

Article

The Evaluation System of the Sustainable Development of Municipal Solid Waste Landfills and Its Application

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Abstract: Improving the understanding of the stabilization process is of great significance to guide the sustainable development of municipal solid waste (MSW) landfills. An evaluation system of the stabilization process of MSW landfills has been established. The indices of the evaluation system involve the degradation degree of MSW, the release of landfill gas production potential, and the settlement of landfills. Based on the biochemical-consolidation-solute migration coupled model, an evaluation method of the MSW landfill stabilization process is proposed by combining field tests with numerical simulation. The stabilization process of the Jiangcungou landfill in China is investigated by using the proposed method. The analyzed results show that the stabilization process of high kitchen waste content landfills can be divided into three stages, which is different from the stabilization process of landfills in developed countries. For the Jiangcungou landfill, the ratio of cellulose to lignin in MSW decreases rapidly during the fast degradation stage when obvious settlement occurs. During the slow degradation stage, the hydrolysis rate is slow and settlement develops slowly. When the landfill reaches the stabilization stage, the ratio of cellulose to lignin of MSW changes very slowly; most of the landfill gas potential has been released; the settlement stabilization is completed basically. The change processes of the three evaluation indices are different, of which the degradation stabilization index is the main one. According to the findings above, leachate recirculation is recommended to adjust the degradation environment in the landfill, which can be helpful to avoid acidification at the fast degradation stage. Temporary cover is suggested to improve landfill gas collection efficiency at the beginning of the stable methanogenic stage. The landfill site closure should be operated when the settlement rate is low.

Keywords: municipal solid waste; sustainable development; evaluation system; stabilization process; coupled model



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1. Introduction

A large amount of municipal solid waste (MSW) is generated every year, and the growth rate of MSW production is accelerating significantly with the development of urbanization, which results in a global environmental issue. The sanitary landfill technique has been widely used to dispose of MSW in most countries [1,2]. MSW contains degradable components. Complex physical, chemical, and biological processes occur within landfills. Leachate with a substantial amount of pollutants and landfill gas containing greenhouse gases (i.e., methane and carbon dioxide) are generated, making the landfill act as a large bioreactor [3]. At the same time, the landfill becomes an earth structure as MSW is added. Deformation and moisture or gas transport occur in the landfill, inducing geotechnical problems, such as differential settlement and landfill slope failure [4]. The stabilization of MSW landfills includes the following aspects: settlement, leachate, and landfill gas generation being completed, and the content of pollution components in leachate achieving

the requirements of the discharge standards. The whole process usually takes decades, or even hundreds of years [5,6]. The landfill stabilization process can be shortened significantly if appropriate operation measures are carried out, which can increase the MSW landfill capacity, improve the collection efficiency of landfill gas, and reduce the emission of pollutants in leachate [7–10]. It is of great environmental and economic value to predict the biochemical and mechanical behaviors during the long-term stabilization process of landfills. The evaluation of the stabilization process is significant for sustainable development that meets the disposal needs of MSW without inducing environmental disasters.

There is no unified standard for the selection of evaluation indices of the landfill stabilization process due to the complex biochemical and mechanical behaviors in landfills. The common evaluation indices involve the degradable component content, the generation production of leachate and landfill gas, the pollutant content in leachate, and the landfill settlement [5,11]. The degradation degree of MSW has been considered as the representative evaluation index of the stabilization process of landfills in developed countries [12,13]. Many field and laboratory tests have been carried out to fully investigate the degradation stabilization process of MSW, and the results indicated that the ratio of cellulose to lignin content (C/L) in MSW decreases with the increase in filling depth (or filling age). The change of the C/L value is affected by the initial composition and moisture content of MSW [6,14]. The single evaluation index, which is the value of C/L, is convenient for the practical application of the evaluation system. However, it is difficult to predict the complex mechanical behavior in landfills by the variation of C/L. The index assessment method has also been used to estimate the stabilization state of landfills by considering multiple evaluation indices [15–18]. Wang and Zhao [15] have divided the landfill stabilization process into four stages by proposing an evaluation system based on the index assessment method, the evaluation indices involved leachate quality parameters, leachate, and landfill gas generation production, and settlement rate of landfill. Jiang et al. [16] have used a similar method to analyze the laboratory test results of four MSW columns. The selection of evaluation indices pays more attention to the MSW components and biochemical parameters, the indices include that COD, BOD₅, BOD₅/COD, and NH₃-N in leachate; the percentage of CH₄ of landfill gas; the generation rate of leachate and landfill gas; the residual methane production potential of MSW; volatile solids content in MSW; and the C/L. The above studies are very valuable, however, a simplified exponential attenuation model is applied to predict the variation of evaluation indices of landfill stabilization in the index assessment method, which cannot take into account the interaction of biochemical and mechanical behaviors in landfills. The long term prediction of the stabilization process of landfills may deviate from the actual situation.

An evaluation system of the sustainable development of MSW landfills is established in this paper, which describes the stabilization state of landfills from three aspects: the content of degradable components in MSW, the generation of landfill gas, and the settlement of landfill. A prediction method of the long term stabilization process of MSW landfills is proposed by combining borehole sampling test and numerical simulation. The proposed system is applied to evaluate the stabilization process of the Jiangcungou landfill, in Xi'an city, China. The interaction of biochemical and mechanical behaviors in the Jiangcungou landfill are analyzed. The variations of three indices are investigated quantitatively to the characteristic of each stabilization stage of the landfill, which is compared with the stabilization process of the typical landfills with low kitchen waste content in developed countries. Finally, suggestions on manage landfills with high kitchen waste content are addressed based on the results of the investigations.

2. Materials and Methods

2.1. Evaluation Indices of the Stabilization Process of MSW Landfills

2.1.1. Degradation Stabilization Index, A_1

MSWs have been in a closed environment for a long time in the landfill, therefore, anaerobic decomposition is the main process of degradation in landfills. The anaerobic

decomposition process can be simplified into two stages: hydrolysis and methanogenesis [19]. During the decomposition process, biodegradable components of MSW transform from the solid phase into the gas and liquid phase, which results in the flow of leachate with high concentration pollutants and landfill gas in landfills, and the deformation of the solid skeleton of MSWs [20]. The complicated biodegradation processes in landfills make engineering properties of MSWs changing with time [21], which is different from the traditional hydro-mechanical coupled behaviors in soil (i.e., unsaturated consolidation problem). Therefore, the anaerobic decomposition of MSW is the core aspect of the stabilization process of landfills.

