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Test Equipment and Application of Gas Permeation Characteristic of MSW

Gang Zeng[1] and Dan Hu[2]
[1,2]*School of Civil Engineering and Architecture, Hubei University of Arts and Science, Xiangyang 441053, China*
E-mail: zg_cersm@163.com

ABSTRACT: In order to study the gas permeation characteristics of municipal solid waste (MSW), a set of test equipment is independently developed. The experimental equipment measures MSW's gas permeability, porosity, and gas preferential flow parameters. The composition and operation method of the equipment are introduced. Moreover, the self-developed equipment carries out laboratory tests on gas permeation of MSW under the influence factors of initial pressure and moisture content. Test application results show that the equipment can realize all pre-designed functions. The experimental results showed that the peak value of the gas breakthrough curve increased gradually with the increase of initial pressure and increased with the growth of moisture content. When the moisture content is 54.6%, 70.6%, and 86.6% as the initial pressure is 0.05 MPa, the gas permeability of MSW is 1.096×10^{-12} m^2, 0.937×10^{-12} m^2, and 0.787×10^{-12} m^2, respectively, and the porosity is 0.573, 0.501, and 0.358, respectively. When the initial pressure of 0.02 MPa, 0.05 MPa, and 0.1 MPa as the moisture content is 54.6%, the peak value of gas flow rate at the outlet of MSW is 0.006 L/s, 0.012 L/s, and 0.02 L/s, respectively, and the time of gas passing through the sample is 47s, 58s, and 65s, respectively. The research results enrich the experimental equipment for studying the gas permeation characteristics of MSW and provide data support for the subsequent research on the migration model of landfill gas.

KEYWORDS: Municipal solid waste, Gas permeability, Porosity, Gas preferential flow, and Laboratory test.

1. INTRODUCTION

The Municipal solid waste (MSW) has reached 360 million tons in 2022 and increase at a rate of 10% per year, according to the statistics of China's National Environmental Protection Bureau.

The output of MSW is so massive that it has become the focus of urban construction. The timely and safe disposal of MSW is particularly necessary otherwise it may bring negative effects such as "garbage encircling the city" (Zeng and Ma, 2021). The harmless treatment of MSW mainly includes sanitary landfills, incineration, and composting. Sanitary landfills have been a common way of MSW disposal because of their simple operation, large capacity, and low investment (Zeng et al., 2020; Ke et al., 2023; Shu et al., 2023). MSW has the characteristics of various components, different sizes, and strong anisotropy (Wu et al., 2012; Woodman et al., 2013). Due to the treatment method of layered landfill and compaction of waste, there is obvious horizontal stacking, resulting in apparent anisotropy of MSW (Zhang and Lin, 2019). The significant heterogeneity of MSW's pore structure determines its permeability distribution, which directly affects the gas migration path (Capelo and Castro, 2007; Jung et al., 2011; Tinet et al., 2011).

Landfill gas is one of the main pollutants generated by landfill, which is generated by the anaerobic degradation of organic substances. Landfill gas is inflammable and explosive, has a poisonous odor, and has a great greenhouse effect. However, it can be used as a new type of energy after collecting royalties. The gas permeation characteristic of MSW is the key to efficient landfill gas collection.

There is a significant dominant seepage phenomenon in the landfill (Rosqvist and Destouni, 2000; Liu et al., 2016; Zhang and Yuan, 2019). Mccrenanor and Reinhart (2000) tried to use the dual permeability or dual porosity model to describe the dominant flow of leachate in refuse. Rosqvist et al. (2005) explained the crossing curve test through the leachate transport model in MSW and found that the dominant flow phenomenon lasted for a long time. Han et al. (2011) measured the water flow rate in the cylinder with a uniform sample size of 4cm and found that the dominant flow phenomenon is still obvious. Liu et al. (2016) studied the gas pressure dropping test to describe the gas preferential flow in the waste column. Zhang and Yuan (2019) carried out dye tracing and solute breakthrough tests to study the preferential flow in MSW and quantify the flow character. What's more, MSW's gas permeation characteristics equipment still needs to be developed.

