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Coupling model of aerobic waste degradation considering temperature, initial moisture content and air injection volume

Jun Ma[1,2,3], Lei Liu[1,3], Sai Ge[1], Qiang Xue[1,3], Jiangshan Li[1], Yong Wan[1] and Xinminnan Hui[1,2]

Abstract

A quantitative description of aerobic waste degradation is important in evaluating landfill waste stability and economic management. This research aimed to develop a coupling model to predict the degree of aerobic waste degradation. On the basis of the first-order kinetic equation and the law of conservation of mass, we first developed the coupling model of aerobic waste degradation that considered temperature, initial moisture content and air injection volume to simulate and predict the chemical oxygen demand in the leachate. Three different laboratory experiments on aerobic waste degradation were simulated to test the model applicability. Parameter sensitivity analyses were conducted to evaluate the reliability of parameters. The coupling model can simulate aerobic waste degradation, and the obtained simulation agreed with the corresponding results of the experiment. Comparison of the experiment and simulation demonstrated that the coupling model is a new approach to predict aerobic waste degradation and can be considered as the basis for selecting the economic air injection volume and appropriate management in the future.

Keywords

Waste, aerobic, degradation, coupling model, simulation, chemical oxygen demand

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Introduction

Landfill aeration is considered as one of the most important methods to operate landfills in a sustainable manner (Matsuto et al., 2015). Numerous studies verified through laboratory-scale and field-scale tests that landfill aeration results in decreased leachate pollution, methane emission and accelerated organic matter degradation (Heyer et al., 1999; Hrad and Huber-Humer, 2016; Hrad et al., 2013; Hudgins and Harper, 1999; Ko et al., 2013; Leikam et al., 1999; Raga and Cossu, 2014; Raga et al., 2015; Ritzkowski and Stegmann, 2007, 2012, 2013; Ritzkowski et al., 2006). The quantitative prediction of waste degradation under aerobic condition is important in assessing the degree of landfill waste stability. Cellulose/lignin, 5-day biochemical oxygen demand/chemical oxygen demand (BOD_5/COD), respiration index (RI_4), and biomethane potential production (GB_{21}) are indexes for evaluating the degree of waste stabilisation (Cossu and Raga, 2008; Doublet et al., 2011; Foo and Hameed, 2009; Francou et al., 2008; Ghani et al., 2017). However, research on these indexes in the quantitative prediction of models is limited. Most of the existing models are derived from composting and are too complex for calculations (Denes et al., 2015; Fytanidis and Voudrias, 2014). Considerable differences exist between composting and aerobic waste degradation, such as processes, methods, components and field of application, among others. Composting is often defined as the aerobic degradation of organic waste through microbial activity and growth (Haug, 1993). This process is commonly used to treat, diminish the mass of and recycle solid organic waste as an amendment of agricultural soils (Bernal et al., 2009). Therefore, the composting model is not completely suitable for aerobic waste degradation.

Waste degradation models are mainly based on two biochemical kinetic equations. The first type of kinetics is the Monod equation (Fytanidis and Voudrias, 2014; Lin et al., 2008; Nikoli and Voudrias, 2009; Qin et al., 2007; Rees-White et al., 2008; Xi et al., 2008); the second type is first-order kinetics (El Fadel and Findikakis, 1996; Lu et al., 1984; Slezak et al., 2010; Vavilin

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[1]State Key Laboratory of Geomechanics and Geotechnical Engineering, Chinese Academy of Sciences, Wuhan, China
[2]University of Chinese Academy of Sciences, Beijing, China
[3]Hubei Province Key Laboratory of Contaminated Sludge and Soil Science and Engineering, Wuhan, China

Corresponding author:
Qiang Xue, State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China.
Email: qiangx@whrsm.ac.cn

et al., 2003), which is widely used in the field of aerobic substance degradation (Baptista et al., 2010; Higgins and Walker, 2001). The Monod equation is typically used to describe the substrate-limiting growth of microbial populations, while first-order kinetics represents an empirical approach. Although, the model mechanisms are clear and definite, their applications in assessing the degree of waste stability are rare. In most cases, these models are applied to describe aerobic compost degradation, mainly focusing on bacteria, fungi, cellulose and lignin. For example, Zhang et al. (2012) established an aerobic compost degradation coupling model, and Denes et al. (2015) proposed a more comprehensive aerobic compost degradation coupling model based on Zhang's model. This type of model can describe in detail the degradation process and variation in organic matter, but the parameters are difficult to obtain. Experiments cannot be conducted in large quantities because of complexity. A conceptual model proposed by Komilis (2006) mainly focused on solid waste composting, but the composting model is not completely suitable for aerobic waste degradation. Hence, a new model must be proposed. Previous research provided a theoretical basis for establishing a relatively simplified index as a model parameter to describe aerobic waste degradation.

This work aimed to develop and primarily test a new model that can predict COD variation in aerobic waste degradation process. For this purpose, a coupling model of aerobic waste degradation with temperature, initial moisture content and air injection volume under consideration was proposed on the basis of first-order kinetic equation and the law of conservation of mass. According to three different laboratory experiments on aerobic waste degradation conducted by Ma et al. (2013), Slezak et al. (2010) and Hrad et al. (2013), COD variation in an aerobic waste degradation process was simulated using the Comsol Multiphysics (3.5a) Earth Science Module. The sensitivity of the model to variations in input parameters was analysed, and the applicability of the model was verified by simulating the degradation of fresh and aged wastes under intermittent or continuous air injection. The novelty of the present work was the development of a coupling model with a relatively simplified index to describe aerobic waste degradation. The model in this article can be used as a basis for assessing the degree of landfill waste stability and for selecting the economic air injection volume and appropriate management in the future.

Model development

COD is one of the comprehensive indexes to describe organic matter content in leachate. Thus, COD is selected in this article as the coupling model quantitative characterisation to describe variation in the content of organic matter in leachate and waste.

The coupling model is established based on the basis of the first-order kinetic equation and the law of conservation of mass and considered temperature, initial moisture content and air injection volume. The established assumptions are as follows.

