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Research Article

Evaluation of Leachate Recirculation Effect on the Acceleration of Waste Mineralization Process by Using a Coupled Numerical Model

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Accelerating the waste mineralization is of great significance to control the settlement of transportation facilities nearby landfills. Mineralized waste can also be used as road construction materials to recycle waste resources and reduce the construction cost of transportation facilities. A biochem-hydro-mechanical-solute migration-coupled model for describing complex interactions in landfills with high kitchen waste content has been developed. The proposed model can consider large leachate production and landfill gas entrapment due to the fast degradation of kitchen waste. The quantitative effects of three leachate recirculation conditions are investigated in this article via a typical landfill cell. According to the simulation results, introducing methanogen into landfills with leachate recirculation can relieve acidification caused by fast hydrolysis of kitchen waste and speed up the mineralization process of landfills with high kitchen waste content significantly. Furthermore, landfill gas generation potential loss and fast degradation compression should be considered in the implementation of leachate recirculation in landfills with high kitchen waste content, which helps to maintain the operation of transportation facilities nearby landfills and improve the economic and environmental benefits of leachate treatment.

1. Introduction

A large amount of municipal solid waste (MSW) is generated every year, which results in a global issue. The sanitary landfill technique has been widely used to dispose MSW in many countries [1–3]. Landfills occupy a lot of land resources. The site selection of landfills has an important impact on the planning, construction, and maintenance of nearby transportation facilities [4]. Municipal solid waste (MSW) is a highly compressible material, and the vertical deformation of landfills resulting from MSW compression can be as large as 25–50% of initial fill height [5]. The settlement stabilization process of postclosure landfills is significant for the effective operation of transportation facilities (such as road and bridge), which were built above these landfills. Acceleration of the waste mineralization process can effectively reduce post-settlement and differential settlement of landfills, which would avoid the failure of the above transportation facilities [6–9]. On the contrary, it is an important application of waste recycle to use mineralized waste as a material in road construction [10]. However, the content of residual degradable components in MSW has a significant impact on the strength of the road construction material, and it is necessary to accelerate the waste mineralization process to reduce the content of degradable components, which can improve the mechanical properties of mineralized waste [11].

MSW contains degradable components. Complex physical, chemical, and biological processes occur within landfills. Leachate with a substantial amount of pollutants and landfill gas are continually generated in landfills for a very long time [12, 13]. The treatment of leachate remains an important environmental issue. One of the most common and acclaimed methods of leachate treatment is the circulation of leachate back to the landfill [14–19]. For the landfills in developed countries, many field and laboratory tests have indicated that leachate recirculation offers a series of environmental benefits, which include improving the leachate quality, increasing the moisture content of the landfill body, accelerating the generation of landfill gas, and shortening the stabilization process of landfills [20–26].

All these above studies are very valuable; however, they still present challenges to implement leachate recirculation in landfills in developing countries. Because of the influence of the socioeconomic status on living habits, MSWs in developing countries represented by China have much higher kitchen waste content and initial moisture content than that in developed countries [27]. Kitchen waste is composed of a large amount of intraparticle water and easily hydrolysable components [12]. Decomposition of landfilled kitchen waste presents a large leachate production rate, and a high leachate level was often observed at landfills with high kitchen waste content [28, 29]. Influences of large leachate production should be paid attention to design and implement leachate recirculation in landfills with high kitchen waste content.

MSW landfills have long and complex stabilization processes. Theoretical analysis via the establishment of the numerical model is a common approach to investigate the biodegradation-mechanical interactions in landfills. Leachate and landfill gas transportation in landfills is an important problem for studies of leachate recirculation in landfills. Some research studies on modeling leachate recirculation have been carried out [30–32]. The leachate level generally remains quite low for the "dry tomb" landfills in developed countries. On this account, it is common that the migration of landfill gas during the leachate recirculation is rapid for the landfills with low kitchen waste content, and the gas pressure in a landfill body is assumed to be fixed to atmospheric pressure [33]. However, the leachate level for the landfills with high kitchen waste content is higher, and the generated landfill gas tends to accumulate within the saturated zones. The entrapped landfill gas could have a significant impact on the hydrological properties of MSW [34], and the gas pressure changes with leachate mound and recirculation. The landfill gas accumulation due to the leachate mound needs to be considered in the modeling of leachate recirculation in landfills with high kitchen waste content.

