Research Article
Experimental Study on Compression and Intrinsic Permeability Characteristics of Municipal Solid Waste

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Compression and gas permeability characteristics of municipal solid waste (MSW) are of great significance to the design, construction, management, and operation of landfill. The objective of this paper was to study the compression and gas permeability characteristics of MSW. A compressing test device and gas permeability test device for MSW were introduced, and laboratory tests were carried out. The test results showed that the final strains at the vertical loads of 100 kPa, 200 kPa, 300 kPa, and 400 kPa were 35.8%, 45.1%, 49.2%, and 55.1%, respectively. The natural logarithm of void ratio and pressure was linearly correlated at different times. Intrinsic permeability measured without considering gas compressibility was smaller than that measured with considering gas compressibility. Intrinsic permeability of MSW decreased with the increase of the inlet pressure. It was suggested that the inlet pressure should be set to 3 kPa for the indoor gas permeability test of MSW. Intrinsic permeability of MSW decreases with the increase of water content and compression displacement. Power function and logarithmic model were suitable for the fitting of permeability and porosity of manually prepared fresh MSW samples, while the K-C model was not suitable. With the increase of moisture content, the coefficient and power index of the power function model decreased gradually. And the slope and intercept of the double logarithmic model also decreased gradually with the increase of moisture content.

1. Introduction

According to the statistics of the State Environmental Protection Administration, MSW production in China was 152 million tons in 2010 and will reach 210 million tons by 2020. The output of MSW is expected to increase at an annual rate of 8%–10% [1]. It is estimated that China’s MSW will reach 409 million tons, 457 million tons, and 528 million tons in 2030, 2040, and 2050, respectively. Continuous growth of MSW brings many problems to urban construction and other aspects. The phenomenon of “garbage siege” not only occurs in developing countries such as China and India but also in developed countries such as the United States and France. Domestic waste seems insignificant, but it has become a bottleneck restricting the development of urbanization. Timely, safe, and hygienic disposal of MSW has become a top priority of the society and government.

Sanitary landfill is a widely recognized and effective treatment method of MSW in the world because of its simple operation, large treatment capacity, low investment, and fast efficiency [2, 3]. The essence of the landfill is a biochemical reactor coupled with stress-strain field, biological field, concentration field, and temperature field. In this reactor, the main input material is municipal solid waste, and the main output material is leachate and landfill gas. Understanding the basic engineering characteristics of MSW has important implications for the design, construction, safety management, and stable operation of landfills [4–8].

Deformation and settlement of MSW is one of the main environmental geotechnical engineering problems involved in the landfill [9]. It can provide scientific basis for prediction of landfill volume, increase of storage capacity, cracking failure of the closure cover system, design and maintenance of the gas-liquid drainage system, and site
reuse by landfill settlement research [10]. Compressive deformation characteristics of MSW are of great significance for analysis of landfill settlement [11, 12]. Gas permeability of landfill is an important parameter affecting prediction, collection, utilization, and drainage of landfill gas [13]. The research work of Shi and Zhao [14] showed that the relationship between the permeability coefficient and permeability pressure of MSW was nonlinear. Xu et al. [15] showed that the value of the intrinsic permeability coefficient in the Kozeny–Carman model was found to be influenced by both compression and biodegradation processes. Feng et al. [16] summarized the method, sample size, and influence factor of gas permeability by the falling pressure test. Systematically grasping the gas permeability characteristics of MSW can provide theoretical basis for scientific and effective collection and utilization of landfill gas. However, the research on the compression and gas permeability of MSW was still weak in terms of equipment, experimental data, and theory. The objective of this paper was to introduce the compression and gas permeability device of MSW and conduct the laboratory test to study the compression and gas permeation characteristics of MSW.

2. Materials and Methods

2.1. Experimental Materials. Although the on-site waste samples were 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, it was often necessary to separate the samples obtained in the field to determine the composition of the samples. Artificial compounding of waste samples was a new way to study the regularity of landfills by using similar materials to replace and to compound samples, which was based on the statistics of the distribution ratios of waste components in the landfills at home and abroad [4]. It had the advantages of low cost, good controllability of initial conditions, and high repeatability of test results.

Most cities in China had basically completed the investigation of typical components of local waste. Table 1 shows the composition of MSW in some major cities in China [17]. It was feasible to carry out the laboratory test by artificial sample preparation according to the results of investigation, and the research results obtained from this were comparable to some extent.

The composition and proportion of the MSW samples were finally determined according to the composition of MSW in Wuhan and the difficulty of obtaining test components. The composition and mass of MSW test samples are shown in Table 2. The basic physical indexes such as moisture content (equal to water mass/solid mass), wet density, specific gravity, void ratio, and organic matter were 54.6%, 0.9 g/cm³, 1.86, 2.2, and 57.2%, respectively.