1. Waste in the simulated biochemical reactor is considered as homogeneous. Substances are well-distributed in the reactor.
2. Degradation of organic matter by microorganisms is divided into two parts, namely, solid and liquid phases. The dissolution of organic carbon in the solid phase into liquid phase and the degradation of organic carbon in the liquid and solid phases conform to first-order kinetics.
3. The variation of organic carbon in liquid and solid phases are only caused by degradation.

According to assumption (2), organic carbon reduction rate in solid phase can be expressed as:

$$R_S = \frac{dm_s}{dt} = -k_1 m_s - k_3 m_s \tag{1}$$

where R_S is the organic carbon reduction rate in solid phase (mg d^{-1}); m_s is the mass of organic carbon in solid phase referring to dry matter (mg), k_1 is the rate of organic carbon in solid phase dissolving into liquid phase (d^{-1}), k_3 is direct degradation rate of organic carbon in solid phase (d^{-1}), and t is time (d).

Therefore, the mass of organic carbon in solid phase can be written as:

$$m_s = m_{s0} e^{-(k_1 + k_3)t} \tag{2}$$

where m_{s0} is the initial mass of organic carbon in the solid phase (mg).

The rate of organic carbon increase in the liquid phase can be written as:

$$R_{LS} = k_1 m_s = k_1 m_{s0} e^{-(k_1 + k_3)t} \tag{3}$$

where R_{LS} is the rate of organic carbon increase in liquid phase (mg d^{-1}).

In the liquid phase, the biodegradable portion of organic carbon is known as the biochemical degradation part, and the rest is known as the non-biochemical degradation part, which cannot or hardly degrade. The variation rates in biochemical and non-biochemical degradation parts in the liquid phase can be written as follows, respectively:

$$\begin{aligned} R_{L1} = \frac{dm_1}{dt} &= -k_2 m_1 + 1 - nk_1 m_{s0} e^{-(k_1 + k_3)t} \\ &= -k_2 m - m_2 + 1 - nk_1 m_{s0} e^{-(k_1 + k_3)t} \end{aligned} \tag{4}$$

$$R_{L2} = \frac{dm_2}{dt} = nk_1 m_{s0} e^{-(k_1 + k_3)t} \tag{5}$$

where R_{L1} is the variation rate of biochemical degradation part in liquid phase (mg d^{-1}), R_{L2} is the variation rate of non-biochemical degradation part in liquid phase (mg d^{-1}), m_1 is the organic carbon mass of biochemical degradation part in liquid phase (mg), m_2 is the organic carbon mass of non- biochemical degradation part in liquid phase (mg), m is the total organic carbon mass in liquid phase (mg), n is the proportion of non-biochemical degradation mass m_2 in total organic carbon mass m in liquid phase (mg mg^{-1}). Hence, m_2 is equal to the product of n and m. k_2 denotes the degradation rate of organic carbon mass of biochemical degradation part in liquid phase (d^{-1}).

According to the law of conservation of mass and assumption (3), the variation rate of total organic carbon in the liquid phase is as follows:

$$R_L = \frac{dm}{dt} = R_{L1} + R_{L2} = k_1 m_{s0} e^{-(k_1+k_3)t} - k_2\left(m - m_2\right) \tag{6}$$

where R_L is the variation rate of total organic carbon in the liquid phase (mg d^{-1}).

The most important parameters affecting waste aerobic biodegradation include the following: (1) temperature, (2) oxygen concentration, (3) moisture content in waste, (4) free air space that affects whether air can flow across the waste, (5) particle size that prescribes the effective surface of solid matrix where biodegradation occurs and (6) pH (Baptista et al., 2010; Haug, 1993).

Considering the above mentioned parameters, Haug (1993) proposed the following formula:

$$S_S = \frac{dC_S}{dt} = -k'C_S = -k\, k_{temp}\, k_{mc}\, k_{O_2}\, k_{FAS}\, k_{pH}\, C_S \tag{7}$$

where S_S is the solid waste biodegradation rate (kg (m^{3}s)$^{-1}$), C_S is the concentration of the biodegradable solid waste (kg m^{-3}), k' is the effective/corrected biodegradation rate (s^{-1}), k is the maximum biodegradation rate (s^{-1}), k_{temp} is the temperature correction function (dimensionless), k_{mc} is the moisture content correction function (dimensionless), k_{O_2} is the oxygen concentration correction function (dimensionless), k_{FAS} is the free airspace correction function (dimensionless) and k_{pH} is the pH correction function (dimensionless) (Fytanidis and Voudrias, 2014).

Therefore, the effective degradation rate with temperature, initial moisture content and air injection volume under consideration can be written as:

$$k_i = k_{max,I} f_1(T) f_2(W) f_{3i}(A) \tag{8}$$

where k_i is the effective degradation rate (d^{-1}), i = 1, 2, and 3, $k_{max,I}$ is the maximum degradation rate under optimal conditions (d^{-1}), $f_1(T)$ is the influence factor of temperature, $f_2(W)$ is the influence factor of initial moisture content and $f_{3i}(A)$ is the influence factor of air injection volume. Temperature significantly influences the rate of aerobic waste degradation (Tremier et al., 2005).

The following correction function, that is, cardinal temperature model with inflection (CTMI), was used for temperature. CTMI was originally proposed by Rosso et al. (1993), and was based on the cardinal temperatures T_{min}, T_{max} and T_{opt}. The influence factor of temperature $f_1(T)$ is as follows:

$$f_1(T) = \left(T - T_{max} T - T_{min}{}^2\right) / \\ T_{opt} - T_{min}\left[\begin{matrix}\left(T_{opt} - T_{min}\right)\left(T - T_{opt}\right) - \\ \left(T_{opt} - T_{max}\right)\left(T_{opt} + T_{min} - 2T\right)\end{matrix}\right] \tag{9}$$

where T_{min} is the minimum acceptable temperature, 0 °C (Tremier et al., 2005); T_{max} is the maximum acceptable temperature, 63 °C (Tremier et al., 2005) and T_{opt} is the optimum temperature for the aerobic degradation, 38.2 °C (Tremier et al., 2005); and T is the actual temperature (°C). Although numerous correction functions acceptably fit the experimental data in the literature, Mason (2006) concluded that, despite its empirical origin, CTMI includes an easily estimated set of parameters with a physical meaning in terms of composting/aerobic biodegradation. CTMI has been widely applied in the field of substance degradation (Baptista, 2009; Baptista et al., 2010; Mason, 2009; Sole-Mauri et al., 2007).