To improve the understanding of the effects of leachate recirculation on the landfill stabilization process, a biochem-hydro-mechanical-solute migration-coupled model is established to investigate the influences of leachate recirculation in the landfill with high kitchen waste content. The effects of three leachate recirculation conditions on the stabilization process of a high kitchen waste-content landfill are evaluated by the proposed model. Finally, suggestions on implementing leachate recirculation in landfills with high kitchen waste content are addressed based on the results of the investigations.

2. Biochem-Hydro-Mechanical-Solute Migration-Coupled Model of MSW with High Kitchen Waste Content

2.1. Framework of the Coupled Model. A framework for integrated analysis of the liquid/gas flow, solute migration, and mechanical behaviors of high kitchen waste-content landfills, referred to as the biochem-hydro-mechanical-solute migration-coupled model, is presented here. These coupled processes in landfills are highly dependent on the biodegradation of MSW (see Figure 1).

During the decomposition process, biodegradable components of MSW transform from the solid phase into the gas and liquid phase, which increases pore volume and weakens skeleton strength. The weakened solid skeleton is compressed by a self-weight load, and at the same time, the change of pore volume affects the liquid and gas permeability of MSW. Leachate flow and gas transportation in landfills also have influences on the distribution of pore water pressure and pore gas pressure, which change the effective stress of the MSW solid skeleton and make further compression. The complicated biodegradation processes in landfills make the engineering properties of MSWs changing with time, which are different from the traditional hydro-mechanical coupled behaviors in soil (i.e., consolidation for unsaturated soil). However, the biodegradation process in landfills is related to moisture content, substrate, and solute concentration, and mechanical behaviors have influences on the biodegradation process by changing moisture content and solute concentration in landfilled wastes [35, 36].

2.2. Biodegradation Model. MSWs have been placed 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 divided into four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [37]. Considering that acidogenesis and acetogenesis are rapid, the anaerobic decomposition process of MSWs can be simplified into two stages, i.e., hydrolysis and methanogenesis [38]. This process can be idealized as equations (1) and (2). Because the cellulolytic matter in degradable components accounts for more than 90% of the methane potential of MSWs, the substrate is expressed as cellulose in equation (1), and decomposable components in kitchen waste are simplified as the fast degradation cellulose. In the hydrolysis stage, organic substances are converted into volatile fatty acids (VFA), H_2, and CO_2. There is a substantial amount of intraparticle water in kitchen waste, which is the primary source of leachate in landfills with high kitchen waste content. The hydrolysis of cellulose causes the breakdown of cell walls and releases intraparticle water. It is assumed that the intraparticle water will be instantaneously released with the cellulose hydrolysis in this manuscript. In the methanogenesis stage, the hydrolysis product (that is, VFA) is consumed by methanogen and transformed into CH_4 and CO_2. In equation (1), λ_{iw} is the ratio of the weight of intraparticle water to the weight of cellulose, which can be estimated by kitchen waste composition and moisture content [39].

Hydrolysis of cellulose with intraparticle water is given as follows:

$$C_6H_{10}O_5\left(\lambda_{iw}H_2O\right)+5H_2O \longrightarrow CH_3COOH + 8H_2 + 4CO_2 + \alpha H_2O \tag{1}$$

