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REVIEW ARTICLE

Geoenvironmental Issues in High-Food-Waste-Content Municipal Solid Waste Landfills

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Abstract | The amount of municipal solid waste (MSW) has increased significantly in developing countries. Landfilling is the commonly used treatment for the disposal of MSW. The MSW contains more food waste in developing countries than in developed countries. This work analyzed the degradable components of MSW with different food contents. A theoretical model was introduced to analyze the coupled hydro-mechanical-chemical interactions in the landfilled MSW. The impacts of the degradation on the properties of high-food-waste-content MSW were reviewed, including the compression behavior, strength parameters, and hydraulic conductivity. The major cause of geoenvironmental issues in high-food-waste-content landfills are rapid leachate and landfill gas generation. A practical model for analyzing leachates and gas production was presented. Landfills in China were used as an example to describe engineering measures for leachate drainage and landfill gas collection. These methods proved successful in solving geoenvironmental issues of landfills with high leachate levels. The experiences are useful for engineers who face similar issues with high-food-waste-content landfills in developing countries.

1 Introduction

Urbanization has increased rapidly in the last 40 years in developing countries, such as China, India, Brazil, and South Africa. The increased urban population caused a significant increase in the amount of municipal solid waste (MSW). For example, the annual MSW production in China exceeds 200 million tons, with an annual increase rate of 7–10%[1,2]. The major treatment methods for MSW are landfilling, incineration, and composting. Currently, more than 50% of the MSW in China is disposed in landfills.

Various MSW disposal methods in landfills have been developed in the last decades. Before 1988, open dumps were widely used in China, with no barriers or covers. In the 1990s, the first-generation sanitary landfills were constructed using natural clay as a barrier layer. In the 2000s, second-generation sanitary landfills were built. More reliable measures and techniques, e.g., barrier systems with geosynthetics and landfill gas collection systems, were used to reduce the leakage of leachates and landfill gas emissions.

Landfills in China differ from those in western developed countries due to different engineering properties and degradation behaviors resulting from the physical composition and chemical components. Generally, MSW consists of food waste, paper, textile, wood, plastic, metal, and other materials. Chen et al. (2018) investigated the physical compositions of fresh MSW of different countries. The food waste content is typically higher in most developing countries than in developed countries. The MSW can be classified

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Table 1: Chemical component content of different physical compositions of MSW (%).

Physical composition	Rapidly degradable				Slowly degradable	Inert	
	Rapidly degradable cellulose	Sugar	Protein	Fat	Slowly degradable Cellulose	Lignin	Other
Food	15	60	5	5	–	2	13
Paper	30.5	–	–	–	37.5	15.5	16.5
Wood	15.0	–	–	–	38.8	32.6	13.6
Yard waste	19.2	–	–	–	12.1	36.1	32.6

Table 2: The chemical components of HFWC and LFWC MSW (kg/m^3).

	Rapidly degradable cellulose	Sugar	Fat	Protein	Slowly degradable cellulose	Lignin
HFWC	31	66	5.5	5.5	31	2.0
LFWC	137	28	2.3	2.2	176	8.3

according to the food waste content. The MSW with a food waste content over 40% is referred to as high-food-waste-content (HFWC) MSW, and that with a food waste content less than 40% is low-food-waste-content (LFWC) MSW. The food waste content has a significant influence on the degradation behavior of the MSW.

Many researchers have investigated the degradable chemical components of MSW. Cellulose, sugar, lipid, and protein are the major components[3,4] (Chen et al. 2018; Lobo and Tejero 2007), and cellulose includes rapidly and slowly degrading cellulose. Unlike the slowly degradable cellulose, the other chemical components degrade rapidly. The chemical components of different physical compositions were analyzed in the laboratory and are listed in Table 1.

The content of degradable components in fresh MSW can be obtained using the data of the physical composition of fresh MSW and the chemical components. Fresh MSW has an LFWC in the US and an HFWC in China. The mass content of the rapidly degradable chemical components in HFWC MSW is significantly higher (66%) than that of LFWC MSW (28%) (Table 2). The degradation behavior depends on the content of the rapidly and slowly degradable chemical components.

High content of rapidly degradable chemical components results in high leachate and landfill gas production. The leachate amount of HFWC MSW is significantly higher than that of LFWC MSW. Thus, the results obtained in studies on the leachate production of LFWC MSW are not applicable to HFWC MSW landfills. If the actual leachate production is much higher than the capacity of the pre-designed leachate collection system, the leachate has to be stored in the landfill body. A high leachate level in a landfill significantly reduces gas permeability of the MSW under the leachate table. Most of the landfill gas of HFWC MSW is generated 1–2 years after landfilling. It would cause a low landfill gas collection degree and a high emission amount. The landfill gas amount and rate depend on the components of the MSW. Zheng et al.[5] investigated the methane generation potential of different compositions of HFWC MSW in China. Laboratory results indicate that the landfill gas generation potential of food waste, paper, textile, and wood were 320.3, 233.3, 36.2, and 129.2 L/kg, respectively. The landfill gas generation potential and the generation rate were the highest for food waste, followed by paper. The proportions of rapidly degradable contents in HFWC and LFWC MSW were ca. 45% and 19%, respectively. Thus, landfill gas was generated more rapidly in HFWC MSW than LFWC MSW. These results indicate that a two-step degradation model that considers the food waste content and composition will provide more accurate results for different MSW types.

The water content is much higher for HFWC MSW than for LFWC MSW. Landfills with HFWC MSW typically have high leachate levels and vice versa. High leachate levels result in environmental hazards in landfills. Due to the high pore-water pressure, the risk of slope failure is

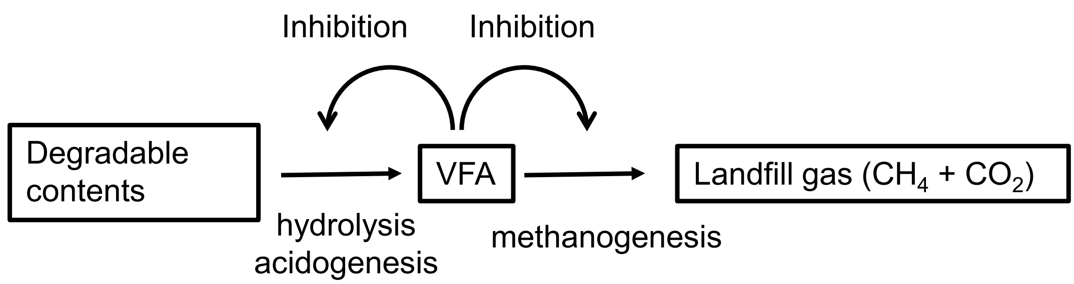

Figure 1: Two-stage anaerobic degradation model.

high. The service period of the barrier system is shortened if high pressure occurs on the landfill bottom, resulting in leachate leakage. A high leachate level in a landfill complicates the landfill gas collection.

This paper focuses on HFWC MSW. First, a theoretical analysis of the degradation and stabilization processes is conducted. Subsequently, the engineering properties of HFWC MSW are summarized, including compression, strength, water retention, and water and gas conductivity. An investigation of leachate and landfill gas production is performed, and engineering measures are presented to address geoenvironmental issues in HFWC MSW landfills.

2 Degradation and Stabilization of Landfilled MSW

2.1 Two-stage anaerobic degradation model

Anaerobic degradation of MSW occurs after landfilling. Four stages have been identified: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Multi-stage anaerobic degradation models for MSW that describe the anaerobic degradation of MSW accurately were proposed[6,7]. However, these models are not suitable for analyzing the coupled degradation and consolidation processes due to their complexity and numerous parameters. A simplified two-stage model for MSW is commonly used, it considers the influences of water, ammonia, hydrogen sulfide, and volatile fatty acids (VFAs) on the degradation rate of the chemical components[8,9]. The water content has a significant impact on the degradation process[10], and a large amount of intra-particle water is released by HFWC MSW. However, the generation of intra-particle water is not considered in most anaerobic degradation models of LFWC MSW.

Chen et al.[11] proposed a simplified two-stage anaerobic degradation model based on the anaerobic digestion model 1 (ADM1) that considers the VFAs on hydrolysis and methanogenesis (Fig. 1). Thirteen chemical components were involved, and the following 7 biochemical reactions occurred during degradation (Eqs. 1–7).