Moisture content is one of the main factors affecting degradation reaction. The basic relationship between moisture content and degradation reaction was proposed by Mora-Naranjo et al. (2004). However, the influence of initial moisture content on degradation can be divided into two types. The influence factor of initial moisture content $f_2(W)$ can be expressed as:

$$f_2(W) = \begin{cases} 1.200 \times 10^{-2} W - 0.18 & W < 100 \\ 1 & W \geq 100 \end{cases} \tag{10}$$

where W is the initial moisture content (% dry matter (DM)). When initial moisture content exceeds 100%, $f_2(W)$ is equal to 1.

Almeira et al. (2015) proposed that when air injection volume exceeds 3000 L (kg DM) $^{-1}$, respiratory activity remains constant, meaning that degradation rates will remain stable even with increasing air injection volume. Thus, k1, k2, and k3 can be considered as the power function of cumulative air injection volume $ki(A)$. The cumulative of air injection volume (A) is the product of daily air injection volume and the time of air injection:

$$ki(A) = a_i \exp(b_i A) + c_i \tag{11}$$

$$A = Rt \tag{12}$$

where a_i, b_i and c_i are constants obtained by numerical simulation; i is equal to 1, 2 and 3, respectively; R is the daily air injection volume (L d^{-1}) and t represents time (d); A is the cumulative air injection volume (L). The influence factor of air injection volume can be written as follows, and I represent 1, 2, and 3:

$$f_{3i}(A) = \left(a_i \exp(b_i A) + c_i\right) / k_{max,I} \tag{13}$$

Table 1. Degradation parameters used in coupling model.

	Y (g g^{-1})	kt (d^{-1})	k1 (d^{-1})	k2 (d^{-1})	k3 (d^{-1})
$k_{max,\,I}$ (Slezak et al., 2010)	5.500×10^{-2}	8.010×10^{-3}	4.400×10^{-4}	2.355×10^{-1}	7.569×10^{-3}

Model application

Numerical simulation case one

A laboratory-scale test of aerobic waste degradation was simulated according to Ma et al. (2013). Three laboratory-scale columns were constructed using 20 cm diameter polyacrylic plastic pipes with a total height of 100 cm to simulate aerobic waste degradation. A 5-cm-thick gravel layer was placed at the bottom of each column as a drainage layer. A total of 13.2 kg of synthesised waste was loaded into each column. The experiment material was fresh municipal solid waste, and the bulk density of the compacted waste was 600 kg m^{-3}. A layer of gravel was placed on top of the loaded waste to facilitate the even distribution of the recirculated leachate. Leachate collected from each column was recirculated with a flowrate of 38 mL (kg d)$^{-1}$. The columns were operated in a thermostatic room (32.5 °C) for 200 days. Each column was subjected to different daily volumes of air injection, namely, C2, C3 and C4. The air injection rate of 30 L h^{-1} was considered as intermittent air injection because C2, C3 and C4 injected air for 2, 4 and 8 h, respectively, on a daily basis. Thus, the total daily volumes of air injection for C2, C3 and C4 were 60, 120 and 240 L, respectively. In the experiment, the dry waste mass was 6.640 kg. Thus, the threshold value of the cumulative air injection volume A was equal to 19,918.8 L. Degradation parameters are shown in Table 1.

In Table 1, Y is the yield coefficient representing the quantity of organic carbon in leachate from organic carbon in the solid phase (g g^{-1}), kt is the total degradation rate of organic carbon in the solid phase (d^{-1}), which is the sum of the rate of organic carbon in the solid phase dissolving into liquid phase k1 and the direct degradation rate of organic carbon in the solid phase k3. Therefore, the product of yield coefficient Y and the total degradation rate of organic carbon in the solid-phase kt is the rate of organic carbon in the solid phase dissolving into the liquid phase k1.

For example, the maximum product of $f_{31}(A)$ and k1 corresponds to kmax, 1. As shown in Figure 1, at the cumulative air injection volume A of 1.992×10^4 L, k1 is equal to kmax, 1, which is 4.400×10^{-4} d^{-1}.

The laboratory-scale test was simulated by Comsol Multiphysics (3.5a) Earth Science Module, and simulation parameters are shown in Table 2. The influence factors of air injection volume are shown in Table 3.

In Table 2, the COD/total organic carbon (COD/TOC) values are estimated according to Foo and Hameed (2009) on the basis of COD values. After several simulations, the COD/TOC values showed a slight influence on the results.

The COD simulation results obtained by the coupling model and experiment results of the laboratory scale test are shown in Figures 2–4.

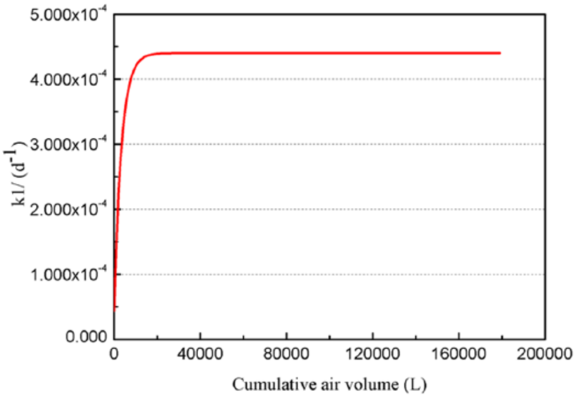

Figure 1. Influence of cumulative air injection volume on k1.

The COD simulation results of aerobic waste degradation from the coupling model were similar to those of the experimental results. However, the results of COD simulation decreased faster than those of experiments, and COD simulation results yielded shorter stabilisation times than the experimental results under three different air injection rate conditions. Moreover, at the end of the laboratory-scale test, the COD of C2, C3 and C4 were 4170, 2640 and 1870 mg L^{-1}, respectively; whereas those of the simulation of C2, C3 and C4 were 5625, 5547 and 5614 mg L^{-1}, respectively, which all exceeded the experimental results. The difference between the results of the experiment and the simulation decreased with increasing daily air injection volume.