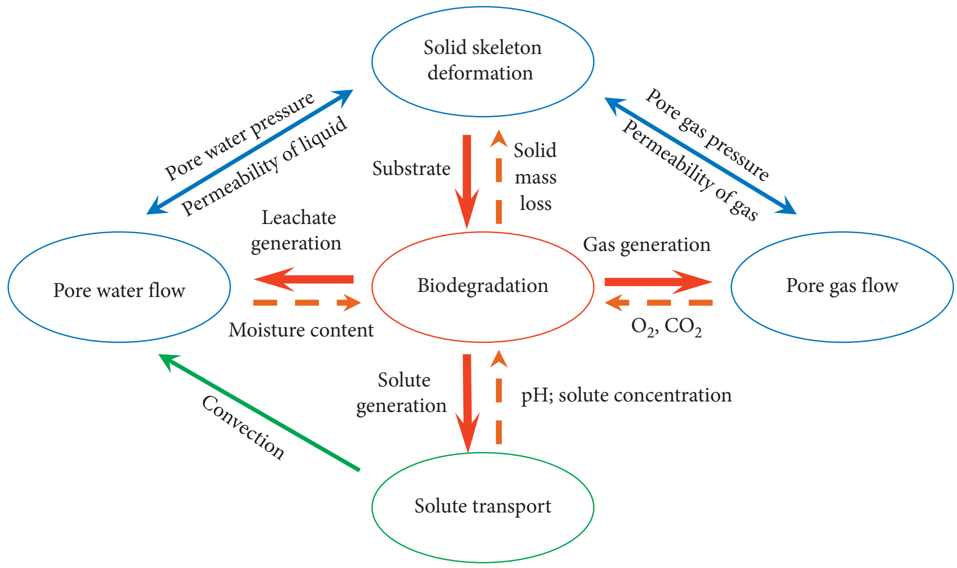

Figure 1: Biodegradation-hydraulic-mechanical coupled behaviors in landfilled MSW.

Methanogenesis of VFA is given as follows:

$$CH_3COOH + 7.43H_2 + 0.93CO_2 + 0.029NH_3 \longrightarrow 2.79CH_4 + 3.8H_2O + 0.029C_5H_7NO_2 \quad (2)$$

The generation rate of VFA can be described as equation (3), which considers the effects of moisture content, product inhibition, and substrate (that is, cellulose) content:

$$R_g = \theta_E f_{ih}(m_c) f_{ih}(c_1) b, \quad (3)$$

$$\theta_E = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad (4)$$

$$f_{ih}(m_c) = 1 - \left[\frac{m_c(t_0) - m_c(t)}{m_c(t_0)}\right]^{\alpha}, \quad (5)$$

$$f_{ih}(c_1) = \exp(-k_h c_1), \quad (6)$$

where R_g is the generation rate of VFA (g/(m^3/day)), θ_E is the effective volumetric moisture content, θ_s and θ_r are saturated volumetric moisture content and residual volumetric moisture content, respectively, which can be determined by a soil-water characteristic curve, $f_{ih}(m_c)$ is the substrate content inhibition function, $m_c(t_0)$ is the initial degradable component content (kg/m^3), $m_c(t)$ is the degradable component content (kg/m^3) at time t, α is the inhibition constant of substrate content, $f_{ih}(c_1)$ is the product inhibition function of VFA, c_1 is the VFA concentration (g/m^3), k_h is the inhibition constant related to VFA content (m^3/g), and b is the maximum hydrolysis rate of cellulose (g/(m^3 day)).

During the methanogenesis stage, VFA is consumed by methanogen, and the accumulation rate of methanogen can be described by the Monod equation [40], which also needs to consider the influences of moisture content and product inhibition (see equation (7)):

$$R_j = \theta_E f_{im}(c_1) \frac{k_{m\max} c_1}{k_s + c_1} c_2, \quad (7)$$

$$f_{im}(c_1) = \exp(-k_m c_1), \quad (8)$$

where R_j is the accumulation rate of methanogen (g/(m^3/day)), $f_{im}(c_1)$ is the production inhibition function of methanogen, k_m is the inhibition constant related to methanogen content (m^3/g), $k_{m\max}$ is the maximum growth rate constant of methanogen (day^{-1}), k_s is the half-saturation constant of methanogen growth (g/m^3), and c_2 is the concentration of methanogen (g/m^3).

The methanogen accumulates with the consumption of VFA, and the decay of VFA is related to the concentration of methanogen [38]. The consumption rate of VFA and the decay rate of methanogen can be expressed as the following equations:

$$R_h = \frac{R_j}{Y} = \theta_E f_{im}(c_1) \frac{k_{m\max} c_1}{Y(k_s + c_1)} c_2, \quad (9)$$

$$R_k = \theta_E k_d c_2, \quad (10)$$

where R_h and R_k are the consumption rate of VFA and the decay rate of methanogen, respectively (g/(m^3 day)), Y is the substrate yield coefficient, and k_d is the decay rate constant of methanogen (day^{-1}).

The consumption rate of substrate, the release rate of intraparticle water in kitchen waste, and the generation rate of landfill gas can be calculated according to the chemical reaction equations above and equations (3)~(10).