2.2. Experimental Methods

2.2.1. Compression Test Device. The schematic diagram of the self-developed test device is shown in Figure 1. The device consists of the sample tube, pressure and balance system, sealing system, gas collection system, leachate collection, and irrigation system.

The main technical parameters are as follows: internal diameter of the sample tube was 250 mm and height was 300 mm. The leverage ratio at the first level was 1:5, and the second leverage ratio was 1:2. The lab space could be saved greatly by this loading method. The weight was converted to the quality of each piece by means of the load applied. The vertical load could be calculated by the leverage principle and the area of the sample. The main functions of the screw jack were to transfer the load provided by the lever to exert vertical pressure on the sample and adjust the lever balance during the experiment. The fastener was made of stainless steel, which could hold two support rods to prevent the stiffness of the support rod from being too high and to avoid the support rod from horizontally tilting due to excessive pressure. The top hoop and middle hoop could prevent lateral deformation and ensure that the specimen was deformed only in the vertical direction.

2.2.2. Intrinsic Permeability Test Device. Intrinsic permeability test equipment was introduced in literature [13]. According to the basic principle of the porosity test, by controlling the opening and closing of each valve, the schematic diagram of porosity measurement is shown in Figure 2.

According to the basic principle of the gas permeability test, by controlling the opening and closing of each valve, the schematic diagram of gas permeability measurement is shown in Figure 3.

2.2.3. Test Method. The total mass of MSW required in the test is shown in Table 2, which was calculated according to the compaction density and sample volume of MSW. Then, the mass of MSW required by each component can be obtained according to the proportion of each component. The particle size of each component in the manually prepared MSW sample was artificially broken to less than 2 cm. The prepared MSW samples were sealed and placed for 24 h to ensure that the samples were sufficiently infiltrated.

The lab test of compression and gas permeability of MSW was carried out. The load duration was 100 days which was applied by separate loading methods in 100 kPa, 200 kPa, 300 kPa, and 400 kPa respectively. The degradation of MSW was inhibited by adding the same amount of vinegar to each sample. The effects of gas compressibility, inlet pressure (1–6 kPa), moisture content (55%, 70%, and 85%), and compression displacement (10–50 mm) on gas permeability of MSW were discussed. The waste sample was filled and compacted layer by layer according to the height stratification, and the height of the sample was controlled to 250 mm in the compression test. The dimension of the gas permeation sample was a cylinder with diameter of 100 mm and height of 300 mm. The test conditions were controlled strictly to minimize the influence of external factors on the test. The settlement of the sample during the test was
measured. After the inspection is correct, the test could be carried out according to the test plan.

The settlement test method was measured symmetrically four times along the sample barrel by a 1 m long steel ruler, and the final value was the average of four times the measurement results. Porosity and intrinsic permeability of MSW were obtained by the data acquisition system.

### Table 1: Composition of MSW in some areas of China (%) [17].

| City      | Organic matter |  | Inorganic matter |  |
|-----------|----------------|---|------------------|---|
|           | Kitchen | Paper | Vegetation | Plastic | Metal | Muck | Others |
| Beijing   | 32.60   | 15.10 | 14.10     | 14.6    | 1.96  | 21.44 | 0.20   |
| Shanghai  | 40.22   | 1.80  | 2.65      | 3.50    | 1.07  | 44.26 | 6.50   |
| Shenzhen  | 51.82   | 12.90 | 4.89      | 8.36    | 1.22  | 19.53 | 1.28   |
| Guangzhou | 36.35   | 10.32 | 3.58      | 6.26    | 3.64  | 22.43 | 14.42  |
| Wuhan     | 39.16   | 4.33  | 1.93      | 7.50    | 0.69  | 32.74 | 13.65  |
| Hefei     | 44.90   | 3.57  | 2.98      | 10.22   | 0.80  | 28.40 | 9.13   |
| Nanjing   | 52.00   | 4.90  | 1.18      | 11.20   | 1.28  | 20.64 | 8.80   |
| Chongqing | 38.76   | 1.04  | 0.97      | 9.10    | 0.53  | 37.99 | 11.61  |
| Wuxi      | 41.00   | 2.90  | 4.98      | 9.83    | 0.90  | 25.29 | 15.10  |
| Shenyang  | 34.96   | 2.11  | 3.25      | 1.74    | 3.05  | 51.65 | 3.24   |