Numerical simulation case two

A laboratory-scale test of aerobic waste degradation was simulated by Comsol Multiphysics according to Slezak et al. (2010). In the experiment, dry waste mass was approximately 3.625 kg. The threshold value of cumulative air injection volume A was 1.088×10^4 L. The model composition of municipal solid waste in this experiment was defined on the basis of the analysis of waste morphological composition for the city of Lodz (Ledakowicz and Kaczorek, 2004). The experimental material was classified as fresh municipal solid waste. The leachate was recirculated daily. The same experimental material was adopted with different air injection rates, namely, 10, 6, 4 and 2 L h^{-1}, which corresponded to R1, R2, R3 and R4, respectively. Continuous air injection was apparent. Thus, the daily air injection volume for R1, R2, R3 and R4 were 240, 144, 96 and 48 L day^{-1}, respectively.

Degradation and simulation parameters are shown in Tables 4 and 5, respectively. The influence factors of air injection volume are shown in Table 6.

Table 2. Simulation parameters used in the coupling model.

WM (kg)	W (%DM)	T (°C)	OC (%)	COD_0 (mg L^{-1})	COD/ TOC	TOC_0 (mg L^{-1})	m (mg)	u (mg L^{-1})	n (%)	m_{20} (mg)	m_{10} (mg)	V (L)	m_0 (mg)	m_{s0} (mg)	R (L d^{-1})
13.20	49.70	32.50	17.18	60,000	5	12,000	m	5m/V	2.5	$n \cdot m_0$	$m_0 - m_{20}$	4.380	262,800/5	2,267,939	60/120/240

WM: waste mass (kg); OC: organic carbon content in solid phase (%);COD_0: initial value COD; TOC: total organic carbon concentration in liquid phase (mg L^{-1}); TOC_0: initial total organic carbon concentration in the liquid phase (mg L^{-1}); u COD at time t (mg L^{-1}); m_{20}: organic carbon initial mass of non-biochemical degradation part in liquid phase (mg); m_{10}: organic carbon initial mass of biochemical degradation part in the liquid phase (mg); V: liquid volume (L); m_0: initial total organic carbon mass in liquid phase (mg); m_{s0}: initial mass of organic carbon in the solid phase (mg); R: daily air injection volume (L d^{-1}).

Table 3. Influence factors of air injection volume used in the coupling model.

Influence factors of volume of air injection	Expression
f31	$\frac{-3.960\ 10^{-4}e^{-2.973\ 10^{-4}Rt}+4.400\ 10^{-4}}{4.400\ 10^{-4}}$
f32	$\frac{-2.136\ 10^{-1}e^{-1.786\ 10^{-4}Rt}+2.370\ 10^{-1}}{2.355\ 10^{-1}}$
f33	$\frac{-6.750\ 10^{-3}e^{-3.510\ 10^{-4}Rt}+7.500\ 10^{-3}}{7.569\ 10^{-3}}$

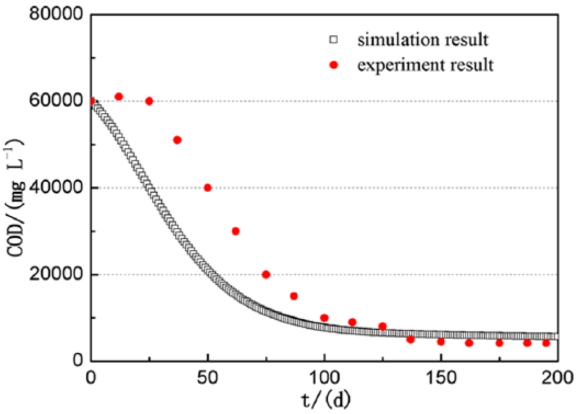

Figure 2. Comparison of COD results in leachate simulation and experiment of C2 (R: 60 L d^{-1}).

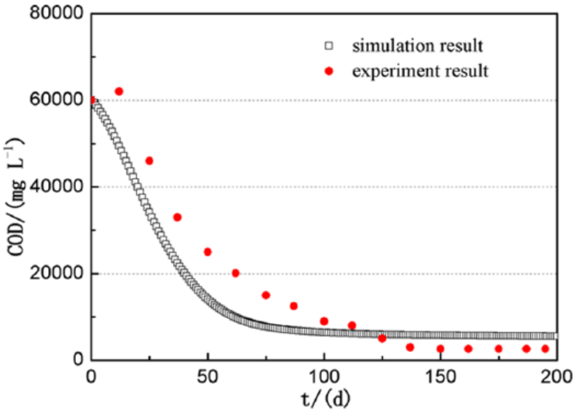

Figure 3. Comparison of COD results in leachate simulation and experiment of C3 (R: 120 L d^{-1}).

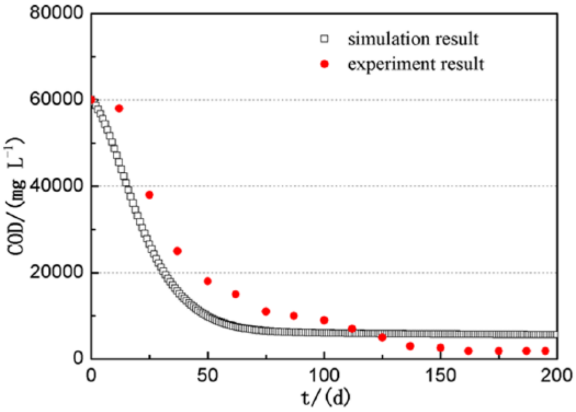

Figure 4. Comparison of COD results in leachate simulation and experiment of C4 (R: 240 L d^{-1}).

The COD simulation obtained by the coupling model and the experimental results of the laboratory-scale test are shown in Figs. 5a to 5d.