2.3. Hydraulic Model. The liquid flow and landfill gas transportation in MSWs are similar to fluid behaviors in the unsaturated porous medium. In addition to the basic assumptions for continuous porous media, a few assumptions are applied to derive the governing equations of the hydraulic model. The liquid is assumed to be incompressible; however, landfill gas is compressible, and the ideal gas law is satisfied (landfill gas is considered as the mixed gas of CO_2 and CH_4 in this paper). The mass conservation equations for both liquid phase and gas phase in MSWs are built as follows:

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

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

where n is the porosity, S is the liquid saturation, ρ_w and ρ_g are the density of liquid and gas, respectively (kg/m^3), $\nabla.$ is the partial differential operator, $\mathbf{k_{iw}}$ and $\mathbf{k_{ig}}$ are the intrinsic permeabilities for liquid and gas, respectively (m^2), k_{rw} and k_{rg} are the relative permeability functions for liquid and gas, respectively, which can be estimated via the van Genuchten model [41], μ_w and 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), f_w is the source term of leachate generation (kg/(m^{3}s)), and f_g is the source term of landfill gas generation (kg/(m^{3}s)).

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

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

$$\rho_g n \frac{\partial S}{\partial s}\frac{\partial u_w}{\partial t} + \left[\frac{n(1-S)M}{RT} - \rho_g n \frac{\partial S}{\partial s} \right] \frac{\partial u_g}{\partial t} + \rho_g (1 - S) \frac{\partial n}{\partial t} = \nabla \cdot \left[\frac{\mathbf{k_{ig}} k_{rg}}{\mu_g} \nabla . \left(\rho_g u_g \right) \right] + f_g, \quad (14)$$

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

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), and R and T are the ideal gas constant and temperature (K), respectively.

2.4. Mechanical Model. The compression characteristics of MSW are of greater complexity than soil, whose solid skeleton can be normally regarded as inert materials. The solid mass loss of MSWs occurs during the biodegradation process, which results from that skeleton compressibility change and further deformation of the landfill body. For these transportation facilities built above postclosure landfills, it is necessary to control the postclosure settlement of landfills to reduce the differential deformation of the facilities. The vertical settlement during the mineralization process of landfills should be paid more concern for estimating the effectiveness of transportation facilities above landfills. A one-dimensional compression model proposed by Chen et al. [42] is used to estimate landfill compression displacements in this paper. This model is based on a series of compression tests on borehole samples and artificial wastes, which can consider the decrease in compressibility of MSWs due to decomposition. The porosity change of the landfill body can be estimated based on the vertical volumetric strain of MSWs, which is described in the implemented model as follows:

$$\varepsilon_z(\sigma', t) = C_C' \log \frac{\sigma'}{\sigma_0'} + \left[\varepsilon_{dc}(\sigma_0') + (C_{C\infty}' - C_C') \log \frac{\sigma'}{\sigma_0'} \right] \cdot \left(1 - \exp(-c_s t) \right), \quad (16)$$

$$\sigma' = \sigma_T - \left[S u_w + (1 - S) u_g \right], \quad (17)$$

where $\varepsilon_z(\sigma', t)$ is the vertical volumetric strain of MSWs having a filled age of t under the effective stress of σ' (kPa), C_C' and $C_{C\infty}'$ are compression ratios for freshly placed 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/gas pressure, σ_0 is preconsolidation 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 preconsolidation pressure σ_0 (kPa), and c_s is the secondary compression rate constant (day^{-1}).

2.5. Solute Migration Model. Because of the dominance of growth and decay of the solute, diffusion and dispersion of the solute can be combined, and the effects of adsorption/

desorption can be neglected [38]. The mass conservation equation for the solute (VFA and methanogen) is expressed as follows, respectively:

$$\frac{\partial}{\partial t}\left(c_i nS\right) = -\nabla\cdot\left(c_i\mathbf{v}_w\right) + \nabla\cdot\left(\mathbf{D}_i\nabla c_i\right) + f_c^i, \quad (i = 1, 2), \tag{18}$$

where $\mathbf{v}_w$ is the fluid velocity of the liquid (m/day), $\boldsymbol{D}_i$ are diffusion coefficients of VFA ($i = 1$) and methanogen ($i = 2$), respectively (m^2/day), and f_c^i are source terms which combined growth and decay of VFA and methanogen, respectively (g/(m^3 day)).

