



Determination of Intrinsic Permeability for Packed Waste of Indonesian Solid Waste

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Abstract. Gas permeability and intrinsic permeability are the major parameters to promote aeration for packed waste. The objectives of this research are to identify physical parameters of gas transfer from a various type of packed wastes and examine ventilation design theory for landfill to enhance waste stabilization. Method to determine value of gas permeability and intrinsic permeability for packed waste is by flushing the packed column containing various type and physical characteristics of wastes with an air pump. Permeability was calculated by measuring pressure gradient on sampling points of the column using inclined manometer at distance 10 cm, 23 cm, 46 cm, 69 cm, 92 cm and 115 cm from origin. Gas permeability is specifically relied on physical parameters of wastes as follows, density, moisture content, particle size and gas velocity on the surface of compacted waste layer. Compost has finer pore structure and smaller pore size than leaves as well as mixed organic (65%) and inorganic wastes (35%). The experiment found the intrinsic permeability of leaves waste are in the order of 10^{-11} to 10^{-8} m², 10^{-11} to 10^{-9} m² for compost and 10^{-9} m² for mixed organic (65%) and inorganic wastes (35%).

Keywords: *intrinsic permeability; packed wastes; permeability.*

1 Introduction

Landfill plays an important role in waste management [1]. However, it will potentially generate GHG (Green House Gases), so it may cause environmental pollution problem. Landfill will definitely emit methane gas (CH₄) that has potential GHG 21 times larger than CO₂. A number of researches were conducted to measure methane gas generation as the largest GHG element in landfill [2-3]. When the amount of waste increased and various products are developed and discarded, natural capacity of decomposition was not sufficient [4]. Waste degradation with aerobic process relying on oxygen availability in the atmosphere is limited and anaerobic process will then predominate [5].

At the initial stage of oxygen intrusion, oxygen diffuses into the waste layer very quickly due to the large flux driven by the large gradient of the oxygen concentration. After that the oxygen concentration is increased slowly due to the

negative feedback of the reduced gradient and decreased oxygen consumption [6]. One alternative technique to control methane and enhance longer aerobic degradation time is by supplying air into waste layer using aeration system. To identify parameters on landfill design with waste type and characteristic in Indonesia, an experiment was conducted to examine gas transfer phenomena for packed waste [5]. The experiment discusses about air movement in packed waste supplied by ventilator, with gas permeability and intrinsic permeability as major parameters. Gas transfer phenomenon in waste cell of Indonesian landfill was not clearly described by the study of landfill gas generation [7] nor by the study of aeration in composting process [8]. Understanding gas transfer phenomenon is important for modeling aerobic and anaerobic biodegradation in a municipal solid waste landfill [9] as well as for analyzing air and landfill gas movement through passive gas vents [10].

Gas transfer is a physical phenomenon, gas molecules diffusion in waste pores. Gas absorption is influenced by pressure gradient and air temperature. Gas diffuses to pores available in waste layer. Gas permeability controls gas transfer through a porous media in response to a pressure gradient on packed waste. Refers to Darcy's law, gas permeability coefficient K_g' can be determined by measuring pressure gradient (ΔP) on packed waste. Parameter ΔP rely on distance (L) from waste surface layer to sampling points at very low velocity (v) that enhance laminar air flow [5]. Darcy's law shows air velocity in pore space v has a linear relation with pressure gradient, except while pressure gradient is very low [11]. Gas permeability K_g' and intrinsic permeability K is calculated using Equation (1) and (2) based on Darcy's law [5].

$$K_g' = \frac{vL}{\Delta P} \quad (\text{Kallel [5]}) \quad (1)$$

$$K = \mu K_g' \quad (\text{Kallel [5]}) \quad (2)$$

Moisture content ω and waste density ρ show physical characteristics of waste. Porosity ϕ as one of physical parameters determined air flow in packed waste is defined as the volume of void space (volume of gas and water) per volume of waste, while gas-filled porosity ε is defined as volume of gas space per waste volume. Dry density ρ_d is defined as mass of dry material per total volume of waste and particle density ρ_p is ratio of dry material mass to unit volume. Porosity ϕ , gas-filled porosity ε and degree of saturation S_r can be estimated using parameters moisture content ω , volumetric moisture content ω_v , particle density ρ_p and dry density ρ_d , using Equation (3), (4) and (5) [5].

$$\varphi = 1 - \frac{\rho_d}{\rho_p} \quad (\text{Kallel [5]}) \quad (3)$$

$$\varepsilon = \varphi - \omega \frac{\rho_d}{\rho_{\text{air}}} \quad (\text{Kallel [5]}) \quad (4)$$

$$S_r = \frac{\omega_v}{\varphi} \quad (\text{Kallel [5]}) \quad (5)$$

2 Methodology

The experiment was conducted using packed waste in a column with a various type of wastes (see Table 1). Those samples had different physical characteristics. Wastes were shredded before measuring pressure gradients.