The COD simulation results of aerobic waste degradation from the coupling model were similar to the experimental results. However, COD experimental results decreased faster than the simulation before COD approached stability. Amplitudes of COD variation decreased after air injection for 90, 90, 60 and 90 days, corresponding to R1, R2, R3 and R4, respectively. At the end of the laboratory-scale test, the COD experimental results of R1, R2, R3 and R4 were 790, 680, 950 and 550 mg L−1, respectively. However, from the 50th day, COD simulations started to decrease to steady-state values. Stabilisation times of the simulation were faster than those of the experimental results. At the end of the simulation, COD results of R1, R2, R3 and R4 were 909, 625, 824 and 786 mg L^{-1}, respectively. The COD simulation of R1, R2 and R3 approached the experimental results, whereas R4 exhibited large deviation.

Numerical simulation case three

A laboratory-scale test of aerobic waste degradation was simulated by Comsol Multiphysics according to Hrad et al. (2013). In the experiment, the dry waste mass was 84.84 kg. The threshold value of the cumulative air injection volume A was 254,520 L. The test waste aged 12–31 years was retrieved from an old landfill and irrigated weekly with 1.2 L of deionised water to

Table 4. Degradation parameters used in the coupling model.

	Y (g g^{-1})	kt (d^{-1})	k1 (d^{-1})	k2 (d^{-1})	k3 (d^{-1})
$k_{max,l}$ (Slezak et al., 2010)	5.500×10^{-2}	8.010×10^{-3}	4.400×10^{-4}	1.880×10^{-1}	7.570×10^{-3}

Table 5. Simulation parameters used in the coupling model.

	WM (kg)	W (%DM)	T (°C)	OC (%)	COD_0 (mg L^{-1})	COD/ TOC	TOC_0 (mg L^{-1})	m (mg)	u (mg L^{-1})	n (%)	m_{20} (mg)	m_{10} (mg)	V (L)	m_0 (mg)	m_{s0} (mg)	R (L d^{-1})
R1	10	≥100	23	13.99	15,100	2.5	15,100/2.5	m	2.5m/V	3	$n\cdot m_0$	$m_0–m_{20}$	6.375	96,262/2.5	699,500	240
R2				6.690	13,800		13,800/2.5							87,975/2.5	334,500	144
R3				8.269	19,000		19,000/2.5							121,125/2.5	413,450	96
R4				8.746	17,700		17,700/2.5							112,837/2.5	437,300	48

Table 6. Influence factors of air injection volume used in the coupling model.

Influence factors of volume of air injection	Expression
f31	$\frac{-3.788\times10^{-4}e^{-3.975\ 10^{-4}Rt}+4.146\times10^{-4}}{4.400\times10^{-4}}$
f32	$\frac{-1.709\times10^{-1}e^{-2.823\ 10^{-4}Rt}+1.896\times10^{-1}}{1.880\times10^{-1}}$
f33	$\frac{-6.830\times10^{-3}e^{-4.428\ 10^{-4}Rt}+7.580\times10^{-3}}{7.570\times10^{-3}}$

accelerate the degradation process. Therefore, the liquid volume V was variable. The rate of continuous air injection was 3 L h^{-1}. Thus, the daily air injection volume was 72 L d^{-1}. Degradation and simulation parameters are shown in Tables 4 and 7, respectively. The influence factors of the air injection volume are shown in Table 8.

As shown in Figure 6, the COD simulation was basically consistent with the experimental result. After 20 weeks (approximately 140 days) of laboratory-scale test, the COD experimental result decreased to approximately 225 mg L^{-1}, whereas the COD simulation result was 337 mg L^{-1} on the 140th day. The COD simulation result decreased faster than the experimental results in the early stage, whereas the situation was reversed after approximately 100 days. Moreover, the difference between simulation and experimental results decreased with time. At the end of the laboratory-scale test, the COD experimental result was 110 mg L^{-1}, whereas the simulation yielded 93.64 mg L^{-1}, which was close to the COD experimental result.

Parameter sensitivity analyses

Parameter sensitivity analyses of the coupling model of aerobic waste degradation with temperature, initial moisture content and air injection volume under consideration were conducted according to Ma et al. (2013). The ranges of parameters were based on Slezak et al. (2010). The simulated results of daily air injection volume of 60 L d^{-1} were consistent with those of other daily volumes of air injection. Thus, the simulated daily air injection volume of 60 L d^{-1} was mainly shown in this study.

Yield coefficient Y

The yield coefficient (Y) ranged from 5.500×10^{-2} g g^{-1} to 1.730×10^{-1} g g^{-1} (Slezak et al., 2010). The minimum, median and maximum values of Y were 5.500×10^{-2}, 1.140×10^{-1} and 1.730×10^{-1} g g^{-1}, respectively. The rates of the dissolution of the organic carbon in the solid phase into the liquid phase k1 were 4.405×10^{-4}, 9.130×10^{-4}, 1.400×10^{-3} d^{-1} corresponding to the minimum, median and maximum values of Y, respectively, whereas direct degradation rate of organic carbon in solid phase k3 were 7.560×10^{-3}, 7.100×10^{-3}, 6.600×10^{-3} d^{-1}. Notably, the total degradation rate of organic carbon in the solid-phase kt was constant, and k1 increased with Y. By contrast, k3 decreased as Y increased.

Figure 7 illustrates the influence of different Y values on the degradation effect of the coupling model. For example, at the daily air injection volume of 60 L d^{-1}, the stable value of COD decreased at a high decrease rate with the decrease in Y. With the decrease in Y, the direct degradation rate of organic carbon in the solid phase increased, whereas the rate of dissolution of organic carbon in the solid phase into the liquid phase decreased. Meanwhile, the degradation rate of the organic carbon mass of biochemical degradation part in the liquid phase k2 was constant. Thus, the stable COD decreased as Y decreased.

