Experiment and model study of gas preferential penetration of municipal solid waste

G Zeng1,2,3, Y X Li1, L T Cao1 and J Wang4
1 Hubei University of Arts and Science, Xiangyang 441053, China
2 Changjiang River Scientific Research Institute, Wuhan 430010, China
3 Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

Corresponding author’s e-mail address: zg_cersm@163.com (G Zeng)

Abstract. Municipal solid waste (MSW) has various components, different sizes and strong heterogeneity. The significant preferential flow effect of MSW directly affects the migration path of landfill gas. Laboratory tests on the gas breakthrough curve of MSW under the influence factors of initial pressure and moisture content were carried out by self-developed gas permeability test device. The experimental results showed that the peak value of gas breakthrough curve increased gradually with the increase of initial pressure, and increased with the increase of moisture content. A mathematical model for describing gas migration in the macro-porous region and the fractured region was established based on the theory of pore-fracture seepage in porous media. The whole process of gas passing through the MSW sample was simulated. The simulation results showed that the higher the ratio of permeability between the crack and the pore, the greater the peak value of gas breakthrough curve, and the shorter the time of gas passing through the sample. As the proportion of fractured area in pore space decreased, the peak value of gas breakthrough curve decreased gradually.

Keywords: municipal solid waste; landfill gas; preferential flow; model

1. Introduction
The composition of municipal solid waste (MSW) is complex, and the particle size and distribution of each component are uneven, which leads to the strong heterogeneity of MSW [1-2]. MSW is a highly heterogeneous medium. Due to the treatment method of layered landfill and compaction of waste, there is obvious horizontal stacking in waste soil, resulting in obvious anisotropy of MSW [3]. The significant heterogeneity of the pore structure of the waste dump determines the heterogeneity of its permeability distribution, which directly affects the gas migration path [4-6]. There is a significant dominant seepage phenomenon in the landfill [7-9]. Mcrenanor et al tried to use the dual permeability or dual porosity model to describe the dominant flow of leachate in refuse [10]. Rosqvist et al explained the crossing curve test through the leachate transport model in MSW, and found that the dominant flow phenomenon lasted for a long time [11]. Han et al. Measured the flow rate of water in the cylinder with a uniform sample size of 4cm, and found that the dominant flow phenomenon is still obvious [12]. Liu et al studied the gas pressure dropping test to describe the gas preferential flow in waste column [8]. Zhang et al carried out the dye tracing tests and solute breakthrough tests to study the preferential flow in MSW and to quantify the flow character [9]. This paper introduces the self-developed test equipment for gas permeability characteristics of MSW, and carries out the indoor test of gas dominant permeability.
characteristics of waste soil under the influence factors of initial pressure and moisture content, and obtains the test rules of gas dominant permeability characteristics, which provides data support for the subsequent model parameters. A pore fracture dual zone permeability model was established based on dual media seepage theory to describe the phenomenon of gas dominant permeability. The reliability of the model was verified by comparing the outflow rate of laboratory test data and model simulation results.

2. Materials and methods

2.1. Materials

Although the on-site waste sampling is relatively real, the representativeness of the samples is still questionable due to the uneven distribution of domestic waste and the randomness of sampling. In addition, the samples obtained from the site often need to be sorted to determine the composition. The artificial preparation of waste samples is a new way to study the regularity of waste disposal, which is based on the data statistics of various components of waste in landfills at home and abroad, using materials with similar properties to replace various components and preparing samples according to the overall proportion. It has the advantages of low cost, controllable conditions and high repeatability. The sample consisted of 50% food, 15% paper, 3% textile, 3% plastic, 3% wood, 6% glass and 20% soil. The basic physical properties of samples were performed in accordance with the standard test method for landfill MSW (CJJ/T 204-2013) [13]. The data of moisture content, density, organic matter content and pore ratio of the samples are as follows: 54.6%, 0.9g/cm³, 57.2%, 2.2. The maximum grain size corresponded to approximately 25% of the cell diameter [14]. The sample size was artificially broken to less than 2.5 cm. Each component of the broken sample was reserved for use.