Hydrolysis of rapidly degradable cellulose:

$$C_6H_{10}O_5 \cdot \lambda_w H_2O + 5H_2O \rightarrow CH_3COOH + 8H_2 + 4CO_2 + \lambda_w H_2O \tag{1}$$

Hydrolysis of slowly degradable cellulose:

$$C_6H_{10}O_5 + 5H_2O \rightarrow CH_3COOH + 8H_2 + 4CO_2 \tag{2}$$

Hydrolysis of total sugar:

$$C_6H_{10}O_5 + 5H_2O \rightarrow CH_3COOH + 8H_2 + 4CO_2 \tag{3}$$

Hydrolysis of protein:

$$C_{46}H_{77}O_{17}N_{12}S + 59.26H_2O \rightarrow 7.88CH_3COOH + 30CO_2 + 63H_2 + 12NH_3 + H_2S \tag{4}$$

Hydrolysis of lipid:

$$C_{55}H_{104}O_6 + 78H_2O \rightarrow 13CH_3COOH + 29CO_2 + 104H_2 \tag{5}$$

Methanogenesis:

$$CH_3COOH + 7.43H_2 + 0.93CO_2 + 0.029NH_3 \rightarrow 2.79CH_4 + 3.8H_2O + 0.029C_5H_7NO_2 \tag{6}$$

Death of biomass:

$$C_5H_7NO_2 + 2H_2O \rightarrow 0.83C_6H_{10}O_5 + NH_3 \tag{7}$$

This simplified anaerobic degradation model considered the release of intra-particle water. The acid environment of the leachate inhibits bacterial activity, delaying methanogenesis and the generation of landfill gas. Acid inhibition occurs until the VFAs are consumed by the biomass. The two-step model by[11] accurately describes these phenomena.

2.2 Coupled Biochemical-Hydro-Mechanical Model for MSW

Complex coupled chemical and physical processes occur in landfills. A few multi-processes coupled models have been developed to describe the degradation behavior of landfilled MSW. Liu et al.[12] established a one-dimensional model based on the unsaturated consolidation theory and combined it with the biodegradation of municipal solid waste, which considered the migration of landfill gas and ignored the migration of leachate. A similar model proposed by[13] was able to predict landfill settlement, as well as taking into account the flow of gas and leachate. The results also indicated that the deformation of the waste skeleton significantly affects the fluid flow. Hettiarachchi et al.[14,15] proposed a coupling model to study the effect of landfill gas and leachate flow on landfill settlement. The model established the relationship between mechanical compression and stress to simulate landfill settlement caused by mechanical compression and biodegradation.

The coupling model above confirmed the influence of hydraulic and biodegradation on landfill settlement. However, few models considered the constitutive behaviors of MSW. McDougall[9] proposed the waste constitutive relationship based on Cam-Clay model. On this basis, a two-stage anaerobic biodegradation model was established considering the influence of environmental factors. The model ignored the landfill gas flow and introduced pore change parameters to describe the relationship between the volume loss of solid and the pore volume change caused by biodegradation and compression. Generally speaking, the coupling model was classical, especially for biodegradation and deformation components, which provided valuable guidance for further research on this problem. Recently, based on the finite-difference codes FLAC,[16–19] have developed a two-dimensional model to simulate MSW coupling processes in bioreactor landfill. The mechanical properties of MSW were evaluated using Mohr–Coulomb constitutive model and Bishop effective stress. The change of the geotechnical properties of MSW was related to the degradation degree. The model was used for slope failure analysis of landfill directly. Based on the strength reduction method, the seepage control layer, covering layer and collection system of the landfill were modeled. Feng et al.[20] also proposed a coupling model which considered the effect of effective stress, saturation and degradation degree on hydraulic performance.

To a certain extent, biochemical-thermo-hydro-mechanical (BCTHM) model can be regarded as a fully coupled multi-field model, which is helpful for the study of the landfill coupling process. A series of comprehensive BCTHM coupling models have been introduced (White et al. 2004)[10,21,22]. These models involved multi-component gas diffusion, leachate solute transport, water evaporation and gas dissolution processes. Settlement was related to mass loss caused by degradation, but creep was not considered. Ricken and Ustohalova[23] established a two-dimensional constitutive model based on the theory of porous media mechanics, which included organic phase transition, gas emission, heat transfer and long-term settlement. Kindlein et al.[24] proposed a coupled thermal water biological model considering macro heat conduction process, two-phase flow, component transport and local degradation, but it did not consider the changes of porosity and hydraulic performance caused by solid skeleton deformation. Yu et al.[25] proposed a one-dimensional sedimentation and gas flow model neglecting leachate flow. Kumar et al.[26] combined Reddy's model with the validated thermal model, taking into account the impact of waste temperature and moisture on degradation. Hubert et al.[27] introduced a coupled model to simulate the long-term behavior of MSW in bioreactor landfill by ignoring gas flow. This model considered the migration of VFA and MB dissolved in leachate due to convection and diffusion, and adopted Cam-Clay model-based biochemical water mechanical constitutive model to describe the deformation behavior of MSW.[11,28] (Fig. 2) established a coupling model considering solute and pore gas transport using convection–diffusion equation, and described it. The compressibility of soil particles is considered in the model. Lu et al.[29] established a numerical model of solid–liquid gas three-phase system based on the mass, momentum, and energy conservation theory of porous media. It can simultaneously simulate the physical processes of leachate, such as phase transformation, gas dissolution, component diffusion, liquid evaporation, pH change and solute migration.

The degradation-consolidation model was used to analyze the stabilization behavior of the landfilled HFWC MSW. Figure 3 shows the stabilization degree of HFWC MSW using different indices. The indices describe the hydrolysis process, leachate generation, settlement development, and gas production. The results show similar trends of the indices. Additionally, the normalized ratio of cellulose to lignin (β) can be

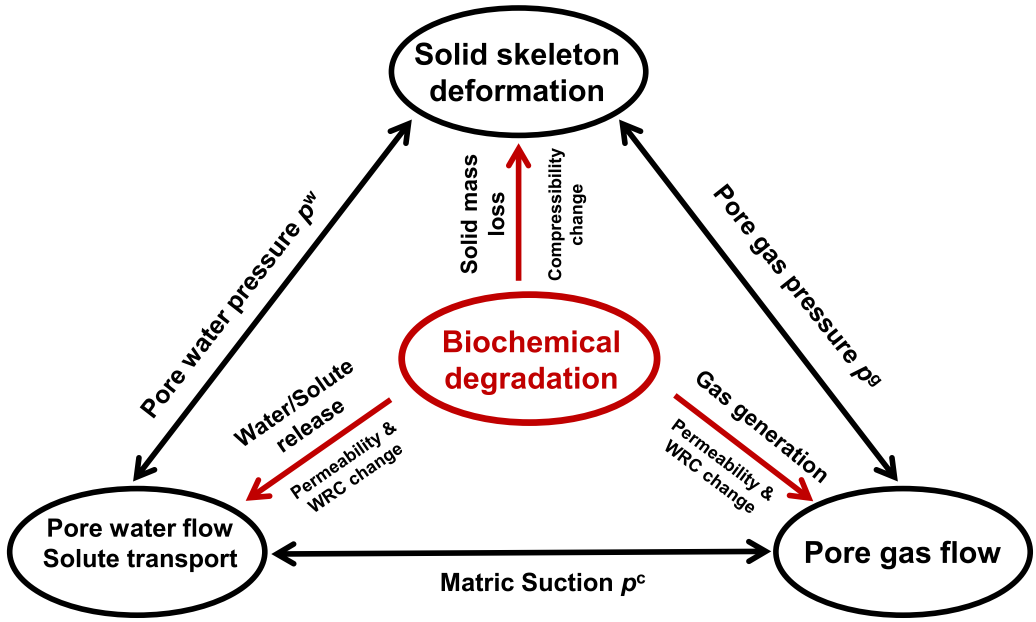

Figure 2: Degradation-consolidation model of landfilled MSW[11].