Similar to the hydraulic model, equation (18) can be further expressed as follows:

$$nS\frac{\partial c_i}{\partial t} - nc_i\frac{\partial S}{\partial s}\frac{\partial u_w}{\partial t} + nc_i\frac{\partial S}{\partial s}\frac{\partial u_g}{\partial t} + c_iS\frac{\partial n}{\partial t} = -\nabla\cdot\left(c_i\mathbf{v}_w\right) + \nabla\cdot\left(\mathbf{D}_i\nabla c_i\right) + f_c^i. \tag{19}$$

2.6. Biochem-Hydro-Mechanical-Solute Migration Coupled Model. The formulations of the biochem-hydro-mechanical-solute migration-coupled model include biochemical kinetics (equations (3), (7), (9), and (10)), skeleton deformation (equation (16)), the conservation of masses for the liquid (equation (13)), landfill gas (equation (14)), and solute (equation (19)).

The sink term of the solid mass and the source terms of leachate, solute, and landfill gas are provided by the biodegradation model as follows:

(1) Solid mass loss of MSW is given as follows:

$$f_m = R_g - R_j. \tag{20}$$

(2) Leachate generation due to the release of intraparticle water in kitchen waste and landfill gas generation is given as follows:

$$\begin{aligned} f_w &= \frac{18\lambda_{iw}}{162 + 18\lambda_{iw}}R_g, \\ f_g &= 3R_h. \end{aligned} \tag{21}$$

(3) VFA and methanogen accumulation is given as follows:

$$\begin{aligned} f_c^1 &= R_g - R_h, \\ f_c^2 &= R_j - R_k. \end{aligned} \tag{22}$$

The biochem-hydro-mechanical-solute migration-coupled model proposed in this paper can describe the interaction between the biodegradation process and mechanical behaviors. The complex behaviors of liquid flow and gas transport in landfills can be simulated by using this coupled model, such as a large amount of leachate is generated due to intraparticle water release in kitchen waste and landfill gas pressure increases with leachate mound. These are important features in high kitchen waste-content landfills [12]. A numerical case for investigating the effect of leachate recirculation in high kitchen waste-content landfill is presented in the following section.

3. Leachate Recirculation in High Kitchen Waste Content Landfill

3.1. Numerical Model of the High Kitchen Waste-Content Landfill Cell. Kitchen waste releases a large amount of intraparticle water during the biodegradation process. Acidification in a landfill body, which is due to the quick release of intraparticle water, may inhibit both hydrolysis and methanogenesis reactions. The stabilization process of high kitchen waste-content landfills will slow down, which can cause a number of engineering problems (e.g., landfill slope failure, impediment of landfill gas generation and flow, and low landfill gas collection efficiency).

A hypothetical landfill cell with a height of 10 m is used to investigate the effects of different leachate recirculation operations in high kitchen waste-content landfill. As shown in Figure 2, 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 model the leachate drainage system working well. The concentration gradients of VFA and methanogen are set to 0. The top boundary is impervious for landfill gas to simulate the effective top cover system. The quantitative effects of three leachate recirculation conditions, are no recirculation (control), water injection, and recirculation with treated leachate, respectively, are investigated via the proposed coupled model. The proposed coupled model is solved by the PDE module of COMSOL Multiphysics 5.3. The coupled model parameters are listed in Table 1, and the analysis results are shown in Figures 3–6.

3.2. Effects of Different Leachate Recirculation Operations. As shown in Figure 3, VFA accumulates rapidly and is converted slowly by methanogen for the case without recirculation. VFA concentration in leachate reaches a peak value of 21.5 g/L during the first 200 days after disposal. The acidification time for VFA concentration is greater than 10 g/L, which means serious inhibition of the biodegradation process occurs in the landfill for nearly 250 days. The VFA consumption rate increases with methanogen growth, and VFA concentration in leachate decreases after 200 days. However, methanogen decays due to the decrease of VFA concentration, which results in the methanogenesis reaction rate decreasing gradually and VFA concentration increasing slightly after 400 days. For the case of water injection, the hydrolysis reaction rate increases with moisture content at an early stage, which leads to a little faster increase of VFA concentration compared with the case without recirculation. However, VFA in leachate is diluted due to the increase of moisture content, and the peak value of VFA concentration decreases to 15.5 g/L. The increase in moisture content can also accelerate the methanogenesis reaction. VFA

