing pore connectivity. \( x=2 \) for Buckingham model and \( x=1.5 \) for Marshall model. Penman further modified the model by removing exponent but inserting 0.66 as coefficient for air content (Kumari and Sanjaya, 2013).

Advection is the gas transportation mechanism of flowing air from high pressure to low pressure. The measurement of the advection through soil is related to the coefficient of air permeability (\( K_a \)). The theory for the flow of air through soil is based on Darcy's law. Existing general models of air permeability are also based on power law function of soil air content (\( \varepsilon \)) same as air diffusion. The generalized form of such models can be written as,

\[ K_a = \alpha \varepsilon^x \]  

Where \( \alpha \) pore connectivity constant and \( x \) is is power law exponent which can be either 2 for Buckingham type and 1.5 for Marshall type (Kumari and Sanjaya, 2013).

In this research study the effect of three soil parameters, such as compaction energy, moisture content and grain size distribution on above mentioned two gas transport parameters were evaluated for commonly available laterite soil. Finally obtained results were compared with existing models.

2. MATERIALS AND METHODOLOGY

2.1. Physical Properties

Commonly available laterite soil was used as the candidate material. Physical properties of laterite soil are illustrated in Table 1. Soil classification according to Unified Soil Classification System (USCS) is also presented in the Table 1 and it was found that soil is poorly graded sand (SP).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>2.69</td>
</tr>
<tr>
<td>Liquid Limit (LL %)</td>
<td>65</td>
</tr>
<tr>
<td>Plastic Limit (PL %)</td>
<td>45</td>
</tr>
<tr>
<td>Plasticity Index (PI %)</td>
<td>20</td>
</tr>
<tr>
<td>Linear shrinkage (%)</td>
<td>5</td>
</tr>
<tr>
<td>Coefficient of Uniformity (( C_u ))</td>
<td>5.33</td>
</tr>
<tr>
<td>Coefficient of Curvature (( C_c ))</td>
<td>1.33</td>
</tr>
<tr>
<td>Gravel Content (%)</td>
<td>0</td>
</tr>
<tr>
<td>Sand Content (%)</td>
<td>98.34</td>
</tr>
<tr>
<td>Fine content (%)</td>
<td>1.66</td>
</tr>
<tr>
<td>Classification according to USCS</td>
<td>SP</td>
</tr>
</tbody>
</table>

2.2. Grain Size Distribution

Three ranges of particle sizes were used to determine the gas transport parameters under the objective of finding the effect of grain size. The ranges are,

1. Less than 2.36 mm
2. Between 2.36 and 4.75 mm
3. Between 4.75 and 9.5 mm
Above three ranges of particle size were selected, because the size of the mould used for sample preparation is small and also the two apparatus used to determine gas transport parameters mainly designed for the small mould. Particle size distribution curve for selected material is shown in Figure 1.

![Figure 1 Particle size distribution of laterite soil](image)

2.3. Compaction Energy

Three types of compaction energy levels were used to find the effect of compaction on gas transport parameters. Maximum dry unit weight values with optimum moisture contents for three compaction energy levels conducted for less than 2.36mm sieve range are shown in Table 2. Graphical representation of compaction results are shown in Figure 2.

<table>
<thead>
<tr>
<th>Energy Level</th>
<th>Maximum dry unit weight (kN/m³)</th>
<th>Optimum moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard energy</td>
<td>15.8</td>
<td>23.4</td>
</tr>
<tr>
<td>Intermediate energy</td>
<td>16.4</td>
<td>19.7</td>
</tr>
<tr>
<td>Modified energy</td>
<td>16.8</td>
<td>18.3</td>
</tr>
</tbody>
</table>

![Figure 2 Compaction curves for three energy levels](image)

All soil samples were prepared under standard Proctor compaction method by varying moisture content. Samples were prepared representing both dry and wet side of optimum moisture content. After preparing 100 cm³ soil samples, kₐ and Dₚ were measured using air permeameter and diffusion
chamber respectively. Since moisture content was already varied in sample preparation, compaction energy and particle sizes were changed to find the effect on $k_a$ and $D_p$.

### 2.4. Determination of Air Permeability

Air permeability of the soil, which is depend on soil-air pressure gradient, can be determined in the laboratory by flowing air at a given inlet pressure through soil core samples. Schematic diagram of the air permeameter is shown in Figure 3 and the apparatus used in the laboratory to measure air permeability is shown in Figure 4.

![Figure 3 Schematic diagram of air permeameter](image1)

![Figure 4 Parts of air permeameter](image2)

Prepared sample under standard compaction method is fixed to the air permeameter on top of the porous plate. Clear horses are connected to the flow meter, sample and also to pressure difference indicator. Pressured air is applied by the compressor machine to the upper layer of the soil sample and air flows through the sample confined by the ring under steady condition and eventually escaped into the atmosphere through the porous plate. Using the pressure gauge, atmospheric air pressure and air pressure at the top of the sample can be measured. Therefore pressure difference through the sample can be determined. Air flow meter is obtained by the flow meter. The graph of flow rate vs. pressure difference is plotted by changing air flow rate. Coefficient of air permeability, $K_a$ ($m^2$) can be determined using Darcy’s equation based on pressure difference across the core using Eq. (3) (Wickramarachchi et al., 2011).

$$k_a = \frac{mH\eta}{A}$$  \hspace{1cm} (3)

Where,
- $m$ - Gradient of flow rate vs. pressure difference graph ($m^3$/Pa.s)
- $H$ - Length of the sample (m)
- $\eta$ – Viscosity of air (Pa.s)
- $A$ – Cross sectional area of the sample ($m^2$)

### 2.5. Determination of Diffusivity

Diffusion coefficient, $D_p$ ($m^2s^{-1}$) is determined in the laboratory by using gas diffusion chamber method. (Wickramarachchi et al., 2011). Schematic diagram of determination of diffusivity and the setup used in laboratory to measure the gas diffusion are shown in Figure 5 and Figure 6 respectively.