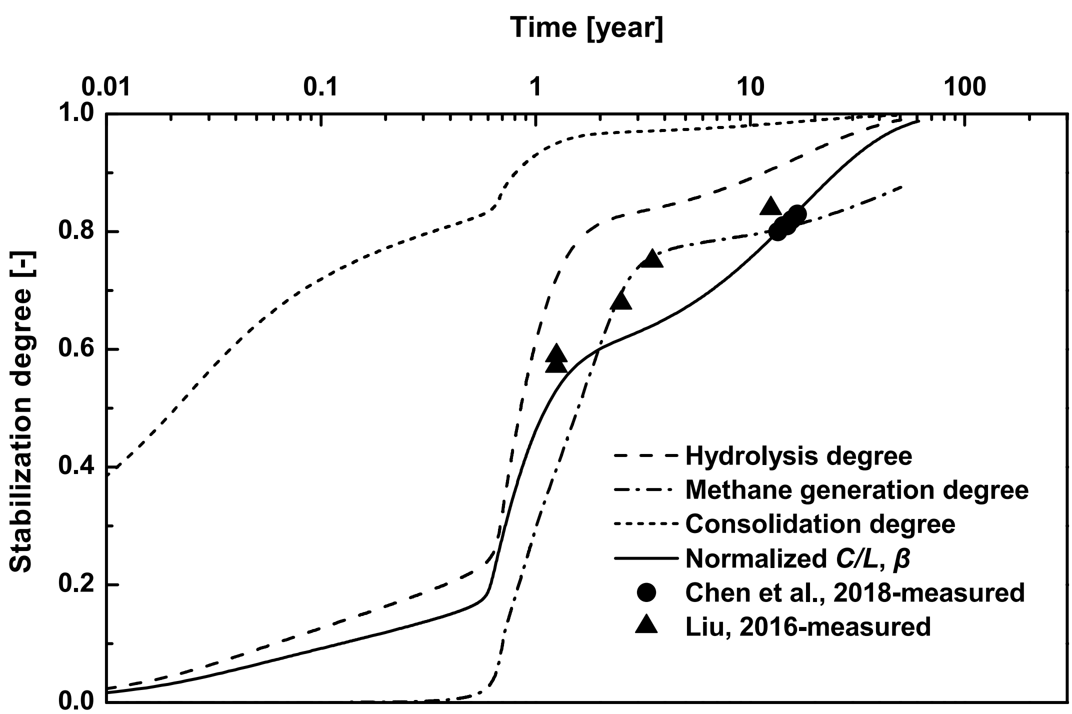

Figure 3: The stabilization degree of HFWC MSW and comparison of calculated and measured β values[11].

used as a criterion for the stabilization of MSW. The parameter β is defined as:

$$\beta = 1 - \frac{R^t_{C/L}}{R^0_{C/L}} \qquad (8)$$

where $R^t_{C/L}$ and $R^0_{C/L}$ are the current and initial ratios of cellulose to lignin, respectively. The parameter β has been used to assess the stabilization degree of HFWC MSW in the Hangzhou and Xi'an landfill in China (Fig. 3). The results indicated that the theoretical results were in good agreement with the measurements of the stabilization behaviors of the landfilled HFWC MSW. The value of β can be easily determined.

The results of the stabilization behavior analysis indicated that the degradation could be separated into three stages, i.e., rapid degradation, slow degradation, and stabilization. The rapid degradation lasted 2–3 years, and 60–80% of the degradable solid mass was lost. Intra-particle water was generated, and more than 60% of the methane production potential was released. The slow degradation stage lasted 20–30 years. More than 90% of the degradable solid mass was lost, and 80% of the methane production potential was released. Subsequently, stabilization occurred in the landfill.

Different processes occur in different stages. Large amounts of leachate are produced during the rapid degradation stage, and landfill gas is generated rapidly due to the high leachate level in the landfill body, increasing the slope failure risk. Leachate draining is required in the rapid degradation stage to reduce the slope failure risk and improve the efficiency of landfill gas collection efficient. It has been suggested to accelerate degradation in the slow degradation stage. Air ventilation can significantly accelerate the degradation process and shorten the slow degradation stage. In the post-stabilization stage, the MSW is almost entirely degraded, and the landfill gas production and surface settlement are negligible, allowing for reuse of the field or the landfilled MSW.

3 Changes in the Engineering Properties During Degradation

An understanding of the engineering properties of MSW can guide the design and operation of landfills. For example, the deformation properties are required to calculate the settlement and lateral displacement, and the strength parameters are needed to assess the slope stability. The liquid and gas conductivity of MSW has to be measured to determine the amount of leachate and landfill gas. During the degradation, the solid MSW is transformed into liquid and gas. Thus, there is a mass loss, and the landfill body softens. The solid particle size changes due to the mass loss, changing the particle size distribution. The changes in the solid mass loss and particle size distribution significantly affect the engineering properties of HFWC MSW.

3.1 One-Dimensional Compression Behavior

Xie (2006) investigated the long-term compression behavior of HFWC MSW. In the first three days, the strain of primary compression was 33.6%, and after 235 days, the strain of secondary compression was 20.7% due to degradation. The creep and degradation levels due to the deformation of the MSW were higher than the primary compression when the applied load was small. Similar results were found by[30,31].

One-dimensional compression experiments were carried out for MSW aged for 3 and 235 days to obtain the primary compression parameters. The results are shown in Fig. 4, indicating that the primary compression of fresh MSW was higher than that of degraded MSW. At the same loading pressure, the distance between the two lines represents the degradation-induced secondary compression, which decreases with an increase in axial loading. Thus, the secondary compression of MSW increased with the stress.

One-dimensional compression models were developed to describe the significant secondary deformation[30,32,33,34,35,36,37,38] (Sowers 1973). Marques et al. (2006) expressed the total compression strain as:

$$\varepsilon = \varepsilon_{\mathrm{p}} + \varepsilon_{\mathrm{c}} + \varepsilon_{\mathrm{d}} \tag{9}$$

where ε_p is the primary strain, ε_c is the creep strain, and ε_d is the degradation-induced secondary strain. The primary strain was calculated as:

$$\varepsilon_{\mathrm{p}} = C_C' \log \frac{\sigma_0 + \Delta\sigma}{\sigma_0} \tag{10}$$

where C_{C}' is the primary compression coefficient, σ_0 is the vertical load(kPa), $\Delta\sigma$ is the load increment (kPa) THE strain induced by creep and degradation was expressed as:

$$\begin{aligned} \varepsilon_{\mathrm{c}} &= b(\Delta\sigma)\left(1 - e^{-ct'}\right) \\ \varepsilon_{\mathrm{b}} &= E_{\mathrm{dg}}\left(1 - e^{-dt''}\right) \end{aligned} \tag{11}$$

where b and c are the creep parameters, t' is the time of applying the load; E_{dg} is the total degradation-induced strain, d is the degradation rate factor, and t'' is the aging time of the MSW.

The compression model by[37] accurately described the secondary compression occurring over time. However, the aging effect of the primary compression was not considered.

Chen et al.[32–34,39] introduced a compression model based on long-term tests that was expressed as:

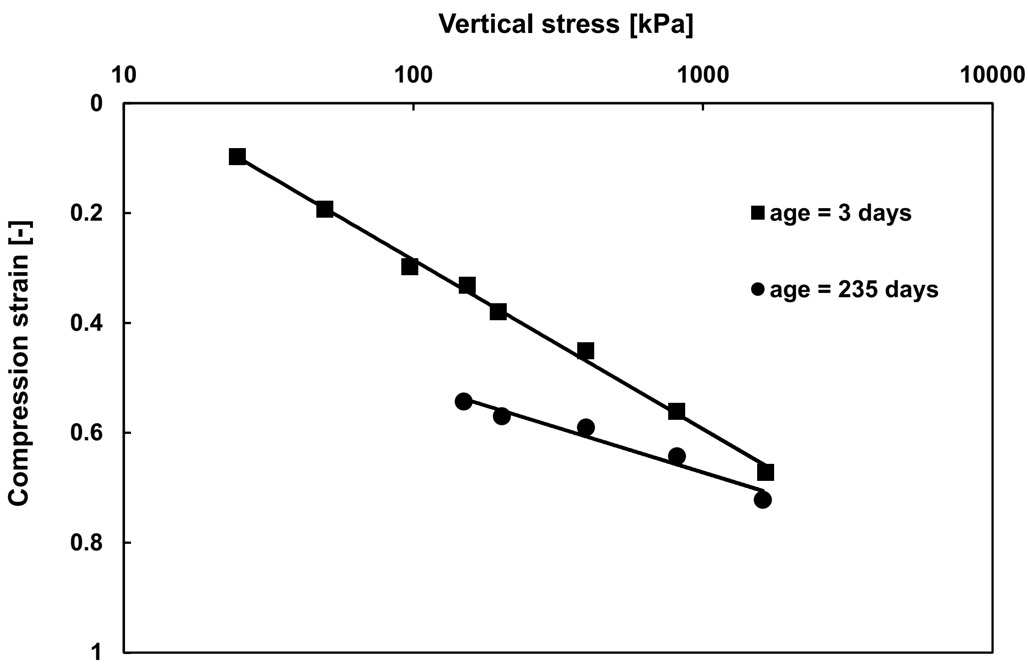

Figure 4: Compression curves of fresh and degraded MSW.

$$\varepsilon = C'_{C0}\lg\frac{\sigma'}{\sigma'_0} + \left(\varepsilon_{s\infty}(\sigma'_0) + (C'_{C\infty} - C'_{C0})\lg\frac{\sigma'}{\sigma'_0}\right)\left(1 - \frac{M_{sd}^{t}}{M_{sd}^{ini}}\right) \quad (12)$$

where C'_{C0} and $C'_{C\infty}$ are the primary compression coefficients of fresh and completely degraded MSW, respectively. $\varepsilon_{s\infty}$ is the total secondary compression, and M_{sd}^{t} and M_{sd}^{ini} are the degradable solid mass of the current and fresh MSW, respectively.