This paper introduces a self-developed equipment for testing the gas permeability characteristics of MSW, such as its composition, principle and operation method. Then, the laboratory test on gas permeation characteristics of MSW under the influence factors of initial pressure and moisture content is carried out. Finally, the experimental rules of gas permeation characteristics are obtained, which provide data support for the determination of subsequent model parameters.

2. INTRODUCTION TO TEST EQUIPMENT

2.1 The Composition of the Test Equipment

The physical diagram of the independently developed test equipment for gas permeability characteristics of MSW is shown in Figure 1. The equipment is composed of a fixed frame, sample cylinder, pneumatic loading system, control system, computers, and data acquisition system, etc.

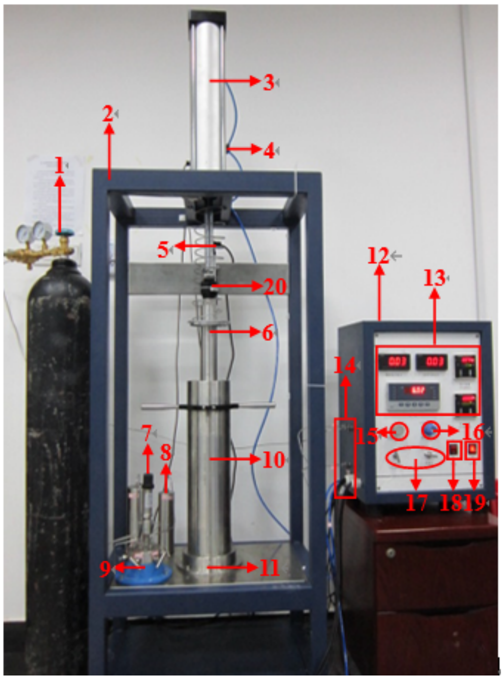

Figure 1 Test equipment for gas permeation of MSW

The components of the test equipment in Figure 1 are described as follows. The number 1 represents nitrogen cylinder, and its function is to provide air source for the test. The number 2 represents fixed frame, and its function is to restore the sample column. The number 3 represents a pressurized cylinder, and its function is to provide a pressurized load to the sample through high purity nitrogen. The number 4 represents the solenoid valve, and its function is to control the pressurized cylinder. The number 5 represents the displacement transducer, and its function is to determine the compression of the sample. The number 6 represents the loading piston, and its function is to withstand gas pressure and transfer it to the sample. The number 7 represents a pressure sensor, and its function is to measure the gas pressure. The number 8 represents a standard gas pressure chamber, and its function is to store gas. The number 9 represents a six-way valve, and its function is to control gas entry into the sample column. The number 10 represents a sample cylinder. The number 11 represents the fixed base, and its function is to provide stable bottom support for the device. The number 12 represents the control box, and its function is to install various control valves. The number 13 represents pressure, displacement, gas pressure, and flow display panel, and its function is to display the values of pressure, displacement, gas pressure and flow during the test. The number 14 represents a connecting line, and its function is to provide the gas flow line. The number 15 represents the sample inlet control valve, and its function is a switch that controls gas entry into the sample column. The number 16 represents the loading pressure control valve, and its function is to control the amount of loading pressure. The number 17 represents the flowmeter control valve, and its function is to control the flowmeter size. The number 18 represents the solenoid valve lifting control button, and its function is to control the rise and fall of the solenoid valve. The number 19 represents a power switch, and its function is to control the rise and fall of the solenoid valve. The number 20 represents a cylinder floating joint, and its function is to make the pressurized cylinder and fittings work within the allowed eccentricity range.

The detailed structure of the experimental apparatus for gas permeation of MSW is shown in Figure 2.