Cellulolytic matter in degradable components accounts for more than 90% of the methane potential of MSWs [12,19]. The ratio of cellulose to lignin content (C/L) in MSW reflects the content of residual degradable components in landfills. The value of C/L is expressed by $R_{C/L}$ in this paper (kg/kg). $R_{C/L}$ can be calculated by dividing the mass of cellulose (C) in a unit mass of MSW by the mass of lignin (L) in a unit mass of MSW. The C/L decreases gradually during the process of hydrolysis, it can be used as the characterization index of the degradation degree of MSWs [22]. The initial values of C/L have a wide range due to the great difference in MSW composition from different countries or regions [23]. Therefore, a parameter, which is represented by Λ_1 , is defined as the degradation stabilization index of landfills. The formula of Λ_1 is shown as follows:

$$\Lambda_1 = \frac{R_{C/L}(t)}{R_{C/L}(t_0)} \quad (1)$$

where: $R_{C/L}(t)$ is the C/L of MSW with filling age t (kg/kg); $R_{C/L}(t_0)$ is the initial C/L of fresh MSW (kg/kg).

2.1.2. Landfill Gas Stabilization Index, Λ_2

The main components of landfill gas are carbon dioxide (CO₂) and methane (CH₄), which are greenhouse gases. The collection of landfill gas is helpful to reduce global carbon emissions. On the other hand, the methane in landfill gas can be used in combustion, thermal power generation, and fuel production [24]. Therefore, the management of landfill gas has a significant environmental and economic value.

Landfill gas is the reaction product of the methanogenesis process. Hydrolysis and methanogenesis are two independent biochemical reactions in the degradation stabilization process of MSW [25]. In some landfills of developing countries, volatile fatty acids (VFA, which is the hydrolysis product) may accumulate rapidly at the early stage of landfill stabilization, which results in the inhibition of the methanogenesis reaction [6]. It is necessary to investigate the generation of landfill gas during the stabilization process of landfills individually. Landfill gas generation potential is an important parameter for assessing the value of MSW resource recovery, which is defined as the cumulative volume of landfill gas produced by the complete degradation of a unit mass of MSW. The landfill gas generation potential (L/kg) is expressed by L in this paper.

The landfill gas stabilization index named Λ_2 is used to describe the release of landfill gas generation potential during the stabilization process:

$$\Lambda_2 = \frac{L_r}{L_0} = \frac{L_0 - L_t}{L_0} \quad (2)$$

where: L_r and L_0 are the residual value and the initial value of landfill gas generation potential, respectively, (L/kg); L_t is the cumulative production of landfill gas per unit mass of MSW at time t (L/kg).

2.1.3. Settlement Stabilization Index, Λ_3

MSW is a highly compressible material, and the vertical displacement of landfills resulting from MSW compression can be as large as 25–50% of the initial fill height [4].

The settlement stabilization process of post-closure landfills is significant for the integrity of landfill facilities (such as cover systems, leachate collection and drainage systems, and landfill gas collection systems). This vertical displacement if managed correctly can result in an advantageous increase in the storage capacity of landfills [26]. The settlement potential parameter, that is Λ_3 , is used to characterize the settlement stabilization process of landfills:

$$\Lambda_3 = \frac{S_\infty - S_t}{S_\infty} \quad (3)$$

where: S_t is the average settlement of landfills at time t (m); S_∞ is the ultimate settlement of landfills (m).

2.2. Evaluation Method of the Stabilization Process of MSW Landfills

2.2.1. Evaluation Method Combining Field Tests with Numerical Simulation

The degradation process of MSW is influenced by many factors, such as the substrate content of degradable components, the moisture content in landfills, and the pH of leachate [19]. The flow of leachate and the compression make the condition of degradation in landfills changing with fill height. The degradation degree of MSW with different filling age can be investigated by borehole specimens drilled from different depths in landfills. Based on the results of field tests, the stabilization process of MSW landfills can be predicted via numerical simulation by using a biochemical-consolidation-solute migration coupled model. The prediction results of the stabilization process of MSW landfills are significant to evaluate the state of landfill stabilization, guide landfill management, and provide the design basis for control measures in landfills. An evaluation method combining field tests with numerical simulation is proposed in this paper. The implementation process of this method is shown in Figure 1, and the specific implementation steps are described as follows:

1. MSW samples with different depths are drilled from the landfill. The C/L of borehole samples with different filling age are tested by the normal fiber washing method.
2. The composition of fresh MSW at a shallow layer of the landfill is analyzed to obtain the initial C/L of MSW, landfill gas generation potential, and the ultimate settlement of the landfill by laboratory tests.
3. The biochemical parameters of MSW are fitted according to the results of laboratory tests. The parameters of mechanical properties of MSW are estimated based on the component content of fresh MSW [21,22] or similar projects experience. If the conditions permit, the degradation-compression tests and the permeability test of leachate and landfill gas should be carried out by using borehole samples, which can obtain more reasonable mechanical parameters of MSW.
4. The variation of three evaluation indices with time is predicted via the coupled model. The stabilization state of the landfill is evaluated according to numerical simulation results. Suggestions on accelerating the stabilization process of the landfill and the management measures of the landfill can be addressed based on the trends of variation of the evaluation indices.

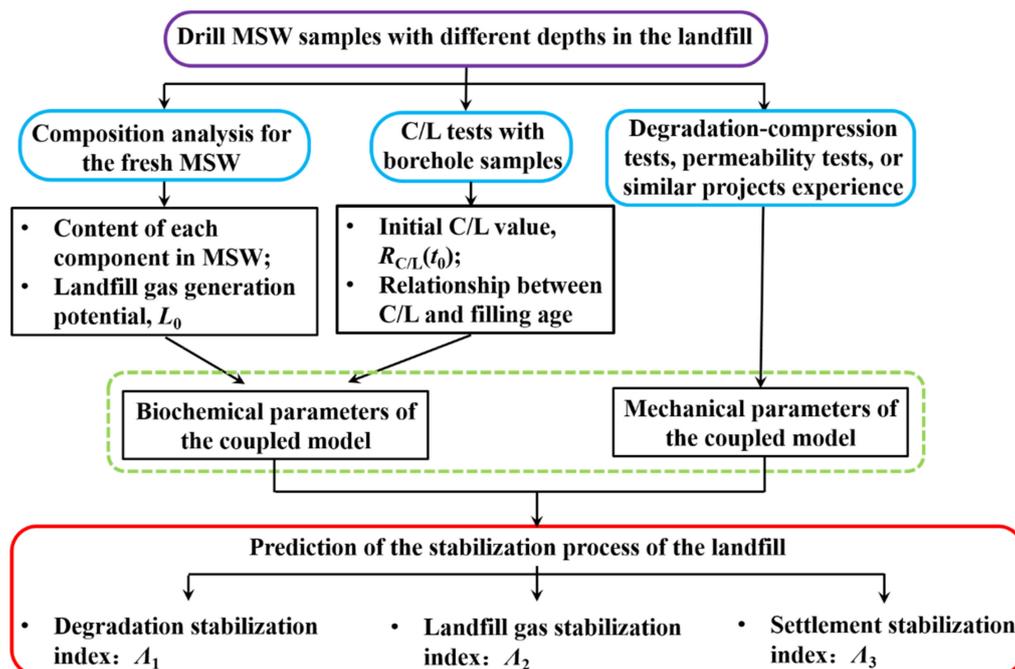


Figure 1. Implementation process of the evaluation method of landfill stabilization.