Table 1 Description of sample composition.

Sample	Density (g.cm ⁻³)			
	0.32	0.46	0.55	0.74
Leaves waste	√	-	-	√
Compost	-	√	√	√
Mixed organic (65%) and inorganic (35%) wastes	√	√	√	-

The experiment consisted of static pressure gradient measurement in a 10.8x10³ cm³ column made of PVC pipe material with 10.5 cm diameter and 125 cm long. Each side of the column was enclosed using same material and set ventilators to enhance fix air velocity. The column was put horizontally. There are seven sampling points on the body of the column to measure static pressure gradients. Air was supplied from an air pump into the column where waste sample was packed. The static pressure gradient measurement on each sampling point was performed with 5-10 kinds of air velocities referred to the method developed by Kallel [5]. Air flow was controlled using control valve and measured by a flow meter (see Figure 1).

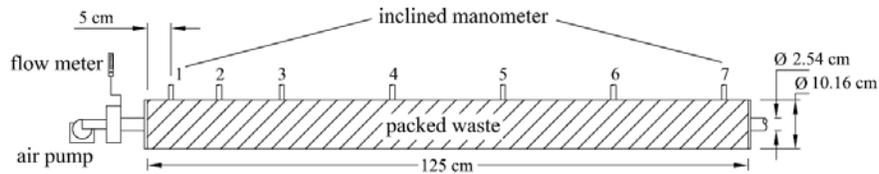


Figure 1 Model on determining gas permeability for packed Indonesian waste.

Samples were taken from a waste treatment facility and also a traditional market in Bandung, Indonesia. After sampling in the waste treatment facility, those wastes were shredded immediately using shredding machine. In every experiment, sample was mixed to gain a uniform condition. The shredded sample was brought to the laboratory to be filled into the column. To simulate density in landfill, the sample was packed until gaining the expected density using manual compactor.

Static pressure gradient ΔP is measured using inclined manometer connected to the sampling points on the column containing packed waste at distances 10 cm, 23 cm, 46 cm, 69 cm, 92 cm and 115 cm. Air velocity v was referred to air velocity in pore space. $\Delta P/L$ ratio is determined from linear graphic between ΔP (y axis) and L (x axis). As air velocity is known before, the gas permeability (K_g) can be obtained and then converted to intrinsic permeability (K) using Darcy equation, Equation (1) and (2) [5]. Density of water ρ_{water} was determined by measuring water temperature in a flask and gas viscosity μ_{gas} by measuring dry environment temperature.

Particle size distribution was mechanically analyzed using sieve analysis. Mesh diameter was gradually smaller in the order of 3.71 cm to 1.06×10^{-2} cm. Samples were dried at approximately 60°C, and then sieved for about 15 minutes. Sample retained in every mesh was weighed. Sample fraction was mentioned as a percentage of total sample weight and analyzed in a semi-logarithmic scale graphic, and figured in a particle-size distribution curve. Diameter in particle-size distribution curve fit to 10% passing was defined as effective particle size, d_{10} [11].

Dry density ρ_d and particle density ρ_p parameters were needed to find porosity ϕ . To find dry densities ρ_d , mass of dry material was measured by drying samples at 105°C. Particle densities ρ_p were determined in triplicate using dry samples and water in a 1000 mL flask put under air suction with a vacuum pump. Displaced water volume is volume of particles. Density of water ρ_{water} is assumed to be 1 g.cm^{-3} .

3 Results and Discussion

Permeability in packed waste was affected by particle size distribution. Particle size distribution of leaves waste and compost were examined using sieve analysis (see Figure 2). Based on same experiment conducted by Kallel [5], intrinsic permeability K was increasing with the effective particle size, d_{10} .