Total degradation rate of organic carbon in the solid phase kt

The value of kt ranged from 8.010×10^{-3} d^{-1} to 1.250×10^{-2} d^{-1} (Slezak et al., 2010). The minimum, median and maximum values of kt were 8.010×10^{-3}, 1.026×10^{-2} and 1.250×10^{-2} d^{-1}, respectively. The minimum, median and maximum values of k1 were 4.405×10^{-4}, 5.640×10^{-4} and 6.880×10^{-4} d^{-1}, respectively, whereas those of k3 were 7.560×10^{-3}, 9.690×10^{-3} and

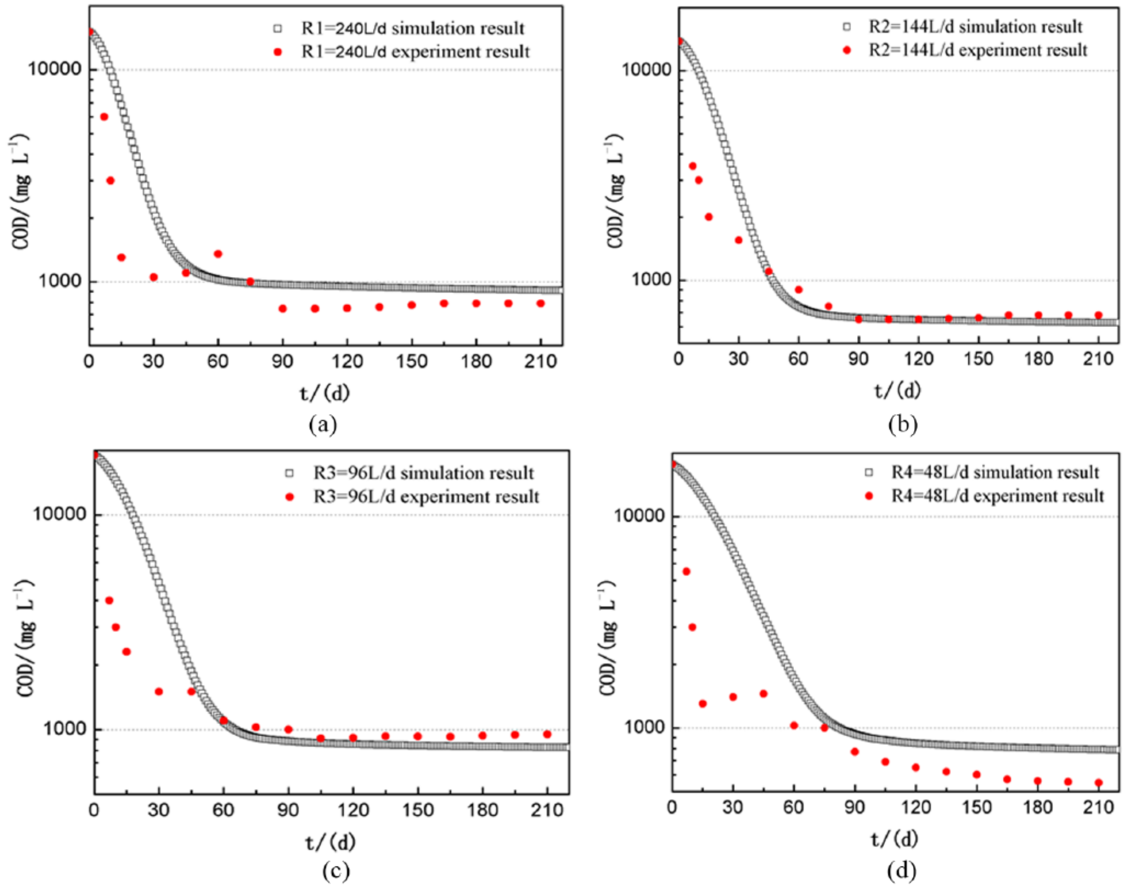

Figure 5. Comparison of COD results in leachate simulation and experiment.

Table 7. Simulation parameters used in coupling model.

WM (kg)	W (%DM)	T (°C)	OC (%)	COD_0 (mg L^{-1})	COD/ TOC	TOC_0 (mg L^{-1})	m (mg)	u (mg L^{-1})	n (%)	m_{20} (mg)	m_{10} (mg)	V(L)	m_0 (mg)	m_{s0} (mg)	R (L d^{-1})
120	41.44	40	6.2	650	1.67	650/1.67	m	1.67m/V	3	$n \cdot m_0$	$m_0 - m_{20}$	35.16 + 1.2 t/7	22,854/1.67	7,440,000	72

Table 8. Influence factors of air injection volume used in the coupling model.

Influence factors of volume of air injection	Expression
f31	$\dfrac{-3.984\times10^{-4}e^{-1.642\ 10^{-5}Rt}+4.423\times10^{-4}}{4.400\times10^{-4}}$
f32	$\dfrac{-1.700\times10^{-1}e^{-2.032\ 10^{-5}Rt}+1.884\times10^{-1}}{1.880\times10^{-1}}$
f33	$\dfrac{-6.830\times10^{-3}e^{-2.038\ 10^{-5}Rt}+7.580\times10^{-3}}{7.570\times10^{-3}}$

1.180×10^{-2} d^{-1}, respectively. Moreover, the ratios of k1/k3 were 5.827×10^{-2}, 5.820×10^{-2} and 5.831×10^{-2}, respectively.

Figure 8 illustrates the influence of different kt on degradation effect of coupling model. For example, with a daily air injection volume of 60 L d^{-1}, the stable COD value increased with the increase in kt. The variation in kt influenced k1 and k3 simultaneously. However, this phenomenon suggests that kt exerts a larger influence on k1 than k3. When kt was equal to the minimum or median value, simulation results were almost equal. By contrast, the stable COD value was higher than other results when kt was equal to the maximum value possibly because of a higher value of k1/k3.

Degradation rate of organic carbon mass in the biochemical degradation part in the liquid phase k2

The k2 values ranged of 1.880×10^{-1} d^{-1} to 2.830×10^{-1} d^{-1} (Slezak et al., 2010). The minimum, median and maximum values of k2 were 1.880×10^{-1}, 2.355×10^{-1} and 2.830×10^{-1} d^{-1}, respectively. Figure 9 illustrates the influence of different k2 values on the degradation effect of the coupling model. For example, at the daily air injection volume of 60 L d^{-1}, (Figure 9(a)), the COD simulation result before COD stabilisation of adopting the median value of k2 was higher than the results with other values,

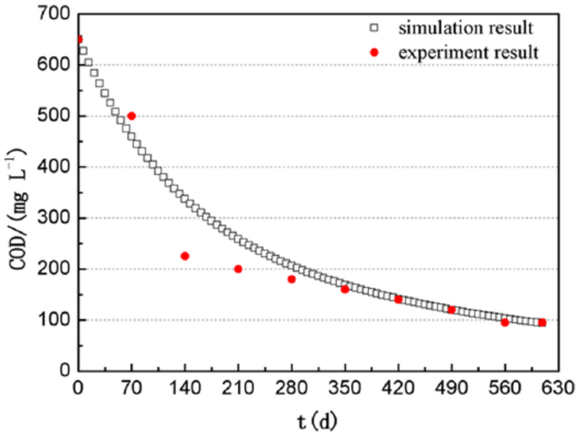

Figure 6. Comparison of COD results in leachate simulation and experiment.