2.2.2. Biochemical-Consolidation-Solute Migration Coupled Model

The formulations of the biochemical-consolidation-solute migration coupled model include biochemical kinetics, skeleton deformation, the flow of leachate and landfill gas, solute migration with leachate flow. Biochemical kinetics provide the sink term of solid mass, and the source terms of leachate, solute, and landfill gas by considering the influence of substrate content, pH of leachate, and moisture content on hydrolysis and methanogenesis [19]. The sink and source terms of the coupled model are list as follow:

Solid mass loss of cellulose in MSW:

$$f_m = \frac{-\theta_E b}{162 + 18\lambda_{iw}} \left\{ 1 - \left[\frac{m_c(t_0) - m_c(t)}{m_c(t_0)} \right]^\alpha \right\} \exp(-k_h c_1) \quad (4)$$

Leachate generation during the hydrolysis period:

$$f_w = \frac{18\lambda_{iw}\theta_E b}{162 + 18\lambda_{iw}} \left\{ 1 - \left[\frac{m_c(t_0) - m_c(t)}{m_c(t_0)} \right]^\alpha \right\} \exp(-k_h c_1) \quad (5)$$

Landfill gas generation with methanogenesis:

$$f_g = \frac{3\theta_E k_{mmax} c_1 c_2}{Y(k_s + c_1)} \exp(-k_m c_1) \quad (6)$$

VFA accumulation in leachate:

$$f_c^1 = \theta_E b \left\{ 1 - \left[\frac{m_c(t_0) - m_c(t)}{m_c(t_0)} \right]^\alpha \right\} \exp(-k_h c_1) - \frac{\theta_E k_{mmax} c_1 c_2}{Y(k_s + c_1)} \exp(-k_m c_1) \quad (7)$$

Methanogen growth and decay in landfill:

$$f_c^2 = \theta_E c_2 \left[\frac{k_{mmax} c_1}{k_s + c_1} \exp(-k_m c_1) - k_d \right] \quad (8)$$

where: Λ_{iw} is the ratio of the weight of intra-particle water to the weight of cellulose (kg/kg), which can be estimated by kitchen waste composition and moisture content [6]; θ_E is the effective volumetric moisture content (%); b is the maximum hydrolysis rate of cellulose (g/(m³day)); $m_c(t_0)$ is the initial degradable component content (kg/m³); $m_c(t)$ is the degradable component content at time t (kg/m³); α is the inhibition constant of substrate content (/); c_1 is the VFA concentration in leachate (g/m³); k_h is the inhibition constant relates to VFA content (m³/g); k_{mmax} is the maximum growth rate constant of methanogen (day⁻¹); k_m is the inhibition constant relate to methanogen content (m³/g); k_s is the half-saturation constant of methanogen growth (day⁻¹); c_2 is the concentration of methanogen (g/m³); Y is the substrate yield coefficient, and k_d is the decay rate constant of methanogen (day⁻¹).

A one-dimensional compression model proposed by Chen et al. [27] is used to estimate the skeleton deformation of MSW in this manuscript. This compression model can consider the compressibility decrease due to decomposition. The settlement of the landfill body can be estimated based on the vertical volumetric strain of MSWs, which is described in the implemented model as:

$$\varepsilon_z(\sigma', t) = C'_C \log \frac{\sigma'}{\sigma'_0} + \left[\varepsilon_{dc}(\sigma'_0) + (C'_{C\infty} - C'_C) \log \frac{\sigma'}{\sigma'_0} \right] (1 - \exp(-c_s t)) \quad (9)$$

$$\sigma' = \sigma_T - [Su_w + (1 - S)u_g] \quad (10)$$

where: $\varepsilon_z(\sigma', t)$ is the vertical volumetric strain of MSWs having a filled age of t under the effective stress of σ' (%); C'_C and $C'_{C\infty}$ are compression ratios for placed fresh MSW and fully decomposed MSW, respectively (/); σ' is the effective stress (kPa), which can be calculated according to total stress σ_T (kPa) and pore water or gas pressure (kPa); σ_0 is pre-consolidation pressure (kPa), which is dependent on initial compaction pressure; $\varepsilon_{dc}(\sigma_0)$ is the sum of ultimate volumetric strains of decomposition compression and mechanical creep under pre-consolidation pressure σ_0 (%) and c_s is the secondary compression rate constant (day⁻¹).

The governing equations of liquid flow and landfill gas transportation in landfills are estimated according to the mass conservation of leachate and landfill gas.

$$\rho_w \frac{\partial}{\partial t} (nS) = \rho_w \nabla \cdot \left[\frac{\mathbf{k}_{iw} k_{rw}}{\mu_w} \nabla \cdot (u_w + \rho_w g z) \right] + f_w \quad (11)$$

$$\frac{\partial}{\partial t} [\rho_g n(1 - S)] = \nabla \cdot \left[\frac{\mathbf{k}_{ig} k_{rg}}{\mu_g} \nabla \cdot (\rho_g u_g) \right] + f_g \quad (12)$$

where: n is the porosity (/); S is the liquid saturation (%); ρ_w and ρ_g are the density of liquid and gas, respectively, (kg/m³); ∇ is the partial differential operator; \mathbf{k}_{iw} and \mathbf{k}_{ig} are the intrinsic permeability for liquid and gas, respectively, (m²); k_{rw} and k_{rg} are the relative permeability functions for liquid and gas, respectively, which can be estimated via the van-Geunckten model [28]; μ_w , μ_g are the dynamic viscosities of liquid and gas, respectively, kg/(ms); u_w is pore water pressure (kPa); u_g is pore gas pressure (kPa).

Liquid saturation of MSW can be expressed as a function of matrix suction under isothermal condition, the van-Geunckten model is used to describe the relationship between saturation and matrix suction in this manuscript. The mass conservation equation for liquid phase (Equation (11)) and gas phase (Equation (12)) can be further expressed as:

$$\begin{aligned} & -\rho_w n \frac{\partial S}{\partial s} \frac{\partial u_w}{\partial t} + \rho_w n \frac{\partial S}{\partial s} \frac{\partial u_g}{\partial t} + \rho_w S \frac{\partial n}{\partial t} \\ & = \rho_w \nabla \cdot \left[\frac{\mathbf{k}_{iw} k_{rw}}{\mu_w} \nabla \cdot (u_w + \rho_w g z) \right] + f_w \end{aligned} \quad (13)$$

$$\rho_g n \frac{\partial S}{\partial s} \frac{\partial u_w}{\partial t} + \left[\frac{n(1-S)M}{RT} - \rho_g n \frac{\partial S}{\partial s} \right] \frac{\partial u_g}{\partial t} + \rho_g (1-S) \frac{\partial n}{\partial t} \quad (14)$$

$$= \nabla \cdot \left[\frac{k_{ig} k_{rg}}{\mu_g} \nabla \cdot (\rho_g u_g) \right] + f_g$$

$$s = u_g - u_w \quad (15)$$

where: s is the suction (kPa); u is the vertical displacement of a landfill (m); M is the molecular weight of landfill gas (kg/mol); R and T are the ideal gas constant (J/(mol·K)) and temperature (K), respectively.