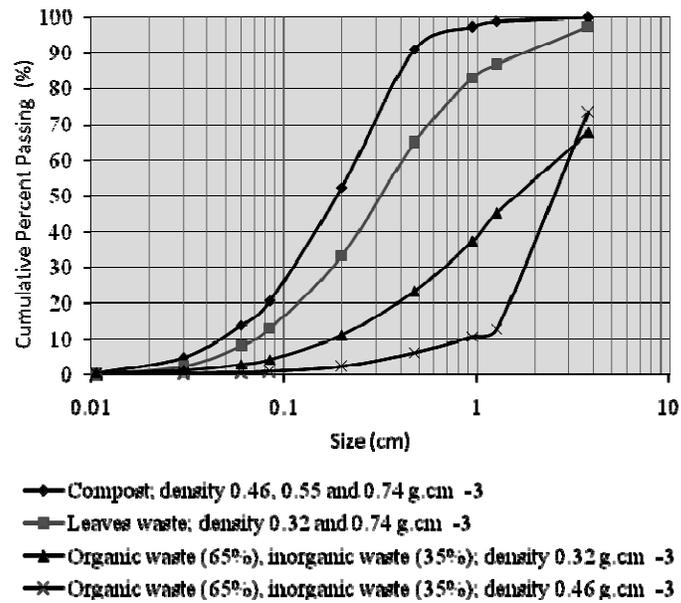


Figure 2 Particle-size distribution analysis.

Table 2 Physical characteristics of samples

Sample	Run	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		ρ (g.cm ⁻³)	ρ_d (g.cm ⁻³)	ρ_p (g.cm ⁻³)	ϕ (-)	ω (-)	ε (-)	ω_v (-)	S_r (-)
Leaves waste	1	0.74	0.57	0.96	0.403	0.226	0.274	0.167	0.414
	2	0.32	0.15	4.18	0.848	0.551	0.768	0.178	0.210
Compost	1	0.46	0.37	4.18	0.911	0.197	0.838	0.091	0.100
	2	0.55	0.45	4.18	0.893	0.197	0.806	0.109	0.122
	3	0.74	0.59	0.63	0.858	0.197	0.741	0.146	0.170
Mixed organic (65%) and inorganic (35%) wastes	1	0.32	0.14	0.63	0.781	0.575	0.702	0.186	0.238
	2	0.46	0.19	0.83	0.772	0.590	0.660	0.273	0.353

Symbols information:

- (1) ρ : waste density
- (2) ρ_d : dry density
- (3) ρ_p : particle density
- (4) ϕ : porosity (gas and water)
- (5) ω : moisture content
- (6) ε : gas-filled porosity
- (7) ω_v : volumetric moisture content
- (8) S_r : degree of saturation

Particle size distribution influenced gas diffusion in packed waste and porosity ϵ is one of physical parameters to show pore structures. In the case of leaves waste, porosity ϵ ranged between 0.2 and 0.8, while compost showed value around 0.7 and 0.8 and mixed organic (65%) and inorganic wastes (35%) between 0.6 and 0.7. Contrary to the experiment by Kallel [5] for incinerator ash, shredded bulky waste and shredded incombustible waste showed wide range values of around 0.03 and 0.6. Pore structures condition of those wastes was finer than leaves waste, compost and mixed organic (65%) and inorganic wastes (35%). This condition affected gas diffusion in packed wastes. Physical characteristics of samples are listed in Table 2.

Different type of samples, at the same density, showed pressure gradient difference though was measured in the same distance (see Figure 3).

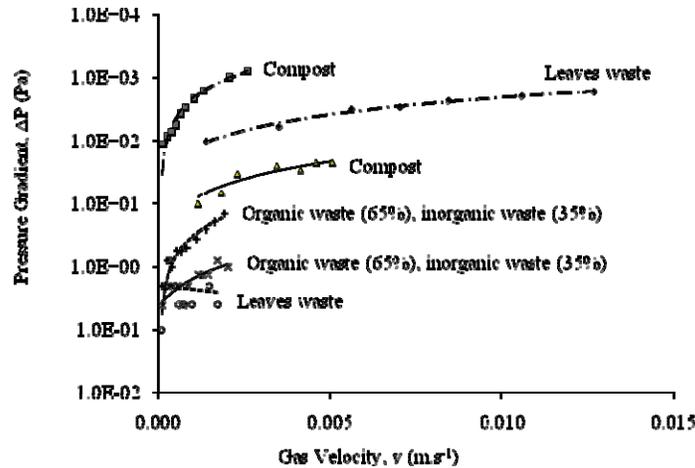


Figure 3 Relationship between pressure gradient and gas velocity (at distance 0.46 m).