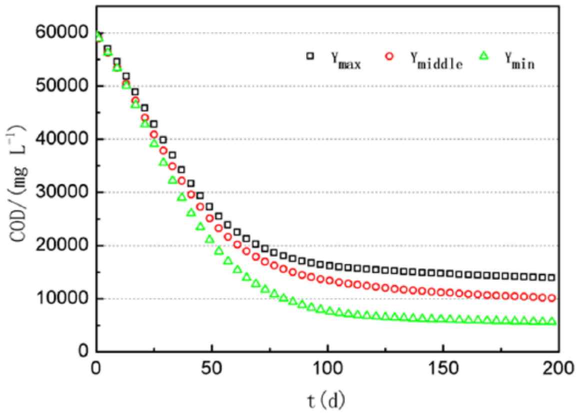

Figure 7. Influence of different Y on the degradation effect of the coupling model.

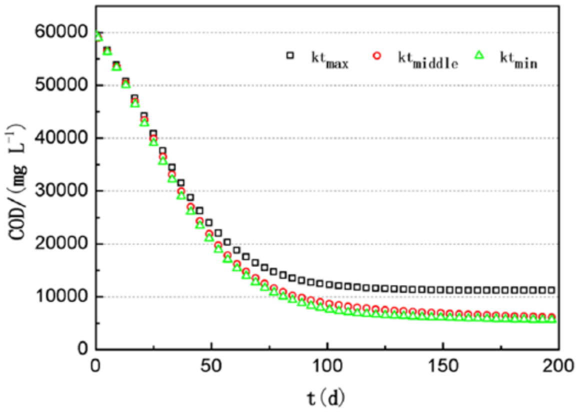

Figure 8. Influence of different kt on the degradation effect of the coupling model.

suggesting that the effect of k2 on the degradation rate may not be a simple monotonous relation, and the median value of k2 approached the optimal degradation rate. After COD stabilisation, the stable COD value decreased with the increase in k2. However, the influence was weaker because of the faster degradation rate of the organic carbon mass of the biochemical degradation part in the liquid phase when k2 increased. Therefore, less organic carbon remained in the liquid phase. The results of other daily air injection volume were consistent with the phenomenon in Figure 9(a), as shown in Figure 9(b) and (c). The k2 values of three simulations were set to 2.355×10^{-1}, 1.880×10^{-1} and 1.880×10^{-1} d^{-1}, respectively, which were the best-fitting values based on multiple numerical simulations. The sensitivity analysis of k2 demonstrated the applicability of k2 values used in the three simulations.

Proportion of non-biochemical degradation mass m_2 in the total organic carbon mass m in the liquid phase n

The proportion of non-biochemical degradation mass m_2 in the total organic carbon mass m in the liquid phase is n. After multiple numerical simulations, n values of three simulations were set to 2.5%, 3% and 3% respectively, which were the best fitting values. Figure 10 illustrates the influence of different n values on the degradation effect of the coupling model. The values of n were set as 3%, 2% and 1%. For example, at the daily air injection volume of 60 L d^{-1}, the stable value of COD decreased at a rapid rate with the decrease in n because the proportion of organic carbon mass of the biochemical degradation part in the total organic carbon mass in the iquid phase increased with the decrease in n, and the remaining organic carbon in the liquid phase decreased. The value of n slightly influenced the results. Therefore, the values of n used in three simulations were reasonable.

Temperature

As shown in Figure 11, COD exhibited a faster decrease rate with the increase in temperature in the range of 30 °C to 40 °C. However, in the range of 40 °C to 60 °C, the COD decrease rate decreased with the increase in temperature. This phenomenon can be attributed to the following causes. With the increase in temperature within a limited range, the aerobic waste degradation reaction is promoted, and the degradation of organic carbon is accelerated. When temperature exceeded the optimal level, the degradation rate decreased. Therefore, the aerobic waste degradation reaction was restrained. Similar results were observed in other studies. The influence of temperature on degradation effect has investigated, and the optimal temperature is 40 °C (Tremier et al., 2005). McKinley and Vestal (1984) proposed that the optimal temperature of microbial activity ranged within 35 °C to 50 °C. Similarly, Davis et al. (1992) demonstrated that mesophilic microorganisms outnumber thermophilic microorganisms regardless of the stage of the process. In addition, the temperature appears to be a crucial factor that controls nitrogen dynamics in the waste. Increasing temperature (>40 °C) decreased the activity of ammonia and nitrite oxidisers (Grunditz and Dalhammar, 2001). Certain ammonia concentration levels can further inhibit nitrification (Hao et al., 2010; Onay and Pohland, 1998). When

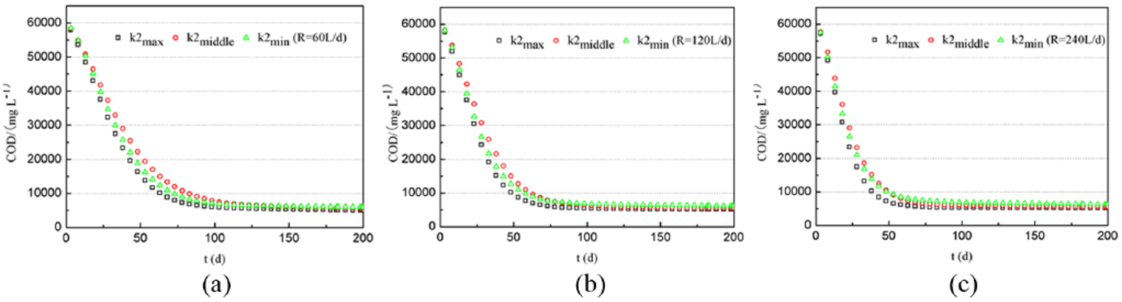

Figure 9. Influence of different k2 on degradation effect of coupling model.