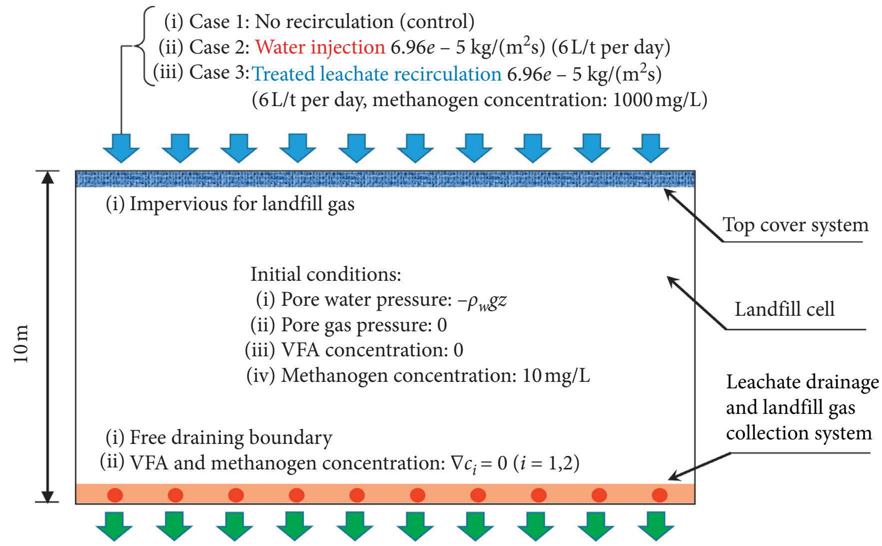

FIGURE 2: A hypothetical case of the high kitchen waste-content landfill cell with different leachate recirculation conditions.

TABLE 1: The coupled model parameters.

Parameter	Unit	Value
Cellulose content in fresh MSW, m_c (dry basis, wt/wt)	%	21.4[a]
Lignin content in fresh MSW, m_l (dry basis, wt/wt)	%	13.9[a]
Intraparticle water constant, λ_{iw}	—	60[a]
Maximum hydrolysis rate of cellulose, b	g/m^3/day	250 (kitchen waste)[b], 100 (other)[b]
Inhibition constant of VFA, k_h	m^3/g	0.1[b]
Inhibition constant of substrate content, n	—	2.8[b]
Maximum growth rate constant of methanogen, $k_{m\max}$	day^{-1}	0.1[b]
Inhibition constant of methanogen, k_m	m^3/g	0.06[b]
Decay rate constant of methanogen, k_d	day^{-1}	0.01[b]
Half-saturation constant of methanogen, k_s	g/m^3	4[b]
Substrate yield coefficient, Y	—	0.08[b]
Intrinsic permeability, k_i	m^2	$6e-12$[c]
Dynamic viscosity, μ	kg/(ms)	$1e-3$ (μ_w), $1.4e-5$ (μ_g)[c]
van Genuchten model parameter, α	—	0.88[c]
van Genuchten model parameter, n	—	1.6[c]
Maximum saturation, S_s	—	0.95[c]
Residual saturation, S_r	—	0.2[c]
Initial void ratio of MSW, e_0	—	3[d]
Modified compression index for fresh MSW, C_C'	—	0.2[d]
Modified compression index for fully decomposed MSW, $C_{C\infty}'$	—	0.1[d]
Total secondary compression strain, $\varepsilon_{dc}(\sigma_0)$	—	0.25[d]
Degradation compression rate constant, c_s	day^{-1}	0.006[d]

[a]Based on typical MSW composition in China [39, 43]; [b]reference from Meima et al. [44] and Chen et al. [45]; [c]reference from Feng et al. [34] and Xu et al. [46]; [d]reference from Li et al. [5] and Chen et al. [42].

concentration drops to a low level after 200 days, and the acid inhibition time is shortened obviously. For the case with treated leachate recirculation, the methanogen in injection leachate consumes the VFA generated by the hydrolysis reaction effectively. No remarkable acidification is observed, and the maximum concentration of VFA in leachate is only 9.6 g/L. Compared with the water injection case, the time when VFA concentration in leachate drops to less than 2 g/L is about 50 days earlier. Treated leachate recirculation is the most effective measure to relieve acid inhibition in the landfill with high kitchen waste content.