At the same density 0.74 g.cm^{-3} , pressure gradient for compost was higher than leaves waste. For instance, pressure gradient for compost at nearly same gas velocity around $1.4 \times 10^{-3} \text{ m.s}^{-1}$ was about 607 Pa while leaves waste only in the order of 98 Pa (see Figure 3). Significant difference was shown between compost and mixed organic (65%) and inorganic (35%) wastes at the distance of 1.46 g.cm^{-3} . For example, pressure gradient for compost at gas velocity about $1.2 \times 10^{-3} \text{ m.s}^{-1}$ was around 9.8 Pa , higher than mixed organic (65%) and inorganic (35%) wastes with value of around 0.7 Pa . Pressure gradient for mixed organic (65%) and inorganic (35%) wastes at density 0.32 g.cm^{-3} and gas velocity about 10^{-3} m.s^{-1} was insignificant higher than leaves waste at the same

density and gas velocity. Pressure gradient for mixed organic (65%) and inorganic (35%) wastes was about 2.7 Pa while leaves waste showed value of 0.2 Pa. It might explain that pore structure of compost was finer as well as had smaller pore diameters than both leaves waste and mixed organic (65%) and inorganic (35%) wastes.

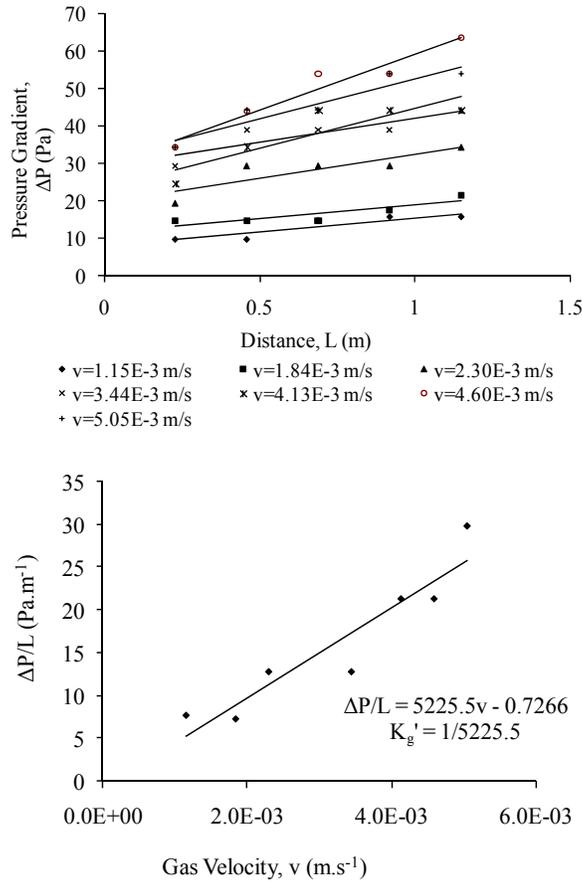
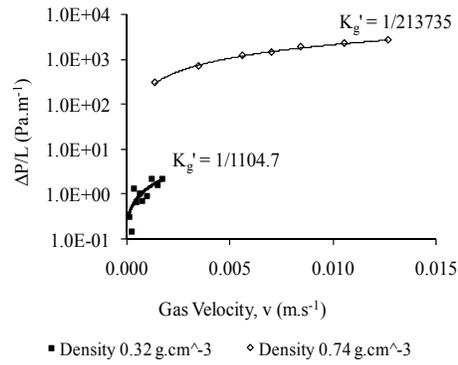
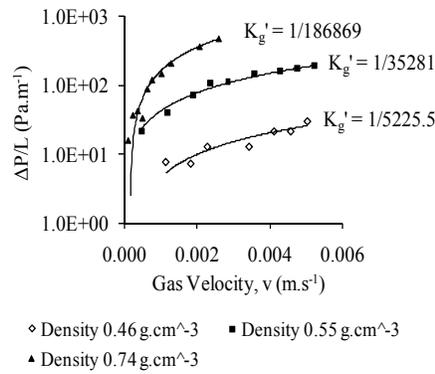


Figure 4 Gas velocity and pressure gradient for gas permeability determination (data of compost sample at density 0.46 g.cm⁻³).

