

**Influence of oxygen flow rate and compost addition on reduction of organic matter
in aerated waste layer containing mainly incineration residue**

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Abstract

Landfilling municipal solid waste incineration (MSWI) residue alkalizes the waste layer, causing a subsequent decrease in microbial activity and a delay in the decomposition of organic matter. In this study, efficiencies of neutralization of the leachate and organic matter decomposition in the waste layer in a column filled with MSWI residue using aeration and compost addition were evaluated. Total organic carbon (TOC) reduction in the waste layer is large at high oxygen flow rate (OFR). To effectively accelerate TOC reduction in the waste layer to which compost was added, a high OFR exceeding that by natural ventilation was required. At day 65, the pH of the leachate when OFR was above $10^2 \text{ mol-O}_2/(\text{day}\cdot\text{m}^3)$ was lower than that when OFR was below $10^1 \text{ mol-O}_2/(\text{day}\cdot\text{m}^3)$. At the same OFR, the pH of waste sample was lower than that of waste sample with compost. Although leachate neutralization could be effected by compost addition, TOC reduction in the waste layer became rather small. It is possible that humic substances in compost prevent the decomposition of TOC in MSWI residue.

Key Words

waste, landfill, aeration, neutralization, acceleration of stabilization

1. Introduction

Landfilling municipal solid waste incineration (MSWI) residue alkalizes the waste layer, causing a subsequent decrease in microbial activity and a delay in the decomposition of organic matter. Landfilling MSWI ratios (incineration/generation) were higher than 50% in Japan, Switzerland, Sweden, and Denmark from 2003 to 2005 (OECD, 2008). However, the waste layer of MSWI residue or incombustible waste still contains organic matter in the form of unburned organic matter (Matsufuji et al., 1980) or wood as contaminant (Sekito et al., 1997). Actually, leachate from the waste layer (MSWI residue and/or incombustible waste) contains organic matter (Hjelmar, 1996; Tanaka et al., 1987; Inanc et al., 2007). The leachate alkalizes the waste layer, causing a subsequent decrease in microbial activity (Matsufuji et al., 1980; Asakura et al., 2007a).

Therefore, from the viewpoint of accelerating landfill stabilization (Stegmann et al., 2003), the waste layer must be neutralized to accelerate the decomposition of organic matter. The authors propose two ways to neutralize the waste layer, i.e., aeration and addition of organic matter. Aeration supplies CO_2 to the waste layer, causing the subsequent neutralization of the alkalized layer and accelerating microbial activity in the aerobic condition (CO_2 should be regenerated by microbial activity.). Organic matter can play the role of a buffer (Cory and McKnight, 2005) and generate CO_2 during decomposition.

In the aerobic condition, neutralization of the waste layer containing mainly MSWI residue (Inanc et al., 2007) and acceleration of organic matter decomposition (Asakura et al., 2007b) can be expected. Many researchers have reported that aeration accelerated organic matter decomposition in landfill that contained much organic waste (Hanashima, 1999; Heyer et al., 1999; O'Keefe and Chynoweth, 2000; Cossu et al., 2001; Read et al.,

2001; Heyer et al., 2005; Ritzkowski and Stegmann, 2005; Tesar et al., 2005; Prantl et al., 2006; Ritzkowski et al., 2006; Bilgili et al., 2008; Erses et al., 2008). However, the oxygen flow rate (OFR) required to accelerate the decomposition is not clear.

Organic matter in the waste layer generates CO₂ after decomposition in the aerobic condition, subsequently acidifying the layer. Therefore, the addition of organic matter and aeration can produce buffer (added organic matter in itself) and acid (CO₂). Through this, we can control the pH of the alkalized waste layer in order to increase microbial activity. It was reported that a mixture of MSWI residue and compost had a lower pH (Ono et al., 2008) and a larger bacterial population (Watanabe et al., 2006) than MSWI residue alone. Therefore, the addition of compost to the MSWI residue can increase microbial activity. The purpose of using compost and not fresh organic matter, such as food waste, is to avoid the drastic generation of landfill gas and organic leachate. In addition, compost contains humic substances, providing pH buffering (Garcia-Gil et al., 2004; Mackowiak et al., 2001). The addition of compost increases organic matter content in the waste layer. Nevertheless, if the addition of compost could neutralize pH in the waste layer to promote microbial activity and accelerate the decomposition of organic matter, the addition would be beneficial.

In this study, efficiencies of neutralization and organic matter decomposition in MSWI residue using aeration and compost addition were evaluated.