The ratio of cellulose weight and lignin weight (C/L) is an important indicator for evaluating the landfill mineralization process [47]. Average C/L for MSWs under different recirculation conditions are shown in Figure 4. During the first 2 years, the decay rates of C/L for both cases, that are the water injection condition and treated leachate recirculation condition, are significantly higher than the case without recirculation, and the decomposition of MSW for the case with treated leachate recirculation is the fastest of three conditions. Average C/L for MSW with treated leachate recirculation reduces to 0.5 within 1.4 years, it is 1.9 years for

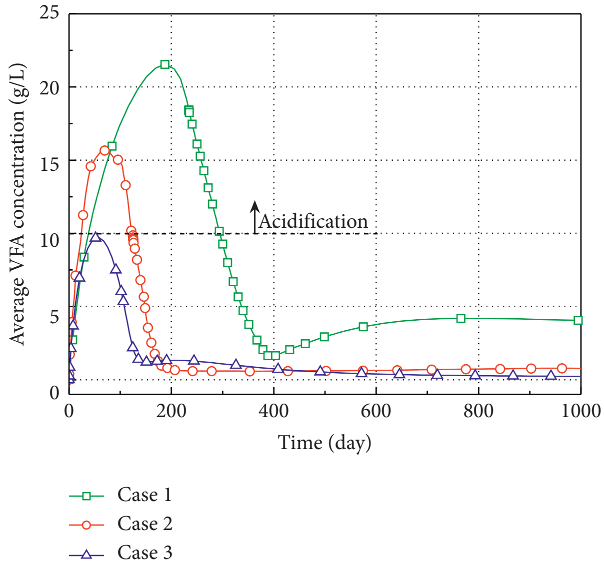

FIGURE 3: VFA concentration in leachate collected at the bottom under different recirculation conditions.

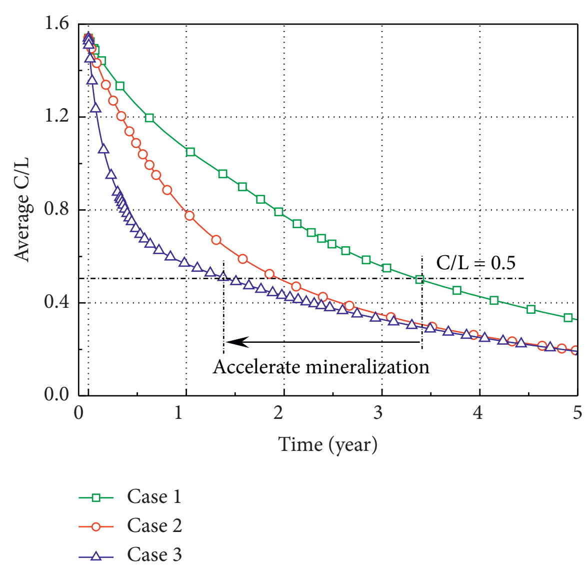

FIGURE 4: Average C/L for MSW under different recirculation conditions.

the case with water injection, and the case without recirculation takes the longest time, that is, 3.4 years, to reduce the average C/L to 0.5. Three conditions have a similar C/L decay rate after 3 years. The increase of moisture content in landfills can accelerate the decomposition of MSW at the initial stage, and the case with treated leachate recirculation accelerates the landfill mineralization process significantly via relieving acidification due to the fast hydrolysis of kitchen waste.

For the case without recirculation, acidification inhibits the methanogenesis reaction at the initial stage, which results in the landfill gas generation rate keeping at a low level until the VFA concentration in leachate begins to decrease.

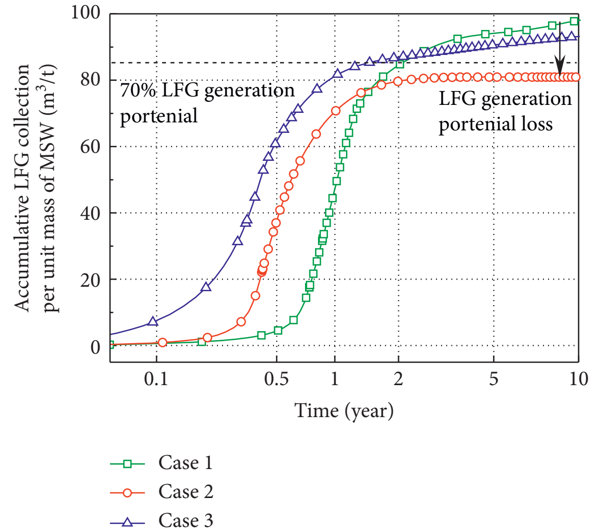

FIGURE 5: Landfill gas collection under different recirculation conditions.