A change in the composition of landfilled MSW changed the strength properties[40–47,48]. Zhan et al.[47] performed triaxial tests on landfilled MSW with different aging times. The results (Fig. 5) indicated that the internal friction angle increased and the cohesion decreased as the aging time increased.[44,46] presented similar results.

3.2 Water Retention Behavior

The water retention properties of MSW are significantly affected by the particle size distribution and porosity. Yang[49] established the soil–water characteristic curve of HFWC MSW under degradation and compression. The particle size distribution is shown in Fig. 6. The percentage of fine particles increased after two months of aging, indicating that large particles were crushed during degradation.

The soil–water characteristic curves are shown in Fig. 7. The van Genuchten model was used for curve fitting. The soil–water characteristic curve of the degraded MSW was located above the curve of the fresh MSW, indicating that the degraded MSW had higher water retention capacity. A lower porosity of the MSW with the same age resulted in higher water retention capacity. The test results showed that degradation resulted in finer particles and lower porosity, increasing the water retention capacity of MSW.

3.3 Hydraulic Conductivity

Liquid and gas flow in MSW is affected by hydraulic conductivity, which is related to the permeability and the fluid properties of the MSW. The hydraulic conductivity is defined as:

$$k_f = \frac{k_i \rho_f g}{\mu_f} k_{rf} \quad (13)$$

where k_f is the hydraulic conductivity of the fluid, k_i is the intrinsic permeability of the medium, ρ_f is the fluid density, μ_f is the fluid viscosity, and k_{rf} is the fluid relative permeability. The intrinsic

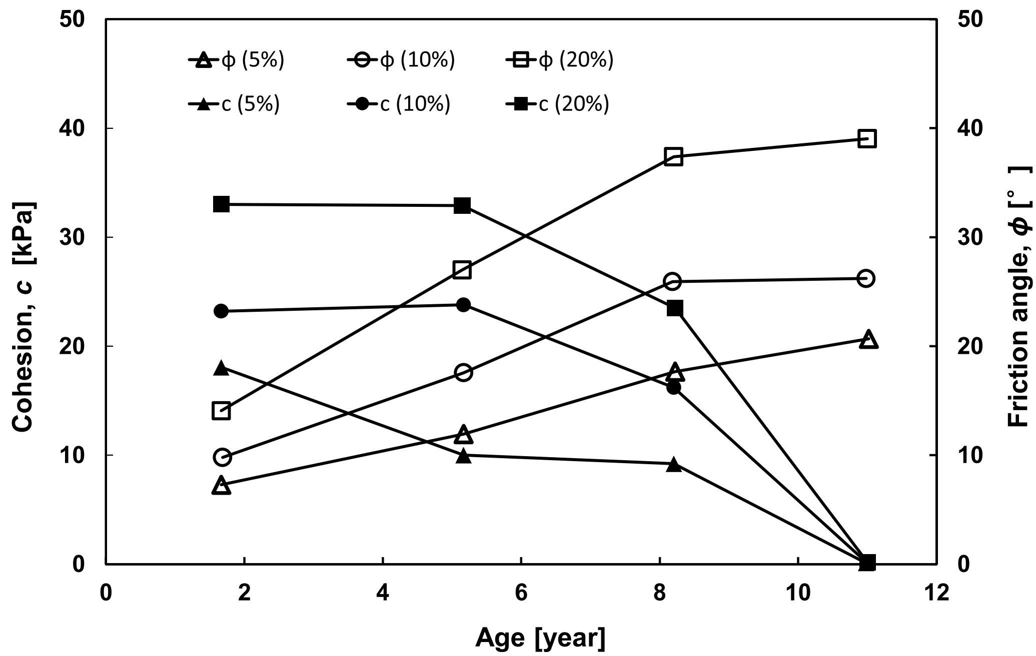

Figure 5: The influence of degradation on the strength properties of MSW[47].

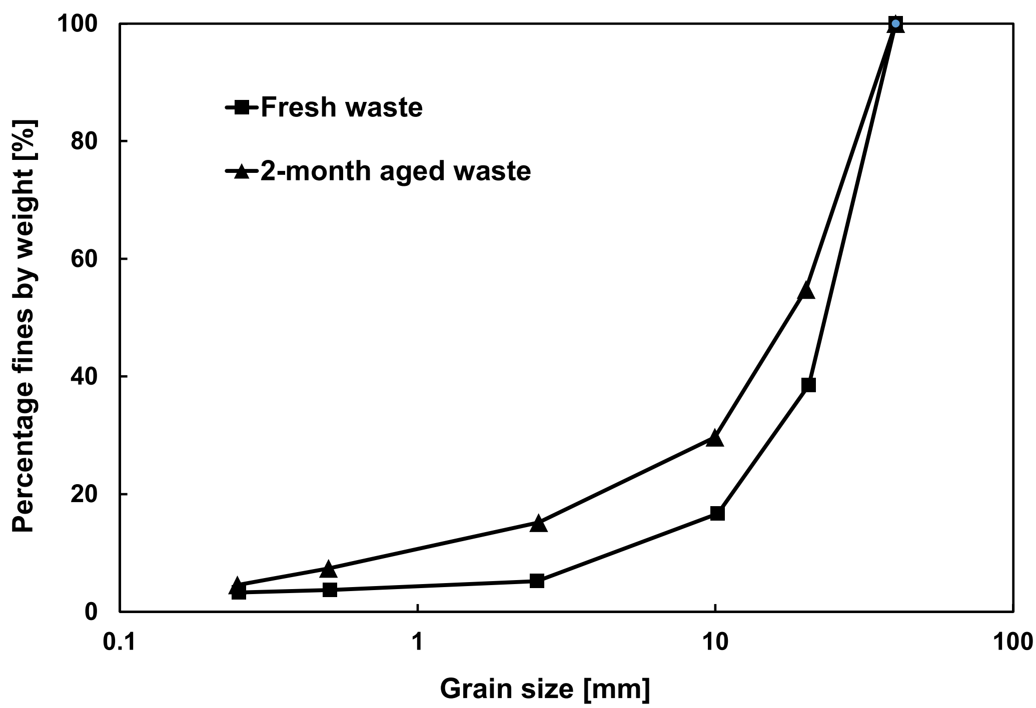

Figure 6: Particle size distribution of fresh and 2-month aged MSW.

permeability depends only on the porous properties, which change during degradation.

The effects of degradation on hydraulic conductivity were studied by[50]. The degree of degradation was described by $R_{C/L}$ (Fig. 8). For MSW with the same porosity, the intrinsic permeability decreased with an increase in the aging time. For MSW with the same aging time, the

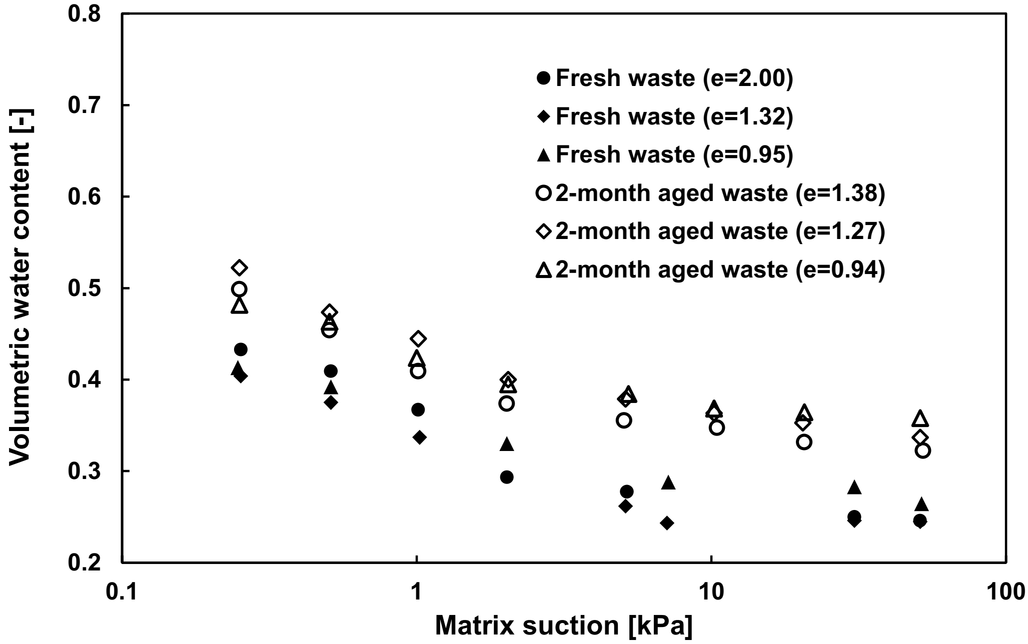

Figure 7: The soil–water characteristic curves of fresh and 2-month aged MSW.