### Table 2: Composition of MSW in the lab test.

| Composition | Kitchen waste | Muck | Paper | Plastic | Fabric | Grass |
|-------------|---------------|------|-------|---------|--------|-------|
| Proportion (%) | 50 | 26 | 15 | 3 | 3 | 3 |
| Mass of the compression test (kg) | 5.5 | 2.86 | 1.65 | 0.33 | 0.33 | 0.33 |
| Mass of the gas permeation test (kg) | 1.06 | 0.55 | 0.32 | 0.06 | 0.06 | 0.06 |

**Figure 1: Compression instrument of MSW.**
3. Results and Analysis

3.1. Settlement Test Result. The sedimentation test data under load are shown in Figure 4. According to Figure 4, strains under vertical loads of 100 kPa, 200 kPa, 300 kPa, and 400 kPa were 35.8%, 45.1%, 49.2%, and 55.1%, respectively. The greater the pressure applied, the larger the compression deformation in the early stage, but the lower the deformation rate in the later stage. This might be due to the reorganization of the pore structure, the movement, and dislocation of the particles, resulting in the compression creep of the MSW sample.

3.2. Relationship between Void Ratio and Load. The void ratio of the sample at any time can be calculated as follows:

\[
\epsilon_t = \frac{(h_0 - h_t)A}{V_{st}} - 1, \tag{1}
\]

where \(\epsilon_t\) is the void ratio of the sample at time \(t\), \(h_0\) is the initial height of the sample, \(h_t\) is the height of the sample at time \(t\), \(A\) is the cross-sectional area of the sample, and \(V_{st}\) is the volume of solid particles in the sample at time \(t\).

As can be seen from Figure 5, the pore ratio of the sample decreased with the increase of load, with a large decrease in the early stage, while the change of the void ratio became stable in the later stage. After the test, the void ratios of the samples were 1.04, 0.74, 0.62, and 0.43, which were 52.7%, 66.4%, 71.8%, and 80.5% lower than the initial void ratios. The pore ratio and load were linearly correlated at various times.

3.3. Effect of Gas Compressibility on Intrinsic Permeability. Ye et al. [18] established a constitutive equation describing gas seepage in unsaturated soil considering gas compressibility based on the theory of gas seepage in porous media. And the flow velocity at the outlet of gas was calculated as follows:

\[
v = \frac{Q_b}{A} = \frac{k}{2\mu} \frac{P_A^2 - P_B^2}{P_B L}, \tag{2}
\]

where \(v\) is the gas flow rate at outlet, m/s; \(k\) is the intrinsic permeability, m²; \(P_A\) is the gas pressure at inlet, kPa; \(Q_b\) is the volume flow of gas flowing through the outlet, mL/s; \(L\) is the length of specimen, mm; \(A\) is the cross-sectional area of the sample, mm²; \(P_B\) is the gas pressure at outlet, the
Intrinsic permeability (10⁻¹³ m²)

Iversen et al. [19] established the gas velocity in porous media without considering gas compressibility based on Darcy’s law as follows:

\[ v = \frac{q_v}{A} = \frac{k}{\mu} \left( P_2 - P_1 \right), \]

where \( v \) is the gas flow rate at outlet, m/s; \( q_v \) is the volume flow of gas flowing through the outlet, mL/s; \( A \) is the cross-sectional area of the sample, mm²; \( k \) is the intrinsic permeability, m²; \( P_1 \) is the gas pressure at inlet, kPa; \( P_2 \) is the gas pressure at outlet, kPa; and \( H \) is the height of the specimen, mm.

As the gas viscosity coefficient was known, and the length or height of the sample can be measured by displacement sensor. The effect of gas compressibility on gas permeability of MSW could be analyzed by monitoring the gas pressure and velocity at the outlet of the refuse sample according to formulas (2) and (3).

The comparison of intrinsic permeability of the MSW sample (moisture content was 85%, and compression displacement was 30 mm) with and without consideration of gas compressibility is shown in Figure 6. From Figure 6, it could be seen that intrinsic permeability measured by considering gas compressibility was slightly larger than that measured by the Iversen model without considering gas compressibility. And the greater the inlet pressure, the greater the difference between the calculated results of the two models.

3.4. Effect of Inlet Pressure on Intrinsic Permeability. It was necessary to determine the most suitable inlet pressure for the indoor gas permeation test. If the inlet pressure was too low, the gas flow velocity might not be monitored at the outlet. If the inlet pressure was too high, the pressure plate would be raised and the test will be affected. The indoor intrinsic permeability test of MSW was carried out under different influencing factors, including compression displacement (10 mm, 20 mm, 30 mm, 40 mm, and 50 mm), inlet pressure (1 kPa, 2 kPa, 3 kPa, 4 kPa, 5 kPa, and 6 kPa), and moisture content (55%, 70%, and 85%). Intrinsic permeability test data of MSW with a moisture content of 55% are shown in Figure 7.