Figure 2 Detail structure of test equipment

2.2 The Technical Parameters of the Test Equipment

The basic technical parameters of the test device are as follows. ① The sample cylinder is made of 316 L stainless steel, corrosion resistant, and the pressure range is 0~1 MPa. ② The diameter of the sample cylinder is 100 mm, the height is 300 mm, the compaction volume is 2,355 mL, and the pressure process is 0~150 mm. ③ The gas pressure standard chamber is composed of a volume of 200 mL and 500 mL, and the working pressure range of the gas pressure standard chamber is 0~16 pMPa. ④ The measurement range of porosity is 0~100%, and the accuracy is 0.01%. ⑤ The stroke of the pressurized cylinder is 0~400 mm, and the working pressure range of the pressurized cylinder is 0~1 MPa. ⑥ The measuring range of the displacement sensor is 0~150 mm, and the accuracy is 0.01 mm. ⑦ The gas flowmeter has two different ranges. 0~500 mL/min is used to carry out the test of small sample permeability, and the accuracy is 0.01 mL/min. 0~5000 mL/min is used to carry out the test of large sample permeability, and the accuracy is 0.1 mL/min. ⑧ The equipment could complete the tests of gas permeability, porosity, and gas preferential flow of MSW.

2.3 The Basic Principle of the Test Equipment

2.3.1 Porosity Test

The measurement of porosity is based on the Boyle's law. The pressure and volume of a quantitative gas in a closed container are inversely proportional at constant temperature. Its formula is shown in Equation 1.

$$V_{SC} \cdot P_1 = (V_{SPC} - V_S + V_{SC}) \cdot P_2 \tag{1}$$

Where, V_{SC} is the volume of the gas standard pressure chamber, and its value can be calibrated. V_{SPC} is the volume of MSW in the sample tube, V_S is the solid particle volume of the sample, P_1 is the initial pressure of the gas standard pressure chamber, P_2 is the stable pressure of the sample tube and the gas standard pressure chamber. The value of V_{SPC} can be calculated according to Equation 1.

The porosity of MSW can be calculated according to the definition. Its formula is shown in Equation 2.

$$\varphi_t = \frac{V_{SPC} - V_S}{V_{SPC}} \tag{2}$$

2.3.2 Gas Permeability Test

The gas permeability of MSW can be obtained by a constant pressure test. The formula for calculating permeability is based on the following assumptions. The expansion of gas is an isothermal process, considering the compressibility of gas, and the flow of gas through MSW conforms to Darcy's law, its calculation formula is shown in Equation 3.

$$k = \frac{2P_B Q_B \mu L}{A(P_A^2 - P_B^2)} \tag{3}$$

Where, k is gas permeability, unit is m^2; P_A is the gas pressure at the entrance of the sample, it's the sum of the value measured by the pressure sensor and atmospheric pressure, and the unit is kPa; Q_B is the volume flow rate of gas flowing through the outlet of the sample, the value is recorded by gas flowmeter, and the unit is mL/s; L is the length of the sample, m; A is the cross-sectional area of the sample, and the unit is mm^2; P_B is the gas pressure at the exit of the sample, the unit is kPa, the value is atmospheric pressure; μ is the viscosity coefficient of the gas, and the unit is $\mu Pa \cdot s$.

2.3.3 Gas Preferential Flow Test

The preferred flow is measured by gas pressure dropping test. The test is used to obtain the breakthrough curve of gas in MSW sample. The measurement of breakthrough curve is an effective method to quantitatively evaluate the gas preferential flow, which can provide data support for the inversion of parameters in the double permeability model. The data of instantaneous flow of gas outlet of MSW sample with time can be monitored by the acquisition system.

2.4 The Operation Process of the Test Equipment

2.4.1 Porosity Test

Check equipment and close all valves before the experiment. Power on the computer's software operating system and control box. Close the valve connected with the sample cylinder and the valve at the bottom of the sample cylinder of the six-way valve. Open the valve connected with the gas pressure standard chamber of the six-way valve, so that the gas enters into the two gas pressure standard chambers. Adjust the valve of the ordinary nitrogen pressure gauge to control the gas pressure entering the sample cylinder, and close the valve when the pressure of the sample cylinder reaches the set value and the pressure is stable. Stabilize before the software control interface point is balanced, and open the valve connecting with the sample cylinder of the six-way valve slowly. When the pressure drops and stabilizes, click balance to stabilize. The pre-equilibrium and post equilibrium pressure data are monitored. The porosity of MSW sample can be calculated by the data acquisition system according to formula 2. The measurement principle of porosity is shown in Figure 3.