The content of VFA and methanogen have a significant influence on the reaction rate of hydrolysis and methanogenesis, respectively. It is necessary to investigate the accumulation and decay of VFA and methanogen during the stabilization process of landfill. The mass conservation equation for solute (VFA and methanogen) are established by neglecting the effects of adsorption/desorption. The governing equation of solute migration is expressed as follow:

$$nS \frac{\partial c_i}{\partial t} - nc_i \frac{\partial S}{\partial s} \frac{\partial u_w}{\partial t} + nc_i \frac{\partial S}{\partial s} \frac{\partial u_g}{\partial t} + c_i S \frac{\partial n}{\partial t} \quad (16)$$

$$= -\nabla \cdot (c_i \mathbf{v}_w) + \nabla \cdot (\mathbf{D}_i \nabla c_i) + f_c^i$$

where: \mathbf{v}_w is the fluid velocity of liquid (m/day); \mathbf{D}_i are diffusion coefficients of VFA ($i = 1$) and methanogen ($i = 2$), respectively.

The framework of the proposed coupled model is composed of Equations (4), (9), (13), (14), and (16). A numerical model of the landfill can be established according to the landfill site conditions, MSW composition in the landfill, operation conditions, and so on. The solid mass loss of cellulose in MSW, the pore gas pressure in the landfill, and the settlement can be estimated by simultaneously solving the Equations (4), (9), and (14).

The degradation stabilization index (Λ_1) is calculated via the solid mass loss of cellulose in MSW (Equation (4)). The landfill gas stabilization index (Λ_2) is obtained based on the variation of pore gas pressure in the landfill (Equation (14)) and boundary conditions. The settlement stabilization index (Λ_3) is estimated according to the vertical deformation of the landfill (Equation (9)).

2.3. Prediction of the Stabilization Process of the Jiangcungou Landfill, in Xi'an, China

The Jiangcungou landfill is the only sanitary landfill in Xi'an city, China. It is a valley type landfill with 70~80 m filling height, and the storage capacity of the landfill has reached $4.9 \times 10^7 \text{ m}^3$. According to the planning, this landfill is designed to be expanded vertically to a filling height of 120 m, which would be one of the highest landfill slopes in China. It is necessary to evaluate the stabilization state of landfilled waste. The prediction of the stabilization process of the landfill will guide the design and construction of the vertical expansion project. Borehole sampling tests were carried out in the landfill, the depth of boreholes ranges from 15 to 50 m. The MSW samples drilled from one of the boreholes was taken as an example to evaluate the stabilization state of the Jiangcungou landfill. The depth of the drill borehole is 40 m, and the borehole samples involve the secondary and third phases of the Jiangcungou landfill, which have a filling age of fewer than 3.5 years (phase II) and about 12.5 years (phase III), respectively (Figure 2). The average unit weight of borehole samples ranges from 11 to 13 kN/m³. The composition of the fresh MSW collected from a shallow layer of the Jiangcungou landfill were analyzed, including 56.5% of kitchen waste, 1.9% of vegetation, 8.9% of paper, 2.5% of fiber, 12.1% of plastic, and 18.1% of other inert substances. Kitchen waste comprises more than half of the MSW in the Jiangcungou landfill, which means it is a typical landfill with high kitchen waste content in China.



Figure 2. MSW drilled from the Jiangcungou landfill.

One fresh MSW sample and seven borehole samples with different filling ages were selected to test the C/L by using the normal form fiber washing method. The laboratory test results are list in Table 1, which shows that the C/L of MSW decreased with time. The C/L of MSW with a filling age of 1-year decreased significantly compared with the fresh MSW. However, the decay of the C/L became slower when the filling age of MSW increases further. The biochemical characteristic parameters of the proposed coupled model are calibrated according to the relationship between the C/L values and the filling ages of borehole samples, the parameters are shown in Table 2. The mechanical characteristic parameters of MSW are selected based on the recommended parameter value range of typical landfills with high kitchen waste content in China [29–31].

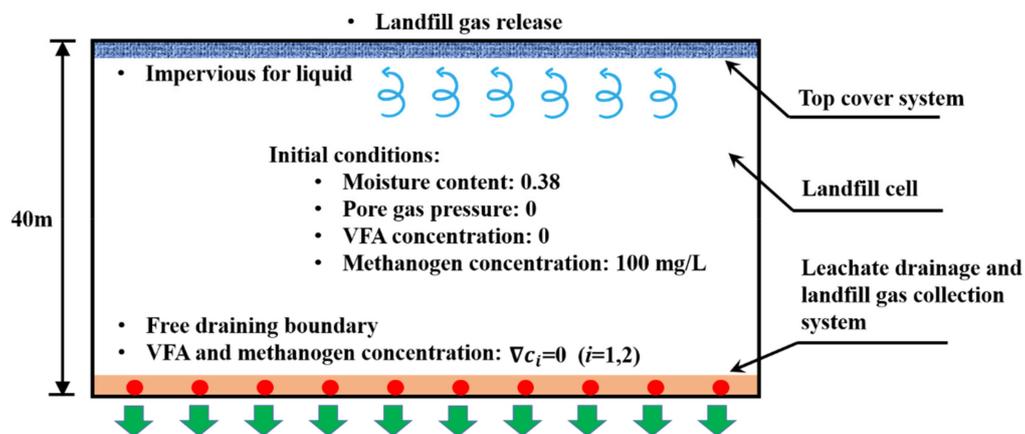
Table 1. The C/L of the fresh MSW and the borehole samples with different depths.

Depth (m)	Filling Age (Year)	$R_{CL}(t)$	Λ_1
shallow layer	0	2.8	1.00
3.8	1.0	1.21	0.43
6.8	1.0	1.16	0.41
16.8	2.5	0.85	0.30
19.8	2.5	0.82	0.29
25.8	3.5	0.71	0.25
28.8	3.5	0.68	0.24
39.8	12.5	0.41	0.15

A numerical model of landfill cell with a height of 40 m is established to predict the stabilization process of the Jiangcungou landfill. As shown in Figure 3, it is assumed that all MSWs in the landfill cell have the same age. The bottom boundary is a free draining boundary for both leachate and landfill gas to simulate the leachate drainage system working well. The concentration gradients of VFA and methanogen are set to 0. The top boundary is impervious for liquid. The C/L of MSW, VFA and methanogen concentration, landfill gas generation, degradation compression of the landfill are evaluated by using the PDE (Partial Differential Equation) module of COMSOL Multiphysics 5.3 to solve the coupled model, and the long-term landfill stabilization process for 40 years is predicted. The change processes of three evaluation indices are calculated according to the solving results of the coupled model, which are discussed and analyzed comprehensively in the next section.