The VFA in leachate is diluted due to water injection, and the stable methanogenesis stage starts earlier than the case without recirculation due to the acidification relief in the landfill. The methanogen in treated leachate can consume a large amount of VFA generated by fast hydrolysis of kitchen waste effectively, and the landfill gas generation rate increases significantly in the first 0.5 years (see Figures 3 and 5). Landfill gas generation increase with the decrease of C/L, about 70% of landfill gas generation potential has been released when the average C/L reduces to 0.5 (see Figures 4 and 5). However, it can be found that the accumulative landfill gas generation for both the case with water injection and the case with treated leachate recirculation is a little lower than the case without recirculation. A part of methanogenesis reaction substrates in leachate is discharged from the leachate drainage system at the bottom of the landfill, which leads to a loss of landfill gas generation potential. Similar phenomena have been found in experimental research by Zhan et al. [12]. For the case with treated leachate recirculation, most methanogenesis reaction substrates are consumed before being discharged from the bottom due to a high concentration of methanogen, and the loss of landfill gas generation potential is not obvious. As shown in Figure 5, the active landfill gas generation period lasts approximately 2 years, and recirculation with treated leachate can promote landfill gas generation at this period. However, the improvement effect on landfill gas generation is limited after 2 years.

Figure 6 indicates that the increase of moisture content via water injection or leachate recirculation can accelerate the long-term degradation compression of landfills with high kitchen waste content. The degradation compression strain takes 6.7 years to reach the settlement stabilization for the case with treated leachate recirculation, but it will take more than 10 years for the case without recirculation. Leachate recirculation will lead to a larger settlement at the initial stage (the degradation compression strain reaches

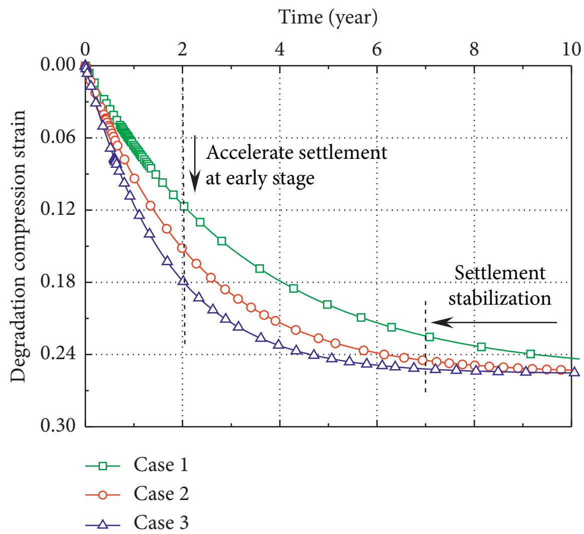

Figure 6: Degradation compression for landfill under different recirculation conditions.

17.9% in the first 2 years for this case), which may cause a failure of landfill infrastructures, such as cover systems, leachate collection and drainage systems, and landfill gas collection systems. The disadvantages of leachate recirculation on landfill infrastructure should be estimated, and the amount of recirculation needs to be evaluated accurately when the recirculation operation is designed [48].

4. Conclusions

This paper has presented the formulation of a coupled model for the analysis of the landfill stabilization process. The biochemical, hydraulic, and mechanical behaviors under different recirculation conditions are investigated via a hypothetical case for the landfill with high kitchen waste content. The following conclusions can be obtained:

(1) The hydrolysis of kitchen waste results in a significant increase of VFA concentration in leachate. Introducing methanogen into the landfill via recirculating with treated leachate can relieve acidification in landfills effectively and accelerate the stabilization process of landfills with high kitchen waste content.

(2) Leachate recirculation has significant effects on accelerating the decomposition of MSWs with high kitchen waste content in the first 2 years, which increases landfill gas generation rate and degradation compression. When the mineralization process enters the slow degradation stage, the effects of leachate recirculation are limited. The economic performance and integrity of landfill infrastructure should be considered in the design of leachate recirculation operation.

(3) A part of landfill gas generation potential will lose due to leachate drainage. Leachate collected from fresh MSW can be used to recirculate when an active landfill gas generation period starts. It would benefit from the supplements of landfill gas generation potential and the removal of the contaminant in fresh leachate.

(4) Leachate recirculation can reduce postclosure settlement effectively, which is helpful to the construction and operation of transportation facilities above landfills. The rapid decomposition of organic content in MSWs due to leachate recirculation results in a significant decrease in residual content of degradable organic content in the mineralized waste, which can improve the mechanical properties as a kind of construction material.

Data Availability

The data used to support the findings of this study are included within this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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