2.2. Method

2.2.1. Test equipment. The test equipment was shown in Figure 1. The equipment could complete the gas permeability, porosity and gas dominance permeability tests of MSW.

![Test equipment for gas permeation of municipal solid waste MSW](image)

**Figure 1.** Test equipment for gas permeation of municipal solid waste MSW

The components of the test equipment were described as follows. 1 was nitrogen cylinder, 2 was fixed frame, 3 was pressurized cylinder, 4 was solenoid valve, 5 was displacement transducer, 6 was loading piston, 7 was pressure sensor, 8 was gas standard pressure chamber, 9 was six-way valve, 10 was sample cylinder, 11 was fixed base, 12 was control box, 13 was pressure, displacement, gas pressure and flow
display panel, 14 was connecting line, 15 was sample inlet control valve, 16 was loading pressure control valve, 17 was flowmeter control valve, 18 was solenoid valve lifting control button, 19 was power switch, 20 was cylinder floating joint.
The operation steps of the test equipment were as follows: (1) close the outlet valve and the inlet valve of the sample pressure chamber of the sample cylinder to prevent the gas from flowing out; (2) fill the gas standard pressure chamber with gas to reach a certain constant pressure value; (3) open the outlet and inlet valves of the sample pressure chamber of the sample cylinder, and record the gas flow at the outlet of the sample pressure chamber of the sample cylinder.

2.2.2. Test method. The main purpose of this paper was to carry out the gas dominant permeability test of samples under the influence of different initial pressure and different moisture content. The parameters in the constructed dual zone permeability model were inversed through the data of gas permeability and porosity of samples. If the pressure was too small, the gas could not pass through the waste sample, so the initial pressure was 0.1MPa, 0.05MPa and 0.02MPa. The moisture content was 54.6%, 70.6% and 86.6% respectively. The moisture content set in the test scheme can be achieved by adding water to the sample.

3. Test results and analysis

3.1. Influence of initial pressure on gas preferential permeation

The test results of gas crossing curve under different initial pressures of 0.1MPa, 0.05 MPa and 0.02MPa were shown in Figure 2. The test was completed as the gas flow rate at the outlet was close to 0 and remained constant.

![Figure 2. Breakthrough curves under different initial pressures](image)

It can be seen from Figure 2 that the gas flow velocity at the outlet presents the same trend which first increases and then decreases with time under the three initial pressure conditions. The reason for this trend was due to the test was a pressure drop method. The gas pressure in the standard chamber was larger in the early stage of the test, which led to the increase of the gas flow rate at the outlet at the first and gradually reaching the peak value. With the gas pressure in the standard pressure chamber decreased continuously as the test goes on, the gas flow rate at the outlet decreases continuously. The peak value of gas flow rate gradually increases and the time for gas to reach stability also increases with the increase of initial pressure.

3.2. Influence of moisture content on gas preferential permeation

The distribution of gas dominant penetration through curve of waste soil with different moisture content was shown in Figure 3. It can be seen from Figure 3 that with the increase of moisture content of the waste sample, the rising amplitude and peak value of the crossing curve of MSW increase gradually, and the time for the gas to reach equilibrium decreases continuously. This may be because the small
pore area is occupied by water, which increases the permeability ratio between the large pore area and the small pore area, which leads to the gas flowing out of the macro-porous area first, thus forming the phenomenon of increasing peak value of the crossing curve. Therefore, the change of gas flow rate was not only related to the total permeability and porosity of MSW, but also needed to consider the changes of permeability and porosity in macropores and micropores.

![Figure 3. Breakthrough curves under different moisture content](image)

The values of total permeability and total porosity of waste samples with increase of moisture content were $1.096 \times 10^{-12} \text{m}^2$, $0.937 \times 10^{-12} \text{m}^2$, $0.787 \times 10^{-12} \text{m}^2$ and $0.573$, $0.501$, $0.358$ respectively. The test methods of permeability and porosity of MSW were introduced by Zeng et al [15].

4. Mathematical model of gas dominant infiltration of MSW

The main difference between dual media and general porous media is that there are two permeabilities and two porosities at any micro element volume in dual media. Gas flowed not only in the two areas of the cracks and pores of MSW, but also between the two areas [16-17].