Table 2. Biochemical characteristic parameters for borehole samples.

Parameter	Unit	Value
Cellulose content in fresh MSW, m_c (wet basis, wt/wt)	%	59.9
Lignin content in fresh MSW, m_l (wet basis, wt/wt)	%	21.4
Maximum hydrolysis rate of cellulose, b	$\text{g}/\text{m}^3/\text{day}$	500 (kitchen waste) 100 (other)
Inhibition constant of VFA, k_h	m^3/g	0.1
Inhibition constant of substrate content, n	/	2.8
Maximum growth rate constant of methanogen, $k_{m\max}$	day^{-1}	0.045
Inhibition constant of methanogen, k_m	m^3/g	0.06
Decay rate constant of methanogen, k_d	day^{-1}	0.01
Half-saturation constant of methanogen, k_s	g/m^3	4
Substrate yield coefficient, Y	/	0.08

**Figure 3.** Numerical landfill case for the stabilization process prediction.

3. Results and Discussion

3.1. Change Processes of the Evaluation Indices of the Jiangcungou Landfill

3.1.1. Degradation Stabilization Process of the Jiangcungou Landfill

The variation of the degradation stabilization index, Λ_1 , is shown in Figure 4. The prediction of C/L corresponds with the laboratory test results for borehole samples. According to the attenuation characteristic of Λ_1 , the degradation stabilization process of the Jiangcungou landfill can be divided into three stages. The first year is the fast degradation stage: the Λ_1 value decreases to 0.42 rapidly after 1 year since MSW was placed in the landfill, most of the kitchen waste is consumed during this period. After that, the reaction rate of hydrolysis slows down significantly, and other degradable components in MSW, such as paper, become to be the main substrate of hydrolysis. The slow degradation stage lasts from 2-year to 15-year. The value of Λ_1 decreases to 0.16 after 15 years, and then the degradation of MSW tends to be complete. The average decay rate of Λ_1 is lower than 0.01/year, which means almost all of the degradable components in MSW are hydrolyzed. Therefore, it can be considered that the degradation stabilization of the Jiangcungou landfill is achieved after 15 years.

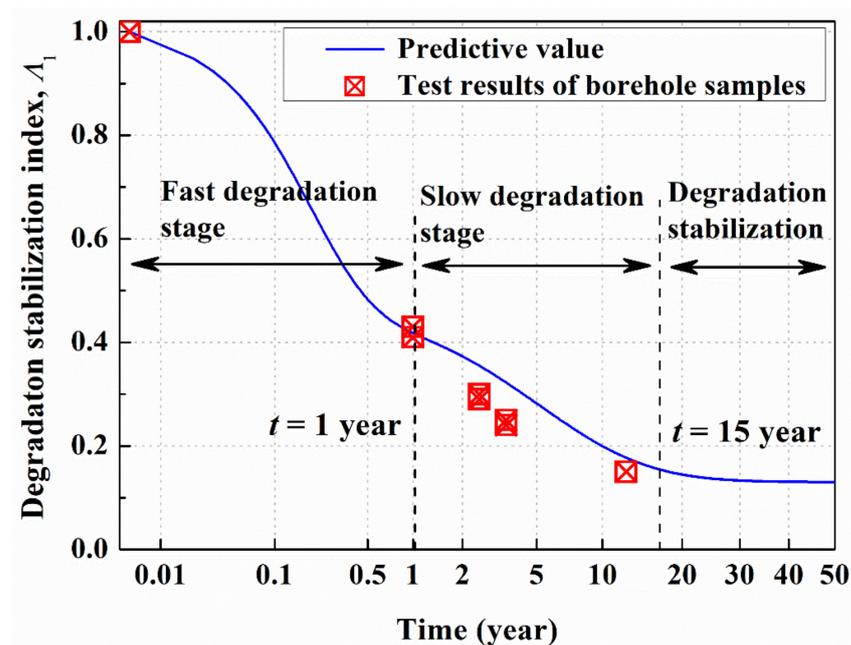


Figure 4. Change of the degradation stabilization index with time.

3.1.2. Landfill Gas Generation Process of the Jiangcungou Landfill

The prediction of the landfill gas stabilization index, Λ_2 , is shown in Figure 5. The variation of Λ_2 value has a similar feature with the decay of Λ_1 due to the interaction between hydrolysis and methanogenesis in the landfill. Hydrolysis is the dominant reaction at the fast degradation stage, and the VFA concentration in leachate increases significantly with the hydrolysis of kitchen waste components, as shown in Figure 6. The VFA concentration reaches a peak value of 25 g/L after the first 93 days. The rapid accumulation of VFA leads to acidification, which will inhibit the methanogenesis reaction [32]. Therefore, the landfill gas generation rate is lower than the hydrolysis rate, and the decay of Λ_2 value lags behind the Λ_1 . The VFA in leachate is the main substrate of the methanogenesis, the VFA consumption rate increases with methanogen growth. The VFA concentration in leachate decreases to lower than 4 g/L after 380 days. The research results by Shao et al. [33] indicated that the VFA concentration should be lower than 4 g/L to relieve the acidification and make the landfill reaching a stable methane generation state. It can be considered that the Jiangcungou landfill reaches a stable methane generation state after the first year.

The generation rate of landfill gas decreases gradually due to the low substrate (VFA) content during the slow degradation stage. The Λ_2 value is 0.38 after 2 years, and the decay rate of Λ_2 becomes slow obviously since then. It is indicated that the first 2 years are the most important period for landfill gas collection. Temporary cover and horizontal drainage ditches are recommended to improve landfill gas collection efficiency during this period. The landfill gas generation potential of the Jiangcungou landfill is evaluated based on the composition of fresh MSW by using the IPCC (Intergovernmental Panel on Climate Change) model [34]. The total landfill gas generation potential for fresh MSW is 144 L/kg, and the residual landfill gas generation potential is only 54.72 L/kg after 2 years. After 15 years, the accumulation of landfill gas generation per unit mass of MSW comes to 102.24 L/kg, which is 70% of the total landfill gas generation potential. The rate of landfill gas potential release keeps a very low level after 15 years, and the accumulation of landfill gas generation only increases by 8.64 L/kg from 15-year to 30-year. Therefore, it can be considered that the release of landfill gas generation potential and the degradation get stabilization state at the same time.