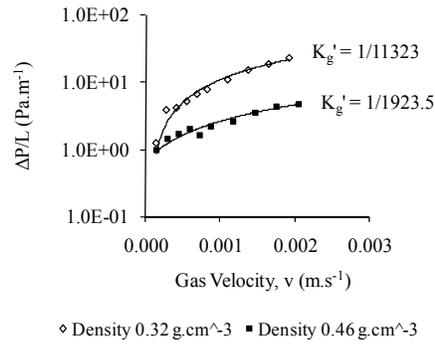
$\Delta P/L$ ratio in several type and density of wastes were determined as the example shown in Figure 4. With a known gas velocity, values of permeability K_g' can be obtained and then converted to intrinsic permeability K .



(a) Leaves waste



(b) Compost



(c) Organic waste (65%), inorganic waste (35%)

Figure 5 Variation of permeability value with density.

Linearity of data demonstrates and confirms homogeneity of packing operation. In analysis developed by Kallel [5], K_g' and K were analyzed by trend line with intercept = 0. However in this study, determination of K_g' and K from the plotted data were analyzed by trend lines with intercept $\neq 0$ resembling value in the observation range. It was then mentioned as K_g' (not K_g) because estimated pressure gradients were at the specific distance, 10 cm, 23 cm, 46 cm, 69 cm, 92 cm and 115 cm, except for compost excluded distance 10 cm from origin point. Analysis using trendline with intercept = 0 for graphics explaining relationship between ΔP and L would cause high standard error and very low R^2 . In addition, pressure gradient at distance less than 10 cm from origin point, which closed to surface waste layer, was found a insignificant value to determine K_g' and K . For example, static pressures of compost sample at density 0.46 g.cm^{-3} was measured using seven various air flows. Figure 4 showed the ratio of $\Delta P/L$ for the compost sample was approximately 5225.5 v. Permeability value which was calculated using Equation (1) was $1/5225.5$.

Gas permeability is influenced by degree of waste compaction (see Figure 5). Leaves waste at densities 0.32 and 0.74 g.cm^{-3} showed value of K_g' 10^{-4} and $10^{-6} \text{ m}^2.\text{Pa}^{-1}.\text{s}^{-1}$. Compost with a various densities of 0.46 , 0.55 and 0.74 g.cm^{-3} showed a range of K_g' values between 10^{-6} and $10^{-9} \text{ m}^2.\text{Pa}^{-1}.\text{s}^{-1}$ while mixed organic (65%) and inorganic (35%) wastes around 10^{-5} and $10^{-4} \text{ m}^2.\text{Pa}^{-1}.\text{s}^{-1}$.

Permeability K_g' tended to decrease with an increase of compaction degree as shown by leaves waste and compost. Conversely, trend of K_g' value shown by mixed organic (65%) and inorganic (35%) wastes. Value of permeability K_g' at density 0.32 g.cm^{-3} , about $8.8 \times 10^{-5} \text{ m}^2.\text{Pa}^{-1}.\text{s}^{-1}$, was lower than density 0.46 g.cm^{-3} ($K_g' = 5.2 \times 10^{-4} \text{ m}^2.\text{Pa}^{-1}.\text{s}^{-1}$). It might explain inhomogeneous degree of compaction at several distances, particularly at distance near the gas source.

Similar to the value of permeability K_g' , intrinsic permeability K tended to decrease with an increase of compaction degree as shown in Figure 6. Value of intrinsic permeability K for leaves waste at density 0.74 g.cm^{-3} was about 10^{-11} m^2 and about 10^{-8} m^2 at density 0.32 g.cm^{-3} . A similar density with leaves waste, 0.74 g.cm^{-3} , compost showed same value of K about 10^{-11} m^2 . At density 0.55 g.cm^{-3} , intrinsic permeability K for compost showed higher value about 10^{-10} m^2 and 10^{-9} m^2 at density 0.46 g.cm^{-3} . Intrinsic permeability K for mixed organic (65%) and inorganic (35%) wastes at density 0.32 and 0.46 g.cm^{-3} were both at the same range value 10^{-9} m^2 .