2. Materials and methods

2.1. Waste samples

MSWI residue (bottom ash from an incinerator with a grate firing system), shredded municipal bulky solid waste (SBW), shredded industrial incombustible solid waste (SIW), and compost were collected as waste samples from solid waste treatment facilities in Japan. SBW and SIW mainly contained plastic, rubber, metal, glass, and ceramic. Shredded vending machine was used as SIW in this study. Compost was made from sludge of treated night soil and food waste. Samples for examination were prepared by mixing the waste samples. MSWI residue, SBW, and SIW were mixed to yield mixed inorganic waste (MIW). Mixed organic waste (MOW) was prepared by mixing MIW (95 Vol%) and compost (5 Vol%). MIW and MOW are called “mixed samples” hereafter. The mixing ratio of compost was determined with reference to the report of Ono et al. (2008). Table 1 shows the mixing ratios of the waste samples.

Table 1 here

2.2. Experimental method

A column was filled with the mixed samples and known quantities of water (simulating rainfall) and air were introduced into it. Then, in order to evaluate the effect of aeration and compost addition on the acceleration of organic matter decomposition, the characteristics of exhaust gas, leachate, and filled sample were measured (see Section 2.3). The experimental procedure is described as follows.

The column dimensions and the filling conditions are shown in Table 2. The mixed samples (<1 cm) were prepared in the wet state by adding water and mixed to obtain the desired field capacity as determined in a preliminary examination (volumetric moisture content: 0.3). Then, using a tamper, the samples were packed densely and piled to 34.8 cm height in seven steps of approximately 5 cm each in the column of 10 cm inner diameter ($V_{waste} = 2733 \text{ cm}^3$). The total number of columns was eight; one set of four columns were filled with MOW and another set of four columns were filled with MIW.

The filled columns were put in a chamber thermostated at 35°C on the assumption of a mesophile to simulate the high temperature of an actual waste layer, as it is known that waste layer temperatures are often higher than the surrounding temperature (Collins and Muennich, 1993; Houi et al., 1997; Tokyo Metropolitan Government, 1996). The temperatures of the waste layer were reported to be from 33 ± 4 to $55 \pm 5^\circ\text{C}$ in France and from 30 to 65°C in Japan.

Air was introduced into the columns from the bottom by a pump or a syringe. The syringe was used for low air flow rate because it was difficult for the pump to maintain the low air flow rate. Air flow rates for one set of MOW or MIW columns were set at four stages, i.e., 5.0×10^1 or 5.0×10^2 mL-air/day by the syringe, and 7.2×10^4 or 4.3×10^5 mL-air/day by the pump at 1.0 kg/cm^2 pressure. These rates corresponded to OFRs of 1.7×10^{-1} , 1.7×10^0 , 2.5×10^2 , and $1.5 \times 10^3 \text{ mol-O}_2/(\text{day} \cdot \text{m}^3)$ (Table 3) (“m³” indicates waste volume: the unit of OFR is $\text{mol-O}_2/(\text{day} \cdot \text{m}^3)$, hereafter). Exhaust gas was released from the top of the column.

When syringe aeration was adopted, the bottom and top of the column were kept closed. Two syringes were connected to the bottom (for airflushing; filled with air) and the top (for gas collection; empty) of the column. Air corresponding to the daily volume

1 was introduced for one minute from the column bottom every day. The volume of
2 exhaust gas in the top syringe was measured and the gas was analyzed by gas
3 chromatography.

4 In regard to the column set with the pump, the top of the column was always open.
5 Air was humidified by forcing the air flow to pass through a bottle containing distilled
6 water and then introduced into the columns from bottom to top continuously to prevent
7 drying of the filled sample (in the case of syringe pumping, humidification of air flow
8 was not required due to the low air flow rate adopted). Exhaust gas was collected with
9 the syringe that was inserted into the exhaust gas outlet and analyzed by gas
10 chromatography.

11 When the pump was stopped for a few minutes or immediately after aeration by
12 the syringe, distilled water was injected by the syringe from the top of the column every
13 day and the leachate was collected from the column bottom. The volume of injected
14 water was 35 mL/day, which corresponded to the annual precipitation in Japan, i.e.,
15 approximately 1600 mm/yr. The aeration test period was 65 days. A schematic diagram
16 of the aeration apparatus is shown in Fig. 1.

17 The following were measured: physical and chemical properties of the mixed
18 samples before and after aeration, and chemical properties of the exhaust (and injection)
19 gas and the leachate during the aeration test period.