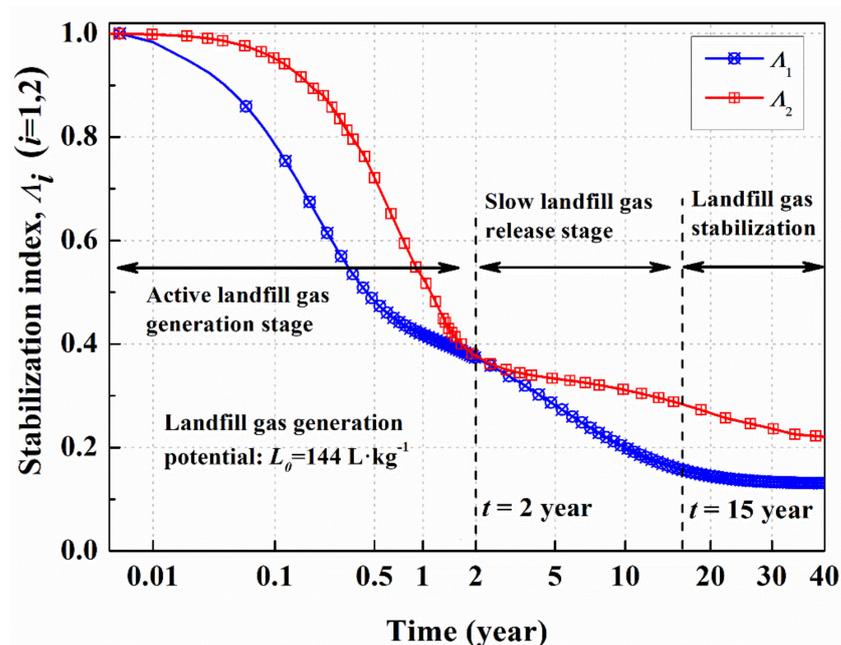


Figure 5. Change of landfill gas stabilization index with time.

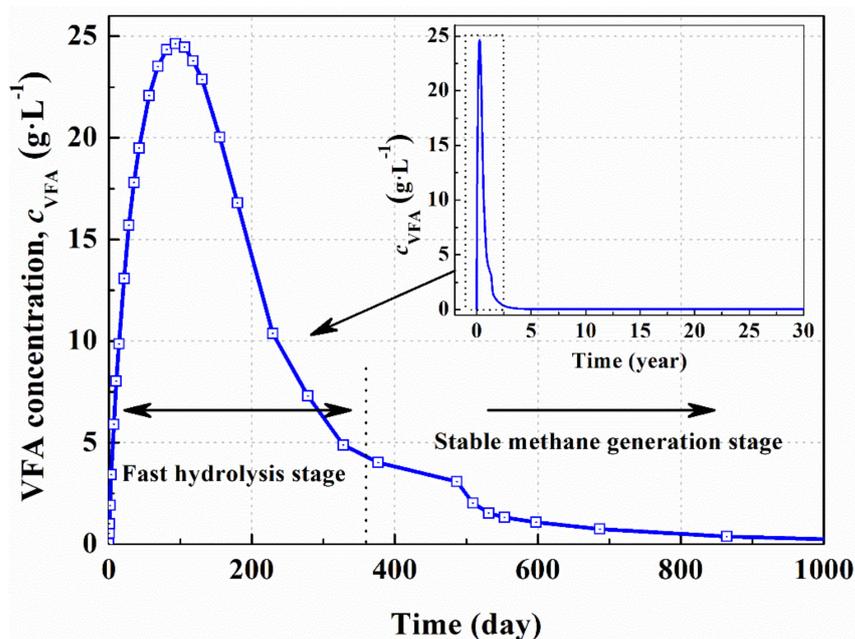


Figure 6. VFA concentration in leachate collected at bottom of the landfill.

It should be noticed a part of the landfill gas generation potential would lose with leachate collected from the drainage system at the bottom of the landfill, which will result that the Λ_2 value calculated based on the landfill gas collection at the top of the landfill is higher than the Λ_1 value at later period of stabilization. Leachate recirculation is recommended to adjust the degradation environment in the landfill, which is not only can be helpful to avoid potential acidification at the fast degradation stage but also can replenish the substrate of methanogenesis.

3.1.3. Settlement Process of the Jiangcungou Landfill

The fast hydrolysis of degradable components leads to a mass loss of MSW solid skeleton, which changes the mechanical properties of MSW significantly. An obvious

degradation settlement occurs in the landfill due to the change of MSW compressibility. As shown in Figure 7, the settlement stabilization index, Λ_3 , reduces to 0.65 within 1 year, which means 35% of the ultimate settlement is completed. However, significant settlement and obvious differential settlement in short term may affect the integrity of landfill infrastructures, such as leachate collection and drainage systems, landfill gas collection systems, and monitoring equipment. Reinforcement measures are recommended to avoid the failure of landfill infrastructures from a potential degradation settlement. The Λ_3 value reduces to 0.07 after 15 years, and the average rate of landfill settlement is about 3.5 cm per year after then, which can be considered as the settlement stabilization state. The landfill site closure should be carried out only when the settlement rate is low at the late stage of slow degradation to limit the adverse effects of differential settlement on the cover system.

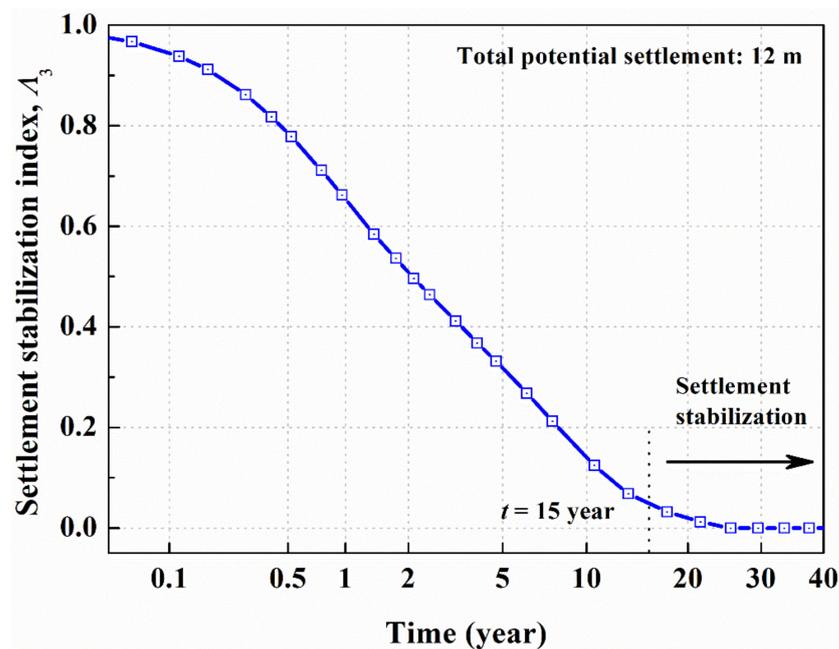


Figure 7. Change of settlement stabilization index with time.