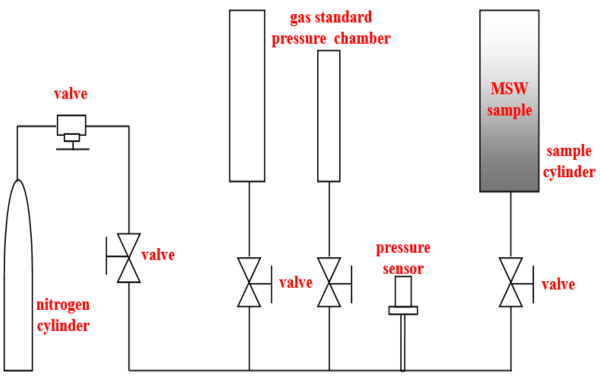

Figure 3 Schematic diagram of porosity measurement

2.4.2 Gas Permeability Test

Open the valve of the 5000 mL gas flowmeter. Close the bottom valve of the sample barrel and the valve connected to the gas pressure standard chamber of the six-way valve. Open the valve connected with the sample cylinder of the six-way valve and the inlet valve of the nitrogen flat cylinder. Adjust the intake pressure into the sample cylinder, and keep the pressure stable when the intake pressure reaches about the set value. The gas permeability of MSW sample can be calculated by the data acquisition system according to formula 3 as the value reaches stability. The measurement principle of gas permeability is shown in Figure 4.

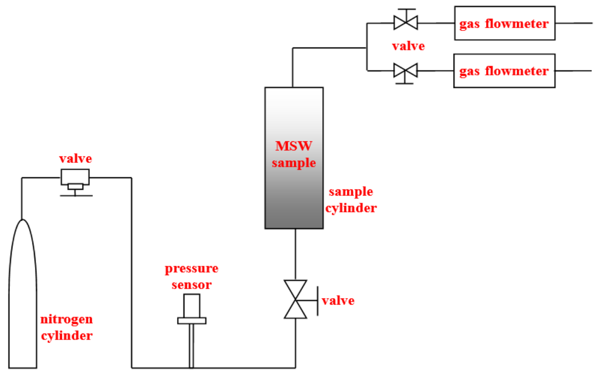

Figure 4 Schematic diagram of gas permeability measurement

2.4.3 Gas Preferential Flow Test

The operation methods of the gas preferential flow test are 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. The measurement principle of gas preferential flow of MSW is shown in Figure 5.

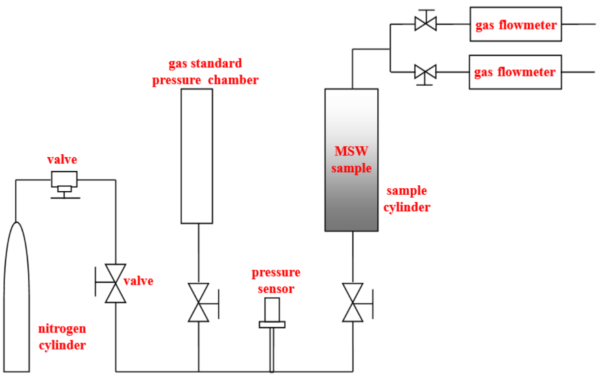

Figure 5 Schematic diagram of gas preferential flow measurement

3. LABORATORY TEST APPLICATION

3.1 Test Materials

Laboratory test materials usually have two methods, on-site sampling and manual preparation. Although the on-site sampling is relatively real, the representativeness of the samples is still questionable due to the uneven distribution of MSW. In addition, the samples obtained from the site often need to be sorted to determine the composition. The artificial preparation based on the data statistics is a new way to study the regularity of MSW, 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. In order to carry out regular research, the experimental material is artificial sample preparation in this study. The sample components and proportion used in the test are determined according to the statistics on the typical components of local domestic waste and the difficulty of obtaining the test components. The sample consisting of MSW is shown in Table 1.