Gas dominant permeability model was written in the form of double permeability as follows:

$$
\frac{\partial}{\partial t} (\rho_f \phi_f) = \nabla (\rho_f \frac{k_f}{\mu} \nabla (P_f)) + Q_{mf} \tag{1}
$$

$$
\frac{\partial}{\partial t} (\rho_m \phi_m) = \nabla (\rho_m \frac{k_m}{\mu} \nabla (P_m)) - Q_{mf} \tag{2}
$$

Where, the subscript $f$ represents the fracture area and the subscript $m$ represents the pore area; $\rho_f$ and $\rho_m$ were the gas density of fracture and pore area respectively; $\phi_f$ and $\phi_m$ were the gas porosity of fracture and pore area respectively; $k_f$ and $k_m$ were the gas permeability of fracture and pore area respectively, $\text{m}^2$; $\mu$ was the viscosity coefficient of the gas, $\text{mPa} \cdot \text{s}$; $P_f$ and $P_m$ were the gas pressure of fracture and pore area respectively, Pa; $Q_{mf}$ was the gas exchange term between pore and fracture area.

There is a relationship between the total permeability and the permeability of the two regions.

$$
k_f = w_f \cdot k_f + (1 - w_f) \cdot k_m \tag{3}
$$

Where, $k_f$ was the total permeability, it can be obtained through indoor test. $w_f$ was the ratio of fracture flow space to total flow space, $0 < w_f < 1$.

There is a relationship between the total porosity and the porosity of the two regions.
\[ \phi_l = w_f \cdot \phi_f + (1 - w_f) \cdot \phi_m \]  

(4)

Where, \( \phi_l \) was the total porosity, it can be obtained through indoor test.

The gas exchange term \( Q_{mf} \) can be expressed as follows:

\[ Q_{mf} = \frac{\delta \cdot \phi_m \cdot (P_m - P_f)}{\mu} \]  

(5)

Where, \( \delta \) was the shape factor, \( \delta = \pi \left( \frac{1}{L_x} + \frac{1}{L_y} + \frac{1}{L_z} \right) ; \) \( L_x, L_y, L_z \) was the length of the specimen in the direction of x, y, z.

5. Parameter determination of gas dominant permeation model

The two Darcy flow models were established by COMSOL multiphysics software to represent the constitutive equations of fluid flow in fracture area and pore area respectively. The numerical simulation model was established, the various parameters, the initial conditions and boundary conditions of the model was set. The numerical simulation model was calculated and the results of the calculation were recorded. The parameters of gas dominant permeation model were optimized by comparing with the results of indoor test.

5.1. Numerical simulation model

The numerical model of one-dimensional vertical gas transport through municipal solid waste sample was simulated by COMSOL Multiphysics. The height of the numerical simulation model was \( H \), which was equal to the height of the waste sample 300mm. The diameter of the cylinder sample was 100mm. The top and bottom ports of the sample cylinder were connected by a conduit with an inner diameter of 2 mm, so the pressure boundary width of the top and bottom ports was 2 mm.

5.2. Parameter setting

The unsteady mathematical model of Darcy's law in COMSOL multiphysics software was as follows:

\[ \delta_S \cdot \frac{\partial p}{\partial t} + \nabla \left[ -\delta_k (k_S / \eta \nabla p + \rho_f g \nabla D) \right] = \delta_Q \cdot Q_S \]  

(6)

Where, the values of the proportional coefficients \( \delta_S, \delta_k, \delta_Q \) were 1.

The relationship between parameter \( S \) and porosity was as follows.

\[ S = \frac{\phi M}{RT} \]  

(7)

The gas permeation medium used in the experiment was nitrogen, and the molar mass of nitrogen was 16g/mol. \( R \) was the gas constant, and the value was equal to 8.314 J/(mol \cdot K). \( T \) was the thermodynamic temperature, 293K.

It should be noted that the format and dimension of the control equation in the software should be the same when setting the parameters, and the permeability in the control equation of fracture area and pore area should be set to the corresponding sum value respectively.