From Figure 7, it could be seen that intrinsic permeability of MSW decreased with the increase of inlet pressure. The average value of intrinsic permeability measured at six different inlet pressures and five different compression displacements was the closest value of intrinsic permeability measured at the inlet pressure of 3 kPa. Therefore, it was suggested that the optimum inlet pressure should be 3 kPa when carrying out the intrinsic permeability test. This result was different from that of Stoltz et al. [20] when conducting the indoor intrinsic permeability test of MSW, and that the value of inlet pressure should be limited to less than 2 kPa. The reason might be that the test results were affected as the top pressure plate of the sample rises if the inlet pressure was greater than 2 kPa in [20].

3.5. Effect of Moisture Content and Compression Displacement on Intrinsic Permeability and Porosity. Intrinsic permeability and porosity test data of three different moisture content MSW samples are shown in Figure 8. As can be seen from Figure 8, intrinsic permeability of MSW samples decreased with the increase of moisture content when the compression displacement was the same. The main reason was that the higher the moisture content was, the more the pore water occupies in the MSW sample, and the less or hindered the gas flow passage, so the permeability of the sample was smaller. The porosity and intrinsic permeability of the sample decreased with the increase of the compression displacement. It was mainly because the more the increase in compression displacement, the more compact the pore was. Moreover, the smaller the pore space of the sample, the smaller the gas flow passage, so the porosity and permeability of the sample were also smaller.

The permeability of waste samples tested in this paper ranges from 10⁻¹³ to 10⁻¹² m², which was two orders of magnitude lower than Stoltz’s. The main reason for the
difference of test results was that the composition of the waste sample was different [13]. The materials of Stoltz contained metal and glass, which were not easy to compress. Therefore, the porosity of MSW measured up to 75% was higher, and the permeability was also higher in literature [20].
Power function model:
\[ k = a\phi^b, \]
where \( a \) and \( b \) are constants, and the unit of \( a \) is \( m^2 \).

The double logarithmic model was proposed by Prof. Poulsen of Denmark based on the experimental data of sand. Its expression is shown in equation (6). The natural logarithm of both sides of equation (6) could be transformed into equation (7):
\[ \frac{k}{k_0} = \left( \frac{\phi}{\phi_0} \right)^a, \]
\[ \lg k = a \lg \phi + b, \]
where \( a \) and \( b \) are constants.

The data of intrinsic permeability and porosity when the moisture content was 85% were selected, and the K-C model, power function, and double logarithmic model were used for fitting the data. The fitting diagram of the power function model and K-C model is shown in Figure 9, and the square values of model fitting parameters and correlation coefficients are shown in Table 3.

It can be seen from Figure 9 and Table 3 that the power function model was suitable for the fitting of intrinsic permeability and porosity of MSW, while the K-C model was not suitable. The coefficient \( a \) and power index \( b \) of the power function model gradually decreased with the increase of moisture content. The K-C model was more suitable for porous media with uniform particles, while MSW samples had more complex components and strong heterogeneity, so the K-C model had poor fitting effect on gas permeability and porosity of MSW.

The square values of double logarithmic model fitting parameters and correlation coefficients are shown in Table 4. According to Table 4, intrinsic permeability and porosity of MSW showed a linear relationship in the double logarithmic model. And the slope and intercept of the double logarithmic model gradually decreased with the increase of moisture content.

4. Conclusion

A compression and intrinsic permeability test device for MSW were introduced, and the lab test of the artificially prepared MSW was carried out. The main conclusions were as follows:

(1) The MSW sample had great compressibility. The final strains at the vertical loads of 100 kPa, 200 kPa, 300 kPa, and 400 kPa were 35.8%, 45.1%, 49.2%, and 55.1%, respectively. The natural logarithm of void ratio and load was linearly correlated at different times.

(2) Intrinsic permeability measured without considering gas compressibility was smaller than that measured with considering gas compressibility.

(3) Intrinsic permeability of MSW decreased with the increase of the inlet pressure. It was suggested that the inlet pressure should be set to 3 kPa for the indoor intrinsic permeability test of MSW.

(4) Intrinsic permeability of MSW decreases with the increase of water content and compression displacement.

(5) Power function and double logarithmic model were suitable for the fitting of intrinsic permeability and porosity of manually prepared fresh MSW samples, while the K-C model was not suitable. With the increase of moisture content, the coefficient and power index of the power function model decreased gradually. And the slope and intercept of the double logarithmic model also decreased gradually with the increase of moisture content.

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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