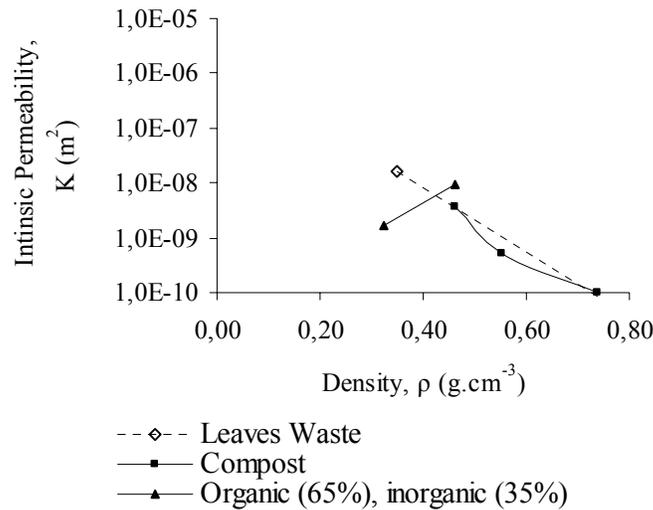


Figure 6 Variation of density influence on intrinsic permeability value.

Compare to experiment results of Kallel [5] which showed values of K between 10^{-10} and 10^{-9} m^2 for different kinds of samples, except for several incinerator ash samples (between 10^{-12} and 10^{-11}) and shredded bulky waste (about 10^{-8} m^2). Degree of compaction was the order of 0.6 to 1.7 g.cm^{-3} with smaller particle-size fraction. Value of K for bulky waste for each density was about 10^{-10} m^2 , though value of K at density 0.884 g.cm^{-3} was larger than at density 0.797 g.cm^{-3} . Similar value was shown by mixed organic (65%) and inorganic (35%) wastes. Value of K at density 0.46 g.cm^{-3} was higher than at density 0.32 g.cm^{-3} , though had same range value to the order of 10^{-9} m^2 (see Table 3). It might be caused by inhomogeneous degree of compaction as mentioned before, though still needed another measurement to the same sample at different density variation.

Table 3 Comparison of density variation and intrinsic permeability value.

(a) Experiment results

Sample	ρ (g.cm^{-3})	K (m^2)
Leaves waste	0.74	8.69E-11
	0.32	1.66E-08
Compost	0.46	3.57E-09
	0.55	5.29E-10
	0.74	9.79E-11
Organic waste (65%), inorganic waste (35%)	0.32	1.63E-09
	0.46	9.58E-09

(b) Experiment results by Kallel [5]

Sample	ρ (g.cm^{-3})	K (m^2)
Bulky waste	0.797	5.3E-10
	0.884	6.0E-10
	0.672	8.6E-10
Incombustible waste	1.277	2.0E-10
	1.404	6.9E-11
Incinerator ash	1.067	2.1E-10
	1.321	5.0E-11

Resistance of gas diffusion can be occurred as effects of moisture content and pore size in packed waste. Figure 7 showed the influence of moisture content on intrinsic permeability. The increase of moisture content for leaves waste tended to decrease intrinsic permeability with highest value of saturation degree about 0.4. Significant influence of moisture content on intrinsic permeability was shown by compost. At density 0.74 g.cm^{-3} , intrinsic permeability K for compost was lower than leaves waste although compost had lower moisture content because compost layer pores were effectively closed, even with a small amount of moisture. The data were considered to represent physical characteristics of wastes in Bandung which generally showed high moisture content, though still needed further experiment to find saturation degree S_r for different physical composition of wastes.

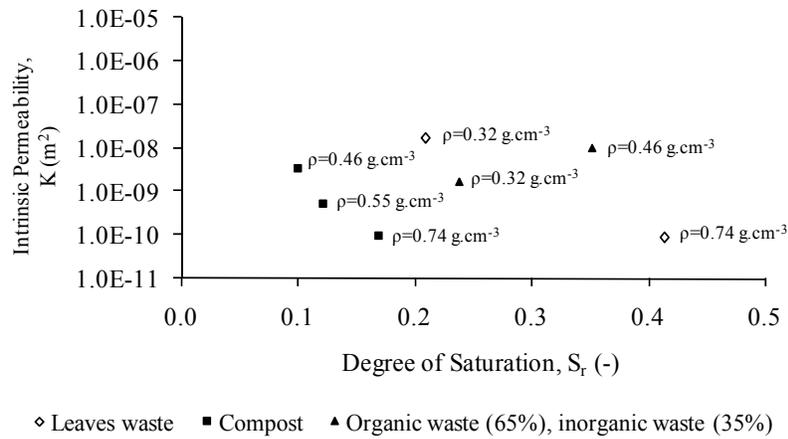


Figure 7 Relationship between intrinsic permeability and degree of saturation.