5.3. Boundary conditions

The first kind of boundary conditions were used at the inlet and outlet of the waste sample cylinder in the numerical simulation. The inlet of the waste sample column was connected with the inlet of the gas standard pressure chamber through a valve, and the gas flow rate at the inlet of the waste sample column changed with time. The boundary condition at the inlet was simplified as the pressure boundary, which was the pressure value monitored by the pressure sensor. It can be input into the software in the form of
MATLAB language through the expression fitted by the test data. The pressure boundary at the outlet of the waste sample cylinder was simplified as atmospheric pressure.

5.4. Variation of gas dominant permeability under different permeability ratios

Figure 4 showed the gas breakthrough curve distribution under different permeability ratios when the volume ratio was 0.1. Where, 5, 10, 20 and so on were the value of permeability ratio. The total permeability of the sample remained constant, and the influence of different permeability ratio of the fracture to the pore space on the gas breakthrough curves were analyzed.

![Figure 4. Breakthrough curves under different $k_f/k_m$](image)

It can be seen from Figure 4 that the larger the permeability ratio of fracture area to pore area, the larger the peak value of gas crossing curve and the shorter the crossing time. This was mainly due to the increase of permeability in the fracture area with the increase of the ratio $k_f/k_m$, which leads to the acceleration of gas flow rate from the macropore area, thus speeding up the speed of gas passing through the waste medium and shortening the crossing time.

5.5. Variation law of crossing curve under different volume ratios

Figure 5 showed the distribution of gas crossing curve under different volume ratios when the permeability ratio was 10.

![Figure 5. Breakthrough curves under different $w_f$](image)
It can be seen from Figure 5 that with the decrease of $w_f$, the proportion of fracture area in pore space decreases, resulting in the decrease of permeability in fracture area and the decrease of gas outflow at the outlet. Therefore, the peak value of crossing curve decreased with the decrease of $w_f$.

5.6 Parameter determination of gas dominant infiltration model under different moisture content

Figure 6 showed the comparison between the simulated values and the indoor test results of the waste sample crossing curve under different moisture content. Where, $C_v$ was the calculated value of the model.

![Figure 6. Simulated and experimental values of the breakthrough curves under different moisture content](image)

It can be seen from Figure 6 that the optimal calculation value of the model was the same as the variation trend of the gas flow rate monitored by the indoor test, but the value was slightly smaller than the gas flow rate measured by the test. It might be that the actual condition was simplified in the model calculation.

The parameters in the dual permeability model of waste samples with different moisture content were determined through the optimal simulation parameters of the crossing curve. The model values were shown in Table 1. The unit of $k_f$ and $k_m$ in the table were $10^{-12} m^2$.

| moisture content | $k_f$ | $k_m$ | $k_f/k_m$ | $\phi_f$ | $\phi_m$ | $w_f$ |
|-----------------|-------|-------|-----------|----------|----------|-------|
| 54.6%           | 3.319 | 0.849 | 3.91      | 0.094    | 0.626    | 0.1004|
| 70.6%           | 3.167 | 0.691 | 4.58      | 0.073    | 0.659    | 0.0992|
| 86.6%           | 2.902 | 0.555 | 5.23      | 0.035    | 0.393    | 0.0989|

It can be seen from table 1 that with the increase of moisture content, $\phi_f$ and $k_m$ decreases continuously. The permeability ratio $k_f/k_m$ increased with the increase of moisture content, while the porosity ratio $\phi_f/\phi_m$ decreased with the increase of moisture content. This was mainly because the increase of moisture content made the non flow space in fracture area occupied by water, which leaded to the decrease of effective flow space for dominant flow channel.