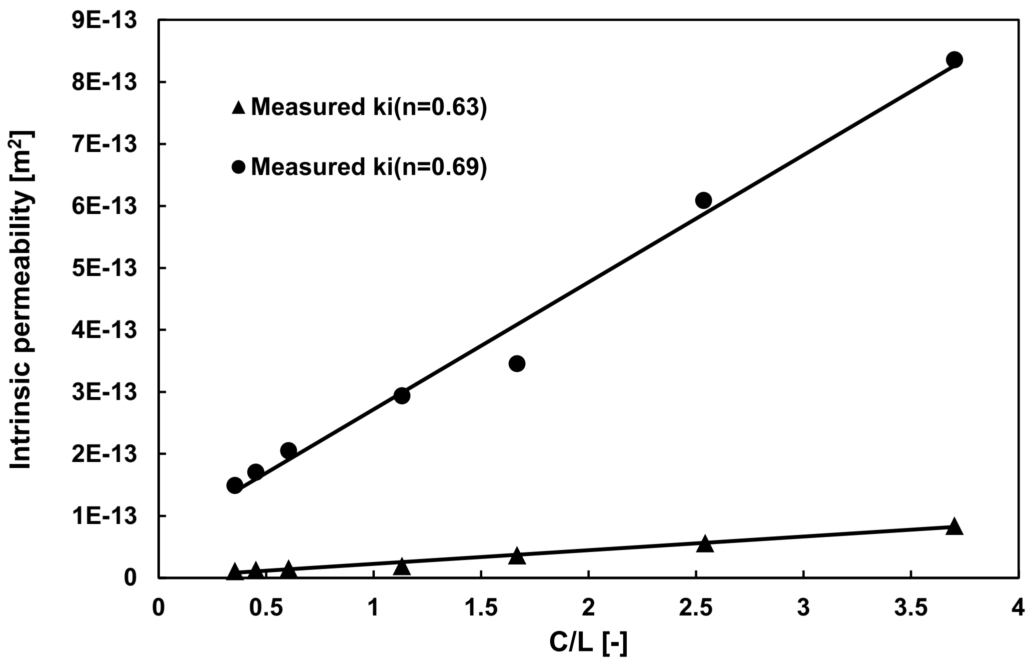

Figure 8: Intrinsic permeability variation with degradation: k_i vs. C/L.

intrinsic permeability increased with the porosity. Similar results were found by[51] Reddy et al. (2010). The decrease in the intrinsic permeability was caused by an increase in the fine particle amount, which deceased the flow paths.

4 High Leachate Level and Drainage System

In HFWC MSW landfills, large amounts of leachate are generated due to degradation, compression, and rainfall infiltration. The leachate production of HFWC MSW was significantly higher than that of LFWC MSW due to the higher water content[32,33]. Due to the low permeability of the MSW near the bottom of the landfill and the clogging of the drainage system, the leachate could not be drained, and the leachate level in the HFWC MSW landfill was high[9,52,53]. In China, the average ratio of the leachate level and the height of the landfill is 0.8, whereas the average ratio for LFWC MSW landfills in western countries is 0.38. A high leachate level can cause geoenvironmental hazards, such as the failure of the landfill[54,55], groundwater and soil contamination[56,57], and difficulties with landfill gas collection[58,59].

4.1 Leachate Production

The leachate production rate has a substantial impact on the leachate level in landfills. Leachate is comprised of rainwater and degradation-induced intraparticle water. In western countries, the leachate amount is typically calculated using the water balance equation[60–62,63] and the hydrologic evaluation of landfill performance (HELP) model[64].

For HFWC MSW, the leachate caused by degradation and compression is the difference between the initial water content and the field moisture capacity. It should be noted leachate is released over time and depends on the state of loading and compression. Thus, the daily leachate amount was calculated as follows:

$$L_n = \frac{I_n(C_{L1}A_1 + C_{L2}A_2 + C_{L3}A_3)}{1000} + \sum_{i=1}^{n} E_i \tag{14}$$

where L_n is the nth stage of the leachate production, I_n is the rainfall in the nth stage, parameter A denotes the catchment area, C_L is the exudation parameter, and subscripts 1, 2, and 3 denote the operation area, middle cover area, and the final covered area.

E_i is the leachate production due to the degradation and compression in the nth calculation stage of the ith layer of the landfilled MSW:

$$E_i = \frac{(M_{i,0} - S_{i,n-1})W_{i,n-1} - (M_{i,0} - S_{i,n})W_{i,n}}{\rho_w} \tag{15}$$

where M is the mass of the fresh landfilled MSW, S is the solid mass loss due to degradation, W is the field moisture capacity, and ρ_w is the water density.

The leachate production of landfills in Shanghai and Guangzhou in China were calculated using the above method and compared with the measured amount and other methods (Fig. 9). The result indicated that the calculation method, which considered the degradation and compression-induced leachate, yielded more reliable results than the conventional method.

4.2 Three-Dimensional Leachate Drainage System

Extremely high leachate levels have caused serious geoenvironmental hazards in China. In addition to a drainage system at the bottom of the landfill, drainage measures were also required in the middle of the landfill to reduce the leachate level. The leachate drainage system in the middle of the landfill consisted of several layers to achieve a rapid decrease in the leachate level. As the leachate level increases and deformation occurs, rapid draining of the leachate can reduce the risk of a landfill slope failure. A permanent leachate control system should be installed to ensure that the leachate level remains below a critical level. The multi-drainage system of the HFWC MSW landfill included vertical and horizontal wells and horizontal drainage between the layers[65] (Fig. 10).

Vertical wells are conventionally used as a contingency or long-term solution to lower the leachate level due to the straightforward construction and good performance. Several field tests have been conducted to analyze the dewatering performance of vertical wells in MSW landfills[66]. However, vertical wells used in previous studies generally had a small diameter, and the well pipes were mostly made of HDPE material, which was prone to bending failure. The study[66] used a large-diameter vertical well, as shown in Fig. 11. The diameter of the vertical well is 1 m. Gravel and a composite drainage network are used as the filter layer to prevent clogging. The well pipe is made of high-strength galvanized steel to provide even settlement. The influence radius of the large-diameter vertical well is 20–30 m, and the pumping rate is 20–50 m^3/days.

A horizontal drainage system was constructed by excavating trenches within the waste during the waste filling operation. This approach has a low cost and provides a large flow rate due to the long length of the trenches. The system was used to keep the leachate level above the well pipe. The optimized structure of the horizontal trench is shown in Fig. 12. The section size should exceed 2 m^2, and the length should be 150–300 m. The spacing between the horizontal trenches should be 100 m. The maximum leachate flow rate of a 100 m-long horizontal trench was 100–150 m^3/days.

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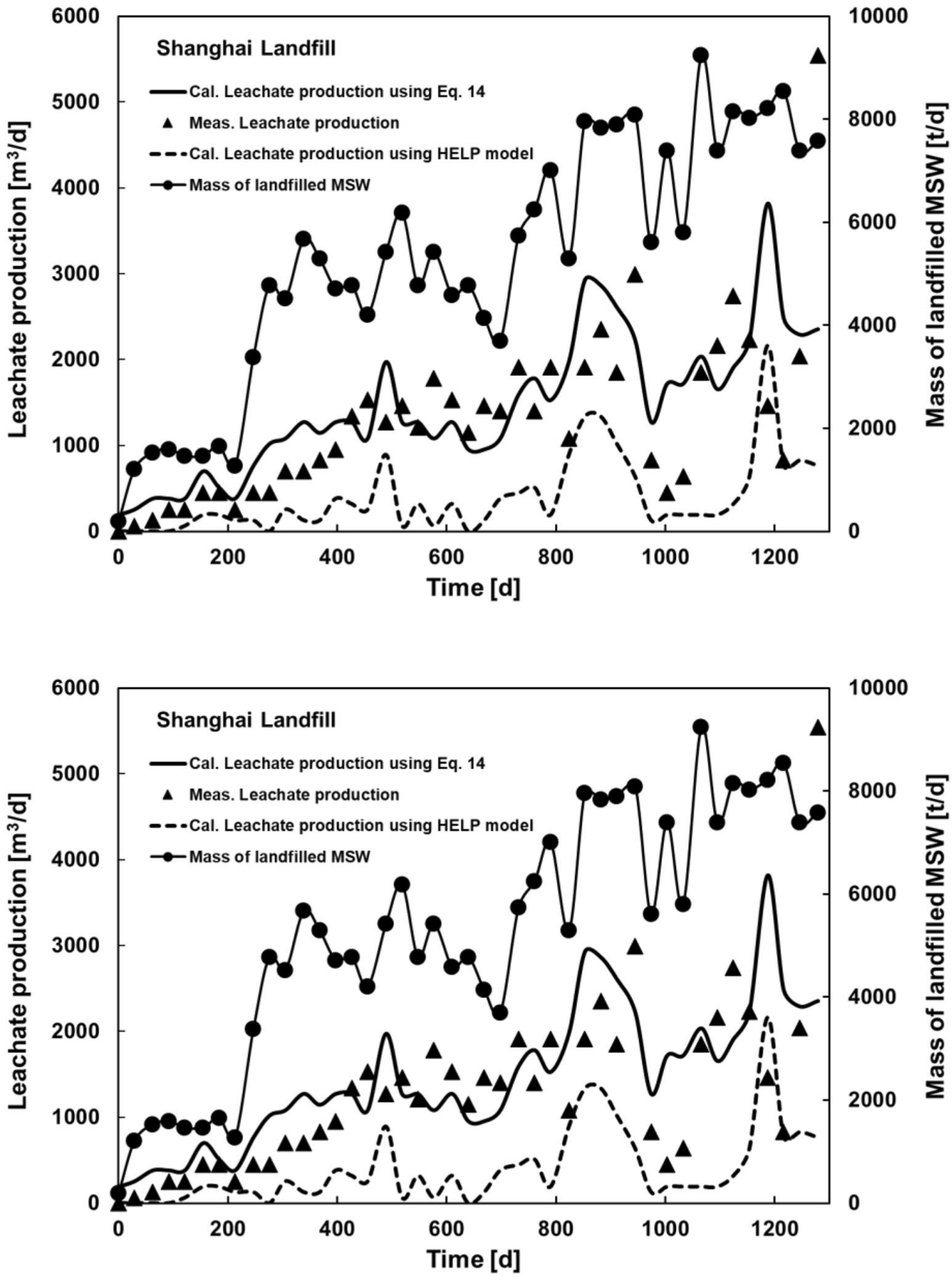