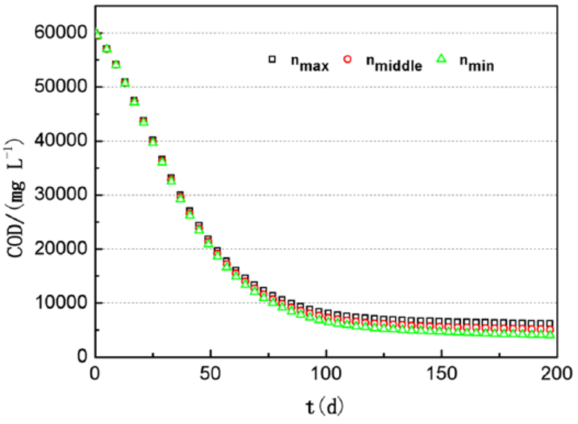

Figure 10. Influence of different n on degradation effect of coupling model.

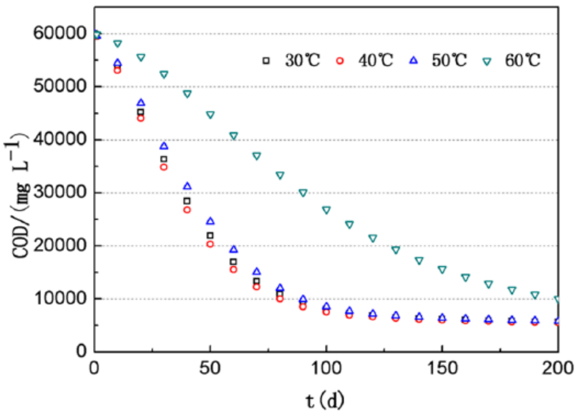

Figure 11. Influence of different temperature on degradation effect of coupling model.

the adopted temperature approached the maximum acceptable temperature (63 °C), the degradation rate considerably decreased. Notably, the temperatures of the three simulations were set to constant ambient temperature levels because of the lack of monitoring data.

Results and discussion

Differences between simulation and experimental results were noted because of the different environment conditions. The difference of COD_0 in three experiments was evident because of different experiment materials. However, the comparison of results showed that the coupling model of aerobic waste degradation considering temperature, initial moisture content and air injection volume can be used to simulate and predict the progress of aerobic waste degradation.

In accordance with Ma et al. (2013), fresh municipal solid waste was used in the experiment, and the air injection mode belonged to intermittent air injection. However, the parameter used in the coupling model calculation was simplified to continuous air injection. Moreover, the waste sample in the laboratory-scale test was a heterogeneous material that could not be uniformly filled with air because of sealed pores. Substances in the coupling model were considered homogeneous, so the aerobic waste degradation reaction was conducted comprehensively. The COD simulation decreased faster than the COD experimental results because of idealised simulation conditions. At the end of the laboratory-scale test, COD simulations were all higher than COD experimental results, possibly because of a high n value. The difference between experimental and simulation results decreased by increasing daily air injection volume because more oxygen remained in waste with the increase in air injection, inducing a comprehensive reaction in the waste. Consequently, the COD experimental result approached the COD simulation results under higher daily air injection volume. In summary, results from the coupling model simulation were similar to the experimental results.

In accordance with Slezak et al. (2010), the experiment was conducted with fresh municipal solid waste and continuous air injection. The COD experimental results decreased faster than the COD simulation results before COD approached stability, possibly because of the addition of compost in the laboratory-scale test. The existence of compost accelerated the aerobic waste degradation reaction in the early stage. However, the COD simulation of aerobic waste degradation from the coupling model yielded similar results to the experimental results.

According to Hrad et al. (2013), the test waste was retrieved from an old landfill, and the air injection mode was continuous air injection. The COD simulation result decreased faster than the COD experimental results in the early stage, then the COD experimental result decreased faster than the COD simulation after the middle stage. This phenomenon could be attributed to the following causes: First, waste was irrigated weekly with 1.2 L of deionised water to accelerate the degradation process, and COD was diluted in the liquid phase; second, the test waste, which was aged 12−31 years, was retrieved from an old landfill. The degradation environment already existed. After the environment reached stability, the aerobic waste degradation reaction of the laboratory-scale test was faster than that of the simulation. However, the COD simulation result was basically consistent with the experimental result.

Parameter sensitivity analyses were conducted according to Ma et al. (2013). Among the parameters, the variation of k2 and n showed less influence on aerobic waste degradation. By contrast, Y, kt and temperature evidently affected the aerobic waste degradation. Therefore, these parameters should be considered carefully in models for future research.

In comparison with other indexes, COD is more conveniently measured. The reliability and applicability of the coupling model of aerobic waste degradation were tested on the basis of the comparison between simulation and experimental results.

Conclusions

On the basis of the first-order kinetics and the law of conservation of mass, the coupling model of aerobic waste degradation considering temperature, initial moisture content and air injection volume was developed. Three different laboratory-scale tests were simulated by the coupling model. Aerobic waste degradation of fresh and aged wastes under intermittent or continuous air injection were simulated and predicted. Simulations were basically consistent with the experimental results. Moreover, parameter sensitivity analyses were conducted. In comparison with other indexes, the COD in the leachate is conveniently measured. In this study, the reliability and applicability of the coupling model of aerobic waste degradation were verified by comparing experimental and simulation results, providing technical support and theoretical basis for the prediction of the waste stabilisation process and can be considered as a basis for selecting the economic air injection volume and appropriate management in the future. However, this study also demonstrated shortcomings. Substances were assumed to be well-distributed in the reactor, but this condition deviates from the actual situation. Most of the water gathers at the bottom of the test device because of gravity; therefore, further research is needed. In addition, the coupling model simulation air injection volume needs to be researched as a method for estimating economic air injection volume in landfills.

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