6. Conclusion
The self-developed gas dominant permeability test equipment can obtain the whole process of gas penetration in waste samples. It was an effective method to quantitatively evaluate the gas dominant flow by measuring the breakthrough curve, which can provide the data of inversion parameters in the dual permeability model. The gas dominant permeability experimental results showed that the peak value of gas breakthrough curve increased gradually with the increase of initial pressure, and increased with the increase of moisture content. A dual permeability model for describing gas dominant penetration was established. The applicability and reliability of the dual permeability model were evaluated by comparing the outflow rate of the monitoring data and the simulation results. The simulation results showed that the higher the ratio of permeability between the crack and the pore, the greater the peak value of gas breakthrough curve, and the shorter the time of gas passing through the sample. As the proportion of fractured area in pore space decreased, the peak value of gas breakthrough curve decreased gradually. The effect of degradation on gas dominant permeability of MSW will be studied in the next step.

7. References

[1] Wu H, Wang H, Zhao Y, et al. Evolution of unsaturated hydraulic properties of municipal solid waste with landfill depth and age[J]. Waste Management, 2012, 32(3): 463–470.
[2] Woodman N D, Siddiqui A A, Powrie W, et al. Quantifying the effect of settlement and gas on solute flow and transport through treated municipal solid waste[J]. Journal of Contaminant Hydrology, 2013, 153:106–121.
[3] Zhang W, Lin M. Evaluating the dual porosity of landfilled municipal solid waste[J]. Environmental Science and Pollution Research, 2019, 26(12): 12080–12088.
[4] Capelo J, Castro M A H. Measuring transient water flow in unsaturated municipal solid waste–a new experimental approach[J]. Waste Management, 2007, 27(6):811–819.
[5] Jung Y, Imhoff P I, Finsterle S. Estimation of landfill gas generation rate and gas permeability field of refuse using inverse modeling[J]. Transport in Porous Media, 2011, 90(1):41–58.
[6] Tinet A J, Oxarango L, Bayard R, et al. Experimental and theoretical assessment of the multi-domain flow behaviour in a waste body during leachate infiltration[J]. Waste Management, 2011, 31(8):1797–1806.
[7] Rosqvist H, Destouni G. Solute transport through preferential pathways in municipal solid waste[J]. Journal of Contaminant Hydrology, 2000, 46(1–2): 39–60.
[8] Liu L, Xue Q, Wan Y, et al. Evaluation of dual permeability of gas flow in municipal solid waste: experiment and modelling[J]. Environmental Progress & Sustainable Energy, 2016, 35(1):41–47.
[9] Zhang W J, Yuan S S. Characterizing preferential flow in landfilled municipal solid waste[J]. Waste Management, 2019.
[10]McCreanor P T, Reinhart D R. Mathematical modelling of leachate routing in a leachate recirculating landfill[J]. Water Research, 2000, 34(4):1285–1295.
[11]Rosqvist N H, Dollar L H, Fourie A B. Preferential flow in municipal solid waste and implications for long-term leachate quality: valuation of laboratory-scale experiments[J]. Waste Management & Research, 2005, 23(4):367–380.
[12]Han B, Scicchitano V, Imhoff P T. Measuring fluid flow properties of waste and assessing alternative conceptual models of pore structure[J]. Waste Management, 2011, 31(3):445–456.
[13]Xue Q. Technical specification for soil test of landfilled municipal solid waste[M]. Beijing, China: China Architecture & Building Press, 2014.
[14]Stoltz G, Gourc J P, Oxarango L. Characterisation of the physico-mechanical parameters of MSW[J]. Waste Management, 2010, 30, 1439–1449.
[15]Zeng G, Liu L, Xue Q, et al. Experimental study of the porosity and permeability of municipal solid waste[J]. Environmental Progress & Sustainable Energy, 2017, 36(6): 1694–1699.
[16] Kohne J M, Mohanty B P, Simunek J. Inverse dual-permeability modeling of preferential water flow in a soil column and implications for field-scale solute transport[J]. Vadose Zone Journal, 2006, 5(1):59–76.

[17] Nie R S, Meng Y F, Jia Y L, et al. Dual porosity and dual permeability modelling of horizontal well in naturally fractured reservoir[J]. Transport in Porous Media, 2012, 92(1):213–235.

Acknowledgments
This research was supported by the CRSRI Open Research Program (CKWV2021874/KY), The Project of Hubei University of Arts and Sciences (XK2021034), National Natural Science Foundation of China (52074112).