Figure 9: Comparison of different leachate production calculation models and the measured values.

Horizontal wells offer potential advantages due to the large ratio of the submerged to the total installed screen length and the ability to extract leachate near the base of the landfill, where pore pressure reduction is required. The first horizontal drainage well project in an HFWC MSW landfill was developed in Hangzhou, China[67]. The landfill had a daily MSW treatment amount of over 4000 tons. The leachate level was just 5 m below the top surface of the landfill. Three wells (50 m and 56 m in length) were successfully installed using an improved casing-protected directional drilling method. Each well was installed at a gradient of 5% (height ÷ length) downward in the direction of flow to facilitate the gravity-driven outflow of the leachate. The well screens were made of 133 mm OD galvanized steel pipe with opening holes with a diameter of 12 mm. Figure 13 shows the leachate flow rate and cumulative flow volume overtime for the

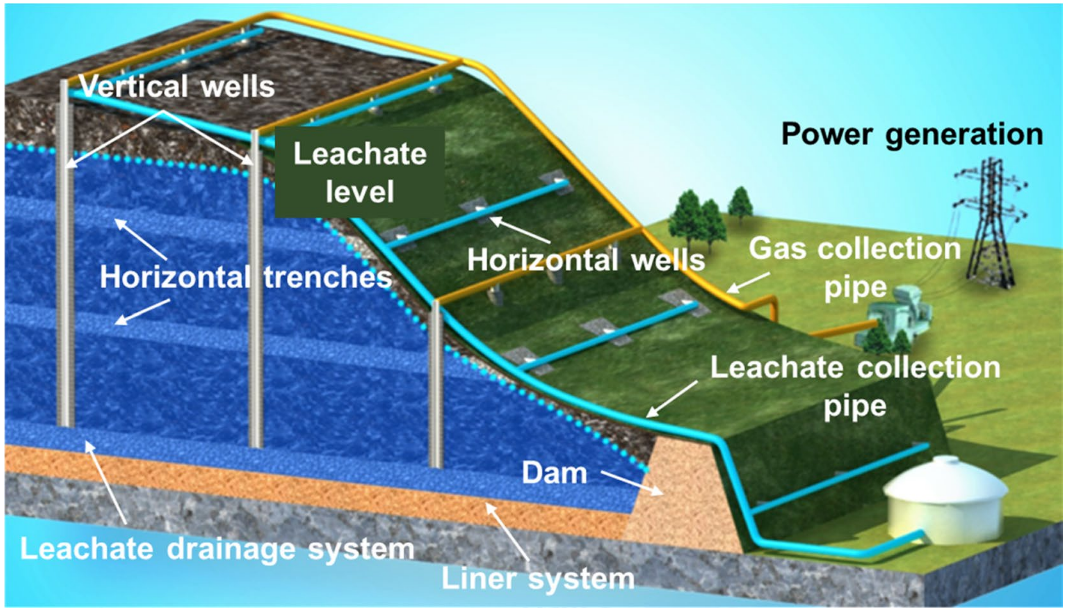

Figure 10: Concept of the 3-dimensional drainage system of a landfill with a high leachate level.

S01 well. The leachate flow rate of S01 well was initially high (75 m^3/day), but decreased rapidly to 20 m^3/day by Day 3. The leachate flow rate increased from 20.5 m^3/day to 34.5 m^3/day between Day 3 and Day 14 and declined gradually to 3 m^3/day by Day 90. The average leachate flow rates of the two wells were 10.66 m^3/day and 3.93 m^3/day, respectively. After 74 days of drainage, the maximum leachate level drawdown around the highest flow well was 2.7 m, and its distance of influence was 50 m (as shown in Fig. 14).

5 Landfill Gas Generation and Efficient Collection

Due to the high leachate level and water saturation state in the HFWC MSW landfill, it is difficult to collect the landfill gas. The accumulated landfill gas causes high pore gas pressure[68,69] (Zhan et al. 2015), which increases the leachate level and the effective stress, potentially resulting in the slope failure of the landfill.[68] reported 80 kPa of pore gas pressure in a Guangzhou landfill in China.

Simplified models were used to investigate landfill gas generation. The LANDGEM model developed by the Environmental Protection Agency (EPA)[70] and the Scholl-Canyon model developed by the Intergovernmental Panel on Climate Change (IPCC)[71] were widely used. Both models are based on the first-order kinetic degradation model. The methane generation potential (L0) and gas generation rate (k) are the most important parameters in both models. Those parameters were updated in recent studies[72–77]. However, those models were established based on the degradation behavior of LFWC MSW landfills and not suitable for HFWC MSW landfills. Due to the significant difference in the composition, the use of these models to analyze landfill gas generation could lead to non-negligible differences compared to actual conditions[78].

The food waste content and initial water content are typically higher in HFWC MSW than in LFWC MSW in China. Thus, landfill gas generation is more likely to occur in HFWC MSW. The ratio of carbon to nitrogen is typically 20:1 in HFWC MSW, which is conducive to methanogenesis.

5.1 Landfill Gas Generation

The following modified two-stage landfill gas generation model for HFWC MSW was introduced:

$$Q_n = \sum_{i=1}^{n} M_i L_{R0}\left(\frac{k_R}{12}\right)e^{-\frac{k_R}{12}\left(t_i - t_{R,lag}\right)} + \sum_{i=1}^{n} M_i L_{S0}\left(\frac{k_S}{12}\right)e^{-\frac{k_S}{12}\left(t_i - t_{S,lag}\right)} \quad (16)$$

where Q_n is the theoretical monthly landfill gas generation rate in the ith month after the landfill operation, t_i is the aging time of the landfilled MSW, M_i is the mass of the MSW in the ith