Table 1 Composition of MSW sample

Constituent	Food	Muck	Paper	Plastic	Textile	Wood
ratio /%	50	26	15	3	3	3

The basic physical properties of samples are performed in accordance with the standard test method for landfilled MSW (CJJ/T 204-2013) (Xue, 2014). The data of physical properties of MSW sample is shown in Table 2. The maximum grain size corresponded to approximately 25% of the cylinder diameter in order to prevent sidewall flow (Stoltz et al., 2010). The sample size was artificially broken to less than 2.5 cm. Each component of the broken sample is reserved for use.

Table 2 Physical properties of MSW sample

Moisture content	Density	Dry density	Pore ratio	Organic matter content
54.6%	0.9 g/cm^3	0.582 g/cm^3	2.2	57.2%

3.2 Sample Preparation

The specimen size is a cylinder with a diameter of 100 mm and a height of 300 mm. The total mass of each sample is calculated according to the test plan and sample volume. The quality of required components can be obtained according to the proportion of each component of waste. Each component of MSW sample is initially weighed (with an accuracy of 0.01 g) according to the requirements.

The evenly mixed MSW components are sealed and allowed to stand for 24 hours to ensure that the moisture is fully infiltrated. Loosen the fixing screw at the bottom and remove the sample cylinder from the fixed ring. A layer of petroleum jelly is applied to the inner wall of the sample cylinder to prevent gas sidewall leakage. The mixed material of MSW is evenly pressed into the cylinder sampler 3 times one by one. The inner wall of the upper sample tube is cleaned after the test material is filled, and the sample cylinder is placed on the fixed base of the fixed frame. Screw the bottom screw to make the sample tube and frame integrated, and screw the valve connector under the sample tube.

3.3 Test Methods

The test process is mainly divided into steps such as weighing, mixing evenly, preparing samples, starting the test, and recording data. The influence factors of the test scheme are initial pressure and moisture content. The initial pressure is set at 0.1 MPa, 0.05 MPa, and 0.02 MPa. The moisture content is 54.6%, 70.6%, and 86.6%. The moisture content set in the test scheme can be achieved by adding water to the sample. The test methods of porosity, gas permeability and gas preferential flow can be found in Section 2.4 for details.

4. RESULTS AND ANALYSIS

4.1 Influence of Initial Pressure on Gas Preferential Flow

The test results of the gas breakthrough curve under different initial pressures of 0.1 MPa, 0.05 MPa, and 0.02 MPa as the moisture content is 54.6% of MSW, are shown in Figure 6. The test is completed as the gas flow rate at the outlet is close to 0 and remains constant.

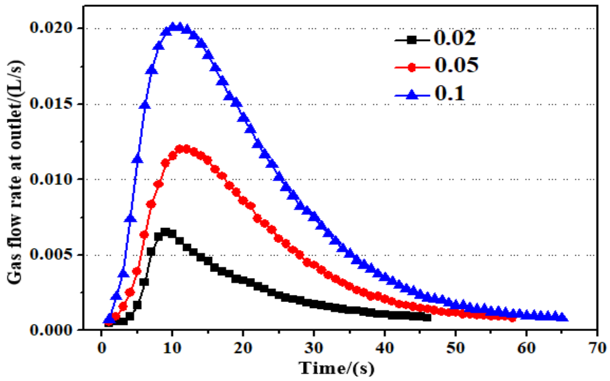

Figure 6 Breakthrough curves under initial pressure (MPa)

It can be seen from Figure 6 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 is due to the test is a pressure drop method. The gas pressure in the standard chamber is 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 decreasing continuously as the test went on, the gas flow rate at the outlet decreased continuously. The peak value of the gas flow rate gradually increases, and the time for gas to reach stability also increases with the increase of initial pressure. When the initial pressure is 0.02 MPa, 0.05 MPa, and 0.1 MPa, the peak value of the gas flow rate at the outlet of MSW sample is 0.006 L/s, 0.012 L/s, and 0.02 L/s, respectively, and the time of gas passing through the sample is 47s, 58s, and 65s, respectively.