3.2. Comparison of Stabilization Process of Landfills with Different Kitchen Waste Content

Because of the influence of socioeconomic status on living habits, MSW in developing countries has a high kitchen waste content. Kitchen waste comprises 40–85% of the MSW in developing countries. Nevertheless, for MSW with a low kitchen waste content, as is common in developed countries, the paper is responsible for the highest concentration of waste and comprises 25–66% of the MSW [35]. Because kitchen waste contains a large amount of water, the water content of MSW in developing countries is considerably higher than that in developed countries [36]. The differences in composition and initial moisture content of MSW lead to different stabilization features of landfills with different kitchen waste contents. The present numerical model is applied to analyze the stabilization process of a typical landfill with low kitchen waste content, which is compared with the stabilization process of the Jiangcungou landfill. The C/L results of the MSW samples with low kitchen waste content [37–42] are plotted against their filling ages in Figure 8, and a fitting curve is created to represent the variation of the C/L of MSW with low kitchen waste content. The biochemical parameters of the proposed coupled model are calibrated according to the fitting curve. The analysis results of three stabilization indices of the hypothetical landfill are compared with that of the Jiangcungou landfill.

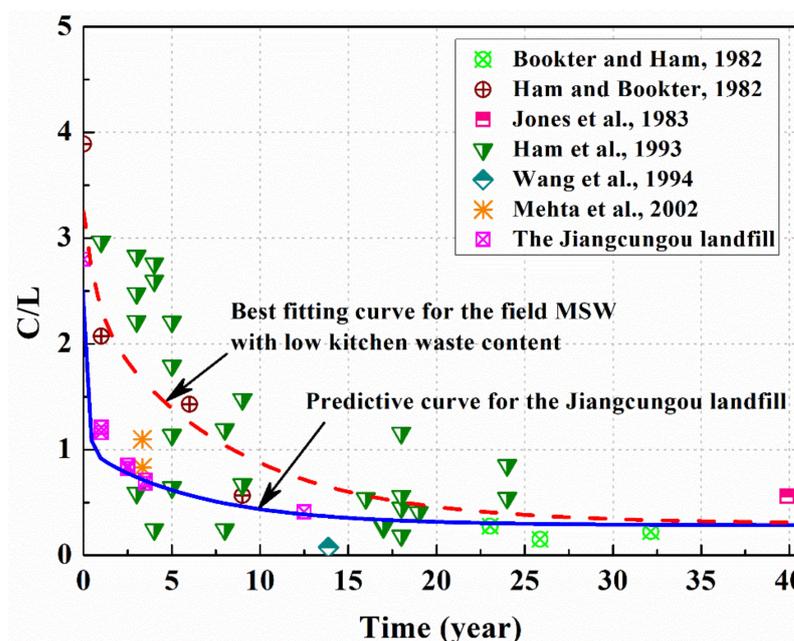


Figure 8. C/L results of MSW with different kitchen waste contents.

It can be observed in Figure 9 that MSW with low kitchen waste content has a slower degradation rate during the early period because there are fewer fast hydrolysis components in the MSW. There is no obvious turning point of Λ_1 value in the stabilization process of landfills with low kitchen waste content. It takes 18 years for the C/L value to decrease to 0.5 for the hypothetical landfill with low kitchen waste content, which is only 7.6 years for the Jiangucngou landfill. The rapid hydrolysis of a large amount of kitchen waste components is the main reason for the significant reduction in Λ_1 value of the Jiangucngou landfill at the early stage.

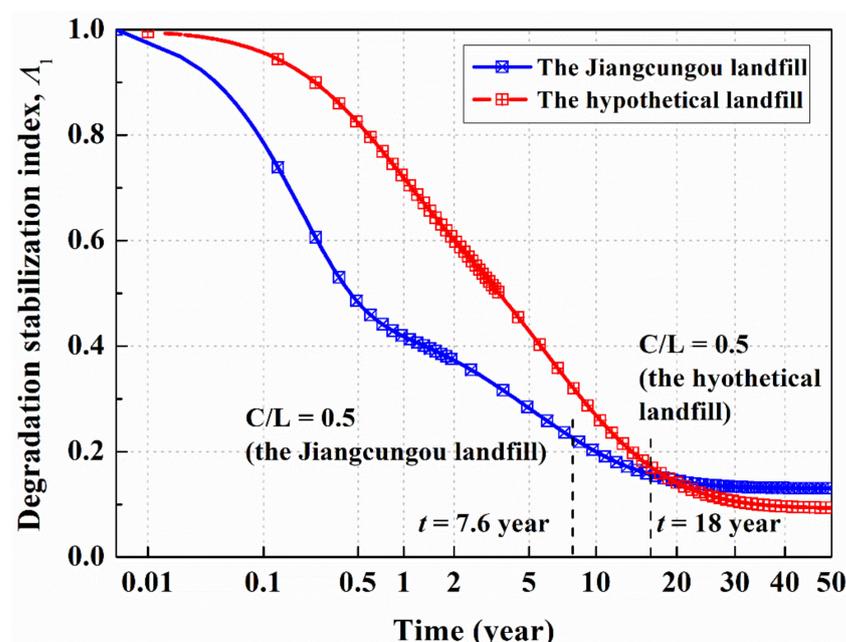


Figure 9. Degradation stabilization index of landfills with different kitchen waste contents.

As shown in Figure 10, there is no remarkable acidification inhibition for the landfill with low kitchen waste content, and the peak of the VFA concentration in leachate is

9.6 g/L. For the landfill with low kitchen waste content, the landfill gas is continuously generated with a larger gas generation potential. 36% of the landfill gas generation potential is released in the landfill with low kitchen waste content within 2 years. However, for the Jiangcungou landfill, the landfill gas generation ratio reaches 64% with the same filling age (see in Figure 11). Most of the gas generation potential in landfills with low kitchen waste content is provided by degradable components with a slow hydrolysis rate, such as paper. The difference in degradable components results in different landfill gas stabilization process of landfills with different kitchen waste contents.