Permeability K_g and intrinsic permeability K are specifically relied on physical characteristics of waste, for example density, moisture content, particle size and gas velocity on the surface of waste layer, that also affected porosity in packed waste. Physical characteristics and intrinsic permeability value of all samples are shown in Table 4.

Tortuosity ξ value is needed to be estimated to measure pore space r which influence gas diffusion into waste layer. Based on experiment by Kallel [5], value of tortuosity ξ are in the order of 2 to 10. Moisture content ω is noticed to affect tortuosity ξ because wet state caused decreasing of free space for gas diffusion. ϵ/ξ ratio is also convenient to obtain effective diffusion coefficient so the influence of porosity on gas diffusion coefficient can be determined.

Table 4 Physical characteristics and intrinsic permeability value.

Sample	Run	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
		ρ (g.cm ⁻³)	ρ_d (g.cm ⁻³)	ρ_p (g.cm ⁻³)	ϕ (-)	ω (-)	ε (-)	ω_v (-)	S_r (-)	K_g' (m ² Pa ⁻¹ s ⁻¹)	K (m ²)
Leaves waste	1	0.74	0.572	0.958	0.403	0.226	0.274	0.167	0.414	4.68E-06	8.69E-11
	2	0.32	0.145	4.175	0.848	0.551	0.768	0.178	0.210	9.05E-04	1.66E-08
Compost	1	0.46	0.371	4.175	0.911	0.197	0.838	0.091	0.100	1.91E-04	3.57E-09
	2	0.55	0.445	4.175	0.893	0.197	0.806	0.109	0.122	2.83E-05	5.29E-10
	3	0.74	0.593	0.628	0.858	0.197	0.741	0.146	0.170	5.35E-06	9.79E-11
Organic waste (65%)	1	0.32	0.137	0.628	0.781	0.575	0.702	0.186	0.238	8.83E-05	1.63E-09
inorganic waste (35%)	2	0.46	0.189	0.831	0.772	0.590	0.660	0.273	0.353	5.20E-04	9.58E-09

Symbols information:

- (1) ρ : waste density
- (2) ρ_d : dry density
- (3) ρ_p : particle density
- (4) ϕ : porosity (gas and water)
- (5) ω : moisture content
- (6) ε : gas-filled porosity
- (7) ω_v : volumetric moisture content
- (8) S_r : degree of saturation
- (9) K_g' : permeability
- (10) K : intrinsic permeability

On the simple application to obtain passive oxygen diffusion to enhance stabilization, it is necessary to calculate pressure gradient for landfill. For instance, waste density ρ in landfill is 462 kg.m⁻³. Assumed that ventilation pipe is set in the landfill area and gas flow should be reached at distance 25 m horizontally, and gravitational acceleration 9.81 m.s⁻². So, the pressure gradient needed to enhance that condition is determined by:

$$\Delta P = \rho \cdot g \cdot h = 462 \text{ kg.m}^{-3} \cdot 9,81 \text{ m.s}^{-2} \cdot 25 \text{ m} = 113,3 \text{ kPa.}$$

Based on experiment by Wildani (2009) in several waste processing facilities in Bandung, average oxygen consumption for organic waste is about 15.1 mg O₂/g Total Solid. From the information above, oxygen necessity and blower capacity for aeration can be determined.

4 Conclusions

Physical parameters are needed for landfill design to examine gas transfer phenomena in packed waste. Experiment was conducted for packed waste aerated with 5-10 gas velocity variation. Pressure gradient was measured using inclined manometer. Permeability was influenced by density and particle-size fraction. Compost had finer pore structure and smaller pore diameter than leaves waste and mixed organic (65%) and inorganic (35%) wastes. At density 0.74 g.cm⁻³, intrinsic permeability for compost is lower than leaves waste though

compost had less moisture content because compost layer pores were effectively closed, even with a small amount of moisture. The experiment found the intrinsic permeability of leaves waste are in the order of 10^{-11} - 10^{-8} m², 10^{-11} - 10^{-9} m² for compost and 10^{-9} m² for mixed organic (65%) and inorganic wastes (35%). Permeability is specifically relied on density ρ , moisture content ω , particle size and gas velocity in pores.

Acknowledgement

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