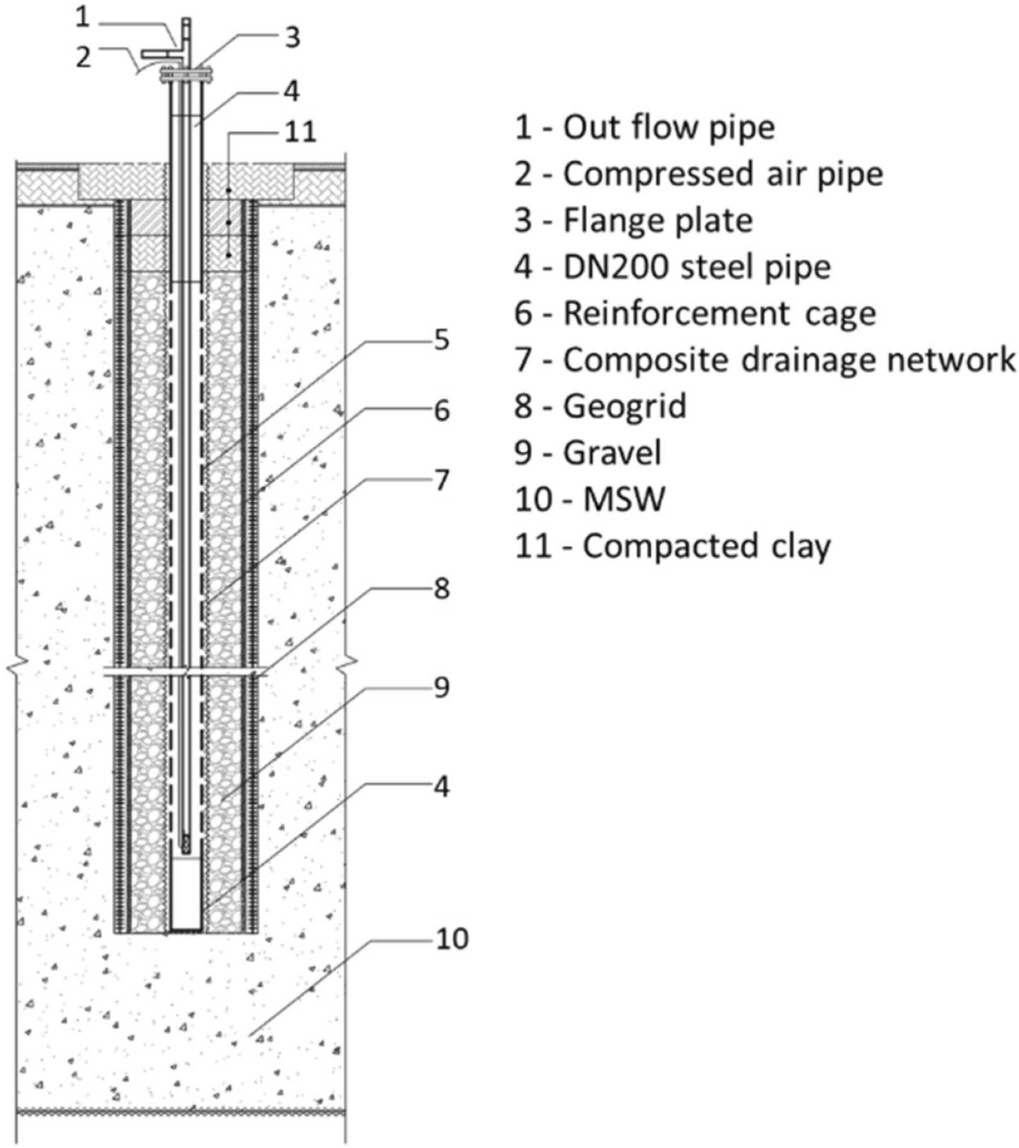

Figure 11: Structural diagram of a large-diameter vertical well.

month, L_{R0} is the theoretical gas generation of the rapidly degradable components per unit mass, L_{S0} is the theoretical gas generation of the slowly degradable components per unit mass, K_R is the gas generation rate of the rapidly degradable components, k_s is the gas generation rate of the slowly degradable components, $t_{R,lag}$ is the gas generation lag time of the rapidly degradable components, and $t_{S,lag}$ is the gas generation lag time of the slowly degradable components.

The relationship between k_R and k_s was analyzed in several studies. The results indicated that k_R was 3–6 times larger than k_L[73,76,78]. The landfill gas generation rates k_R and k_L can be calculated using in-situ gas collection tests and back analysis. The results of in-situ tests in China provided values of 0.7–1.3 and 0.02–0.3 for k_R and k_L, respectively, for HFWC MSW.

5.2 Efficient Collection of Landfill Gas

The first landfill gas resource recovery project in China was implemented in Hangzhou in 1998. Twenty years later, there were 72 similar projects, much less than in the US. Meanwhile, the proportion of landfill gas collection was only 25–40%, much lower than in western countries. As a result, the landfill gas emissions are high, increasing the

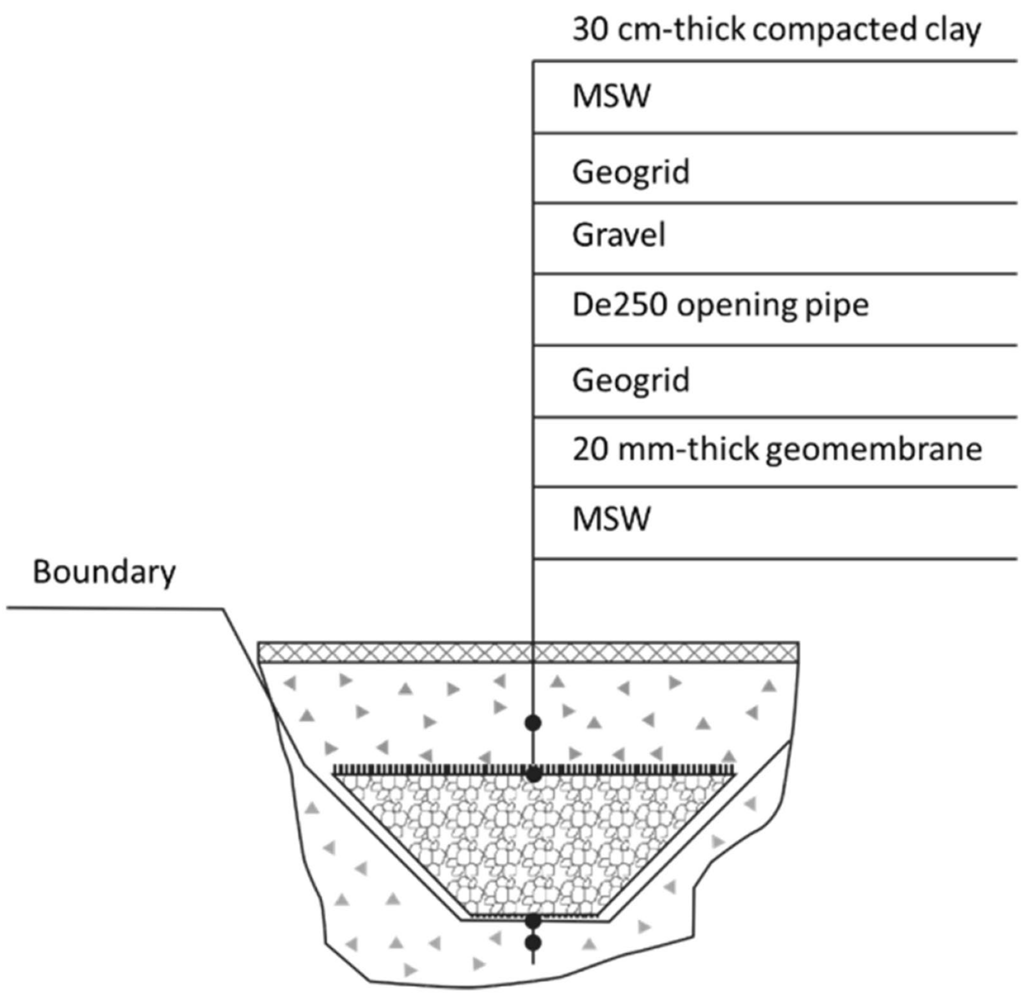

Figure 12: Structural diagram of the horizontal trench.

risk of slope failure. Since most of the landfill gas in HFWC MSW is generated 1–2 years after landfilling, two issues should be addressed, i.e., reducing the permeability of the cover system and increasing the gas permeability of the landfill body.

A geomembrane can be used as a temporary cover for the fresh MSW to reduce the permeability of the cover system. Horizontal gas collection wells can be installed under the geomembrane to capture the landfill gas in the early stage (Fig. 15). The 3-dimensional drainage system can be used to control the leachate level and ensure that the gas has low water saturation.

These engineering measures were implemented in a landfill in Shenzheng in southern China. Figure 16 shows the theoretical calculation of the generated landfill gas, the in-situ collected amount, and the landfill gas collection rate. The landfill gas collection rate is defined as the ratio of the in-situ collected amount and the calculated amount of the landfill gas. The results show a significant increase in the amount of the collected landfill gas after the application of the gas collection measure. The amount of the collected landfill gas increased from 16,000 m^3/h to 8770 m^3/h in 4 years, and the collection rate was 55%. In 2014, a temporary cover and a gas collection system were installed; as a result, the amount of collected landfill gas increased to 45,500 m^3/h, with a collection rate of 90%.