4.2 Influence of Moisture Content on Gas Preferential Flow

The distribution of the gas breakthrough curve of MSW sample with different moisture content as the initial pressure is 0.05 MPa is shown in Figure 7. It can be seen from Figure 7 that with the increase of moisture content of MSW sample, the rising amplitude and peak value of the breakthrough curve of MSW increase gradually, and the time for the gas to reach equilibrium decreases continuously. When the moisture content is 54.6%, 70.6%, and 86.6%, the peak value of the gas flow rate at the outlet of MSW is 0.02 L/s, 0.025 L/s, and 0.029 L/s, respectively, and the time of gas passing through the sample is 58s, 46s, and 40s, respectively. It 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. This will lead to gas flowing out of the large pore area to form an increase in the peak value of the breakthrough curve. Therefore, the change of gas flow rate is not only related to the total permeability and porosity of MSW but also needs to consider the change of permeability and porosity of large and micro-pores.

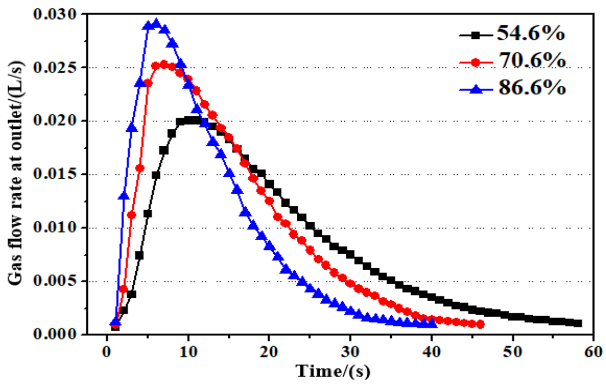

Figure 7 Breakthrough curves under different moisture content

When the moisture content of MSW samples is 54.6%, 70.6%, and 86.6%, the values of total permeability are 1.096×10^{-12} m^2, 0.937×10^{-12} m^2, and 0.787×10^{-12} m^2, respectively, and the total porosity is 0.573, 0.501, and 0.358, respectively.

5. CONCLUSIONS

In this paper, the self-developed gas permeability test equipment of MSW is introduced, the laboratory tests on gas permeation of MSW under initial pressure and moisture content are carried out. The main conclusions are as follows.

(1) The preliminary application results show that the self-developed test equipment can meet the lab test of gas penetration characteristics of MSW. The gas permeability, porosity and the whole process of gas penetration in MSW can be obtained by the device. It is an effective method to quantitatively evaluate the gas preferential flow by measuring the break though curve, which can provide the data of inversion parameters in the dual permeability model.

(2) The peak value of the gas breakthrough curve increased gradually with the increase of initial pressure and increased with the increase of moisture content. The time of gas passing through the sample is increased gradually with the increase of initial pressure but decreased with the increase of moisture content.

(3) When the initial pressure is 0.02 MPa, 0.05 MPa, and 0.1 MPa as the moisture content is 54.6%, the peak value of the gas flow rate at the outlet of the MSW sample is 0.006 L/s, 0.012 L/s, and 0.02 L/s, respectively, and the time of gas passing through the sample is 47s, 58s, and 65s, respectively.

(4) When the moisture content is 54.6%, 70.6%, and 86.6% as the initial pressure is 0.05 MPa, the peak value of the gas flow rate at the outlet of the MSW sample is 0.02 L/s, 0.025 L/s, and 0.029 L/s, respectively, and the time of gas passing through the sample is 58s, 46s, and 40s, respectively.

6. ACKNOWLEDGMENTS

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