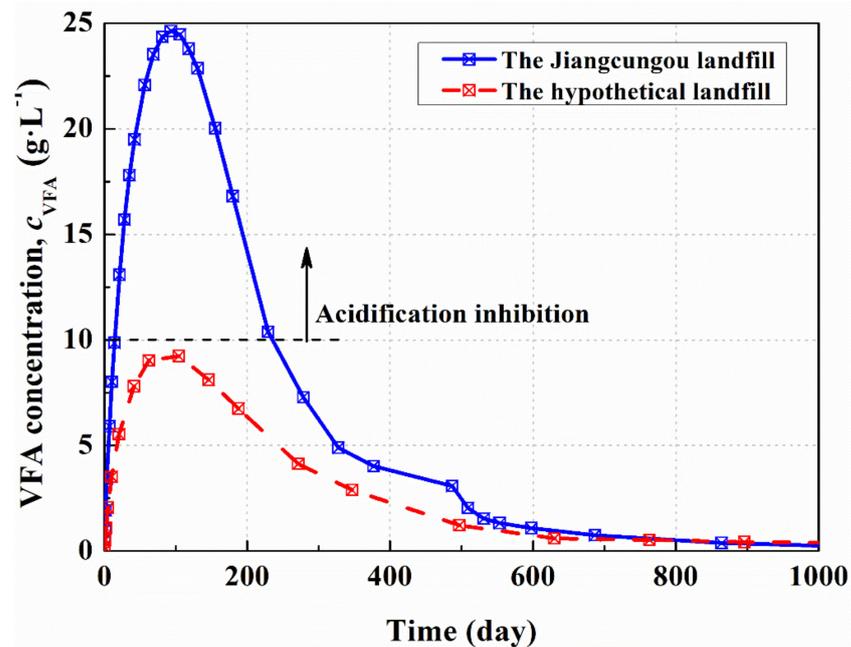


Figure 10. VFA concentration of landfills with different kitchen waste contents.

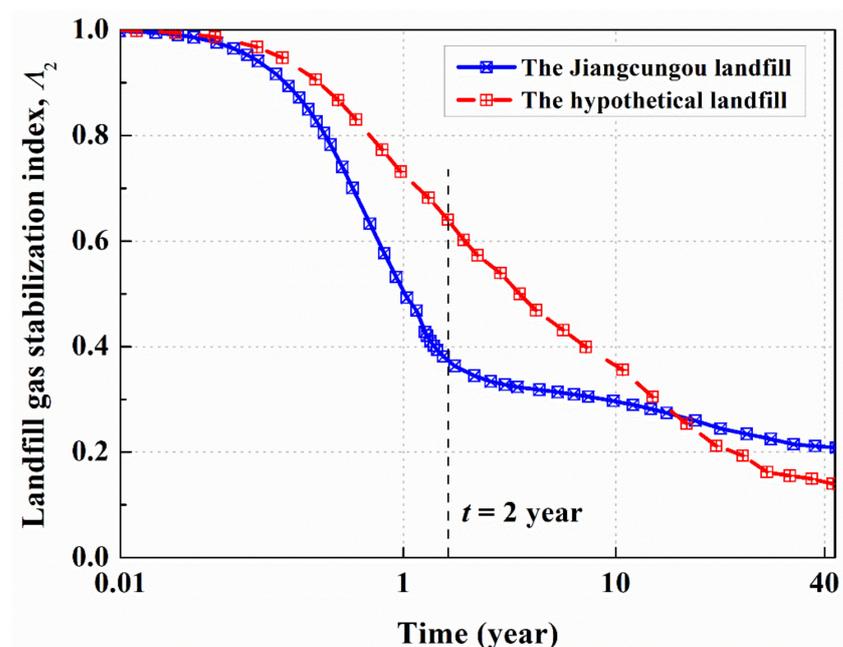


Figure 11. Landfill gas stabilization index of landfills with different kitchen waste contents.

The Jiangcungou landfill has a faster degradation compression rate during the early period. However, the long-term degradation compression strain of the landfill with low

kitchen waste content is smaller than the Jiangcungou landfill, which results that the settlement stabilization arrives earlier. It takes 15 years to reach settlement stabilization for the Jiangcungou landfill in Figure 12, being 3.9 years more than the time required by the landfill with low kitchen waste content.

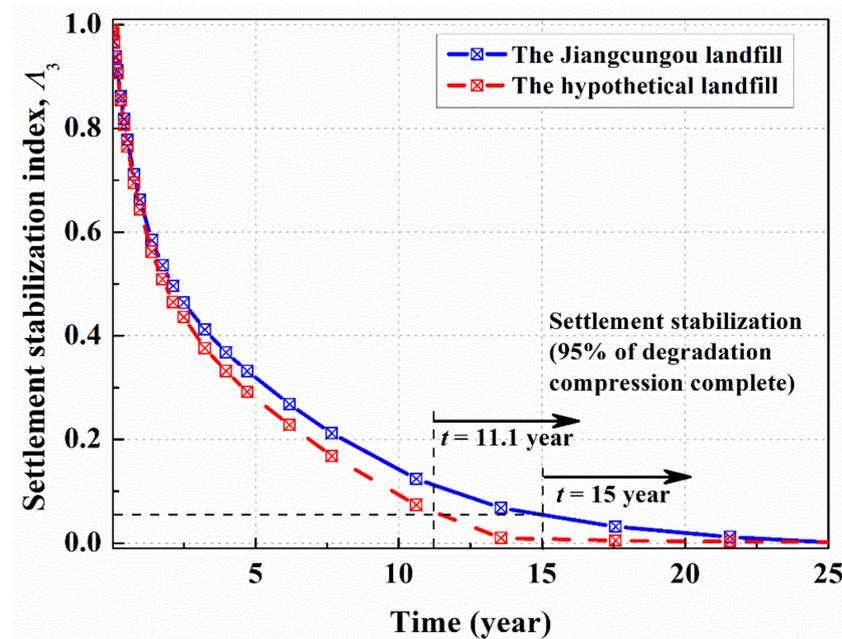


Figure 12. Settlement stabilization index of landfills with different kitchen waste contents.

4. Conclusions

The landfill stabilization process has been quantitatively predicted from three aspects (degradation degree, landfill gas generation potential release, and deformation of the landfill) in this article via the proposed evaluation system. A biochemical-consolidation-solute migration coupled model is established to analyze the landfill stabilization process.

The stabilization process of the Jiangcungou landfill is predicted by combining field tests with numerical simulation. According to the investigation results, the stabilization process of typical landfills with high kitchen waste content can be divided into three stages. For the fast degradation stage, the C/L decreases rapidly, and VFA concentration in leachate increased significantly, a large amount of degradation compression occurs in the landfill. When the slow degradation stage starts, the decay rate of C/L, the release rate of landfill gas generation potential, and the deformation rate of the landfill decrease obviously, the VFA concentration keeps at a low level. It takes about 15 years to reach a stabilization state for the Jiangcungou landfill, which means most of the degradable components are consumed, the settlement and the release of landfill gas generation potential are completed.

The stabilization processes of landfills with different kitchen waste content are compared by using the proposed evaluation method. It has been demonstrated that different composition and initial moisture content of MSW can lead to a significant difference in the stabilization processes. The degradation process of MSW is continuously developed with no significant turning point in the C/L reduction. The dominant degradation component of MSW has a slow hydrolysis rate, which results in a longer time to reach stabilization for the landfills in developed countries.

Some management suggestions can be provided according to the prediction results of the stabilization process of the Jiangcungou landfill: reinforcement measures are recommended to avoid the failure of landfill infrastructures from a large potential differential settlement. Leachate recirculation is recommended to optimize the degradation environment in the landfill, which is can relieve the potential acidification and replenish the substrate to increase the generation of landfill gas at the fast degradation stage.

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