6 Conclusions

The initial content of degradable material differs for HFWC MSW and LFWC MSW. Unlike in LFWC MSW landfills, in anaerobic degradation, significant acid inhibition occurs during hydrolysis and methanogenesis in the early period after landfilling. Thus, the measures to prevent geoenvironmental issues in LFWC MSW landfills, which were successfully applied in developed countries, are not appropriate for HFWC MSW

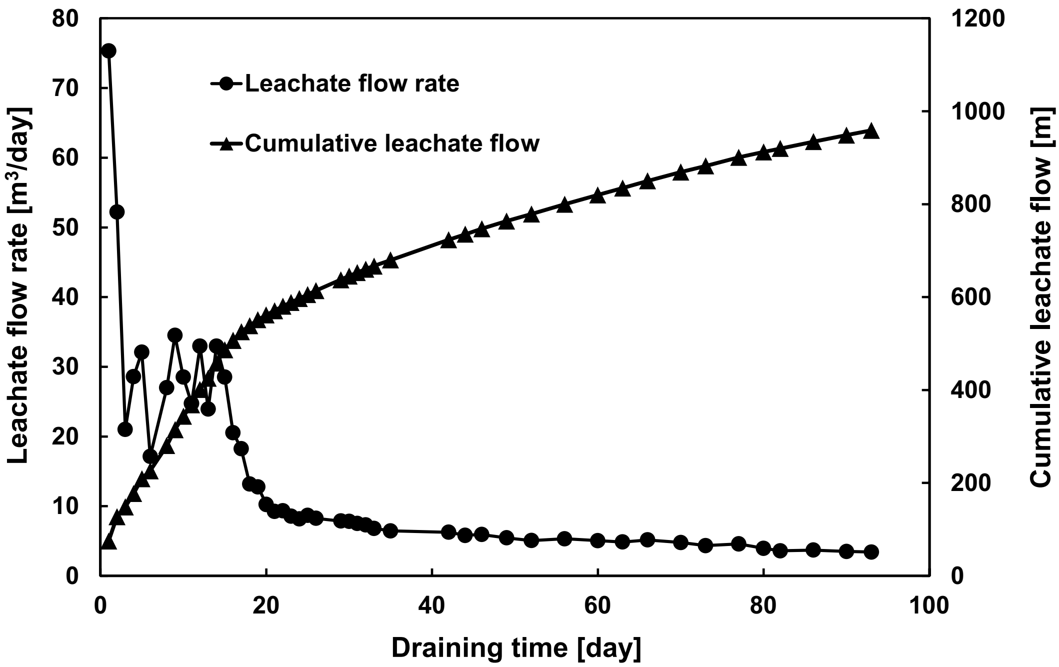

Figure 13: Flux rate and cumulative leachate flow of the S01 well.

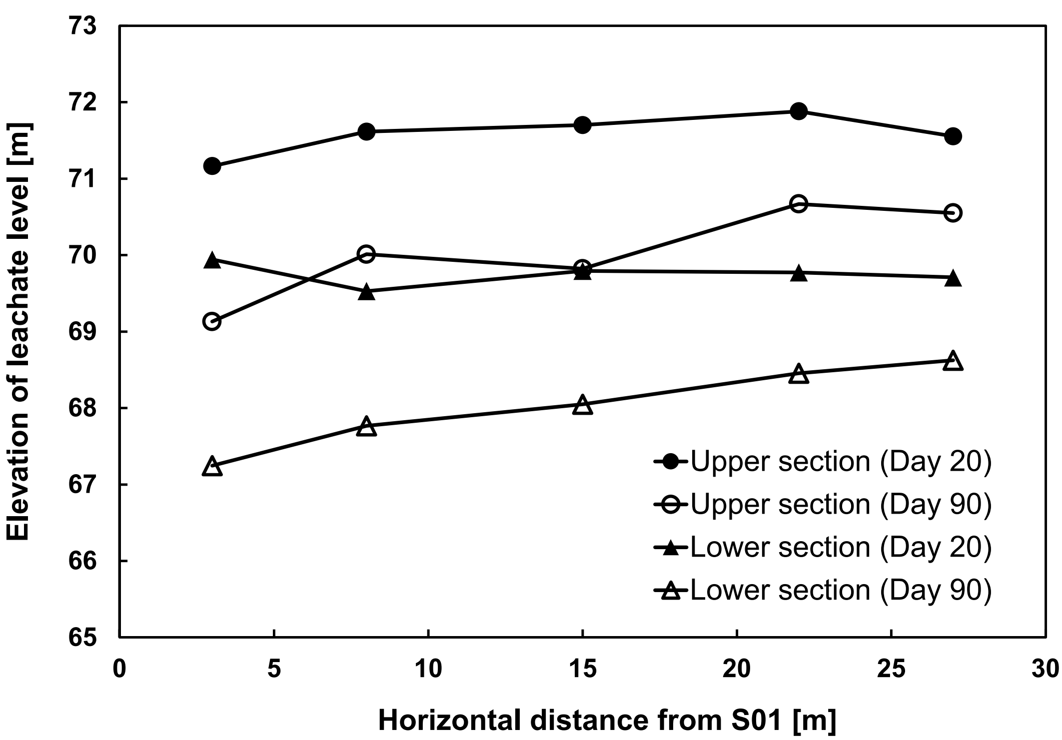

Figure 14: Pore pressure changes after drainage using horizontal well.

landfills. We reviewed recent studies on geoenvironmental issues in HFWC MSW landfills to highlight the problems and potential solutions.

1. A theoretical degradation-consolidation model coupling the biological degradation, deformation, and two-phase flow was

Figure 15: A temporary cover and horizontal gas collection wells.

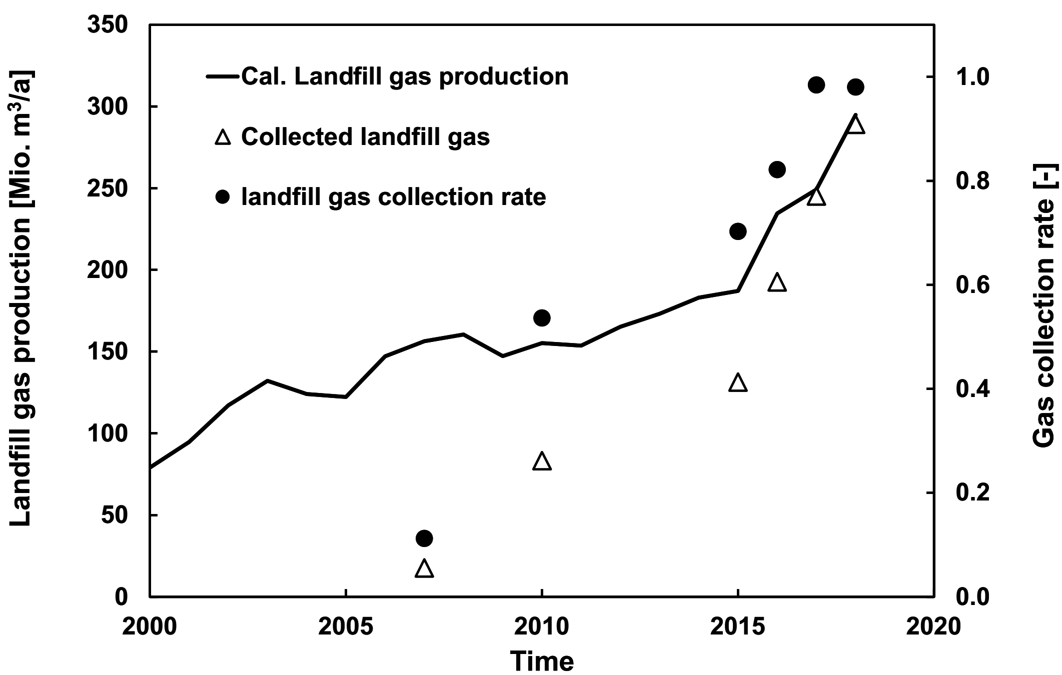

Figure 16: Assessment of the landfill gas collection rate.

described. The significant leachate production due to the release of intra-particle water was captured. The theoretical analysis indicated three stages of degradation/stabilization of the HFWC MSW, i.e., rapid degradation, slow degradation, and post-stabilization.

2. A practical model was used to assess the daily leachate production of HFWC MSW landfills. The design and operation of the leachate collection system of a landfill were based on the assessment of the leachate production.

3. The 3-dimensional drainage system of the landfill consisting of vertical and horizontal wells can be constructed after the landfilling process. This system represents an emergency measure for lowering the risk of slope failure.
4. Landfill gas is a greenhouse gas and a valuable resource, and increasing the amount of collected landfill gas has ecological and economic benefits. More gas can be collected when drainage measures are implemented to lower the leachate level. Additionally, using a landfill cover, less gas is discharged into the atmosphere. Both measures significantly increase the amount of collected landfill gas.

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Author contributions

Conceptualization: YC, WX; Methodology: YC, WX, HK, LZ; Formal analysis and investigation: JH, HL, PM, JL; Writing—original draft preparation: YC, WX, JH, HL, PM; Writing—review and editing: YC, WX; Funding acquisition: YC; Resources: YC, WX; Supervision: YC.

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Declarations

Conflict of interest

There are no conflicts of interest or competing interests.

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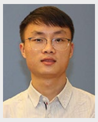

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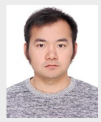

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