The experimental procedure used to determine the gas diffusion coefficient $D_p$ is based on decreasing source concentration with time. The prepared soil sample is placed on top of the chamber. The gas diffusion ($D_p$) is measured at 20°C and Oxygen is used as tracer gas. At the beginning, Nitrogen
cylinder is connected to the N2 inlet and the cell is purged with humidified nitrogen (to prevent humidity loss in the sample) until the oxygen concentration of the entire cell stabilizes to zero (almost no entrapped oxygen remains in the small sample). Oxygen sensor which is connected to the cell indicates O2 concentration and proportional milli-volt value is recorded by the data logger. The source reservoir is then briefly opened by dragging the tray, to reach atmospheric conditions (about 21% oxygen). Once the cell is opened, oxygen migrates from atmosphere into the cell by diffusion due to the concentration gradient. The closed system is then allowed to approach equilibrium (or steady state). Oxygen concentration is measured as a function of time in the diffusion chamber and Dp can be calculated.

Initially oxygen sensor should be calibrated by measuring the initial oxygen concentration of atmosphere and the final oxygen concentration by purging the cell with nitrogen until the oxygen concentration of the entire cell stabilizes to zero. Relative oxygen concentration (Cr) values with respect to time (t) are recorded in data logger. Data logger records millivolt value which sense by the oxygen sensor instead of concentration value as mentioned above. Thus, a plot of ln Cr verses time t becomes linear with gradient \( \frac{D_p \alpha_1^2}{\varepsilon} \) for sufficiently large t. Here \( \alpha_1 \) is calculated from the first iteration of the Eq. (4). From the gradient, gas diffusivity \( D_p \) through porous media can be calculated using Eq. (5).

\[
\alpha_n \tan(\alpha_n L_s) = \frac{\varepsilon}{L_a} \quad (4)
\]

\[
\text{Gradient} = \frac{-D_p \alpha_n^2}{\varepsilon} \quad (5)
\]

Where,

- \( L_s \) – Length of sample (cm)
- \( L_a \) – Length of chamber (cm)
- \( \varepsilon \) – Air content of the soil sample (m³m⁻³)

Gradient - Slope of ln Cₓ vs. time graph (s⁻¹)
3. RESULTS AND DISCUSSION

3.1. Soil-Air Permeability

3.1.1. Effect of Compaction Energy on Air Permeability

Figure 7 illustrates the variation of measured air permeability ($k_a$) of soil samples with different energy levels as a function of moisture content. According to Figure 7, air permeability decreases when energy increases from standard energy to modified energy. It can be clarified as, when energy increases compaction level also increases. Void space inside the soil sample decreases due to higher compaction level. Hence air moving paths are interrupted by solid particles which tend to decrease the air permeability.

![Figure 7 Variation of $K_a$ with moisture content](image1)

3.1.2. Effect of Grain Size Distribution on Air Permeability

Figure 8 illustrates the variation of air permeability ($k_a$) with moisture contents of the soil for three different ranges of sieve sizes. It can be noted that the smallest sieve range (less than 2.36mm) is shown the lowest variation of air permeability while middle sieve range (2.36 – 4.75 mm) is shown the highest variation of air permeability. Although 4.75 – 9.5 mm range have larger grain size particles, when compaction energy is applied some large particles are broken into small particles. It will cause well graded distribution in the sample mould which fill the porous space by reducing air permeability.

![Figure 8 Variation of $K_a$ with moisture content](image2)
3.2. Soil-Gas Diffusivity

3.2.1. Effect of Compaction Energy on Diffusivity

The variation of soil gas diffusivity \( \frac{D_p}{D_o} \) with moisture content for three types of energy levels are depicted in Figure 9. When energy level increases, diffusivity decreases by keeping similar variation with moisture content.

![Figure 9 Variation of \( \frac{D_p}{D_o} \) with moisture content](image1)

3.2.2. Effect of Grain Size Distribution on Diffusivity

Figure 10 illustrates the variation of diffusivity of soil samples with moisture contents of the soil for three different ranges of sieve sizes and intermediate sieve size (2.36 – 4.75 mm) shows the highest variation. It shows the similar variation as air permeability.

![Figure 10 Variation of \( \frac{D_p}{D_o} \) with moisture content](image2)

4. CONCLUSIONS

Based on the series of laboratory experiments, it can be concluded that, intermediate particles sizes compacted with low energy at dry side of optimum moisture content (5 – 10% less than the optimum moisture content) is most suitable for an evapotranspirative cover system in a landfill. It can be noted that findings of this research study were well agreed with existing power law models such as Buckingham and Marshall.
Although direct emission of Methane gas to the environment is badly affects for the humankind, we can use the produced Methane as a fuel for daily usage as a reuse technique. To collect produced methane, gas collection system is required for the landfill. Then we can use Methane as bio gas or convert the energy into source of electricity. But the major problem of the implementation of these kinds of systems is the cost. Otherwise if possible we can use Methane as a fuel in Sri Lanka also as a developing country.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to SATREPS Project for the financial support to make this research a success.

REFERENCES


Kumari, WGP, Sanjaya, SKE 2013, ‘Selection of Suitable Material for Final Cover of an Engineered Landfill in Dry Zone’, Undergraduate research project thesis, University of Ruhuna.