20
21 Table 2 and 3 here

22 Fig. 1 here
23
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2.3. Analytical procedure

In regard to the physical and chemical properties of the mixed samples, moisture content (105°C, 24 hr), particle density (pycnometer method, JIS A 1202), LOI (600°C, 3 hr), total carbon (TC_{solid}), inorganic carbon (IC_{solid}), and TOC (TOC_{solid} = TC_{solid} – IC_{solid}; SHIMADZU TOC-5000A and SSM-5000A) were measured. The detection limit of TOC_{solid} was 50 mg-C/g.

In regard to the chemical properties of the leachate and the exhaust gas, pH (electrode method), TC, IC, and TOC (SHIMADZU TOC-5000A) of the filtrate (0.45 µm pore size) from the leachate, and oxygen [GC-TCD GC-8A (Shimadzu); molecular sieve 5A; carrier gas, He; oven temperature, 50°C; injector temperature, 110°C], and CH₄ and CO₂ [GC-FID GC 390B; Methanizer MT221 (GL Sciences) and H₂ gas; Porapak Q; He for carrier gas; 50°C for oven, 70°C for injector, 150°C for detector, and 385°C for methanizer] of the exhaust (and injection) gas from the column were measured. The detection limits of TOC, oxygen, CH₄, and CO₂ were 5 mg-C/L, 0.1 Vol%, 1 ppmv, and 5 ppmv, respectively.

3. Results

3.1. Changes in physical and chemical properties

Table 3 shows the characteristic changes of the mixed samples by aeration. After the aeration test, LOI decreased, ranging from 68 to 94% of the original contents. In addition, TOC_{solid} of the mixed samples decreased to approximately 77 to 98% of the original while IC_{solid} increased to 104 to 198% of the original.

Changes in the concentrations of oxygen and CO₂ in the exhaust gas are shown in Figs. 2 and 3, respectively. Oxygen concentrations in the exhaust gas were approximately equal to that in the outside air when OFR was above 10². Below 10¹ OFR, oxygen concentrations decreased around days 10 to 30 and increased thereafter. The oxygen concentrations of MIW were low compared with those of MOW during the aeration test below 10¹ OFR. Meanwhile, the CO₂ concentrations of MIW were higher than those of MOW. The maximum concentrations of CH₄ were 25 ppmv for MOW and 35 ppmv for MIW at 1.7×10⁻¹ OFR (data not shown). In regard to injection gas, the average concentrations of oxygen, CO₂, and CH₄ were 20.9 Vol%, 380 ppmv, and 2 ppmv, respectively (n = 13).

Changes in pH and TOC of the leachate are shown in Figs. 4 and 5, respectively. At day 65, the pH of the leachate when OFR was above 10² was lower than that when OFR was below 10¹. At the same OFR, the pH of MOW was lower than that of MIW at day 65. When OFR was below 10¹, TOC increased up to day 20 and decreased thereafter. The maximum values of TOC were 880 mg-C/L for MOW and 370 mg-C/L for MIW when OFR was above 10², and 2700 mg-C/L for MOW and 2030 mg-C/L for MIW when OFR was below 10¹. Therefore, the maximum TOC in the leachate when OFR is above 10² could be reduced to less than half of the maximum TOC when OFR is below 10¹.

Fig. 2, 3, 4, and 5 here

3.2. Carbon balance

Carbon balance around the column before and after the aeration test, i.e., input (carbon in the original sample and inflow as CO_2 in air) and output (carbon in the aerated residue and outflow as exhaust gas and leachate), was determined by measuring $\text{TOC}_{\text{solid}}$, IC_{solid} , and weight of filled sample; CH_4 and CO_2 concentrations in inflow and outflow gas and the mixed gas volume; and TOC and IC in leachate and the leachate volume. The carbon balances are summarized in Table 3 and Fig. 6.

The ratio of carbon output to input ranged from 98 to 101%. Therefore, the authors considered that the measured items and the obtained values for carbon were reasonable, and gas containing carbons other than CH_4 and CO_2 in the exhaust gas, i.e., volatile fatty acid, was negligible in this study. The difference in $\text{TOC}_{\text{solid}}$ (14.5 kg-C/m^3) between the original filled MOW and MIW samples was a result of the addition of compost. The amount of CO_2 in the outflow gas was smaller than that in the inflow gas. Especially in regard to MIW, IC_{solid} increased as $\text{TOC}_{\text{solid}}$ decreased. The amount of increased IC_{solid} was larger than that of carbon in the outflow gas and the leachate.

Fig. 6 here

4. Discussion

In this section, two problems in the acceleration of the decomposition of organic matter in the alkalized waste layer containing mainly MSWI residue, i.e., the relationship between OFR and organic matter reduction, and the effect of compost addition on the acceleration of organic matter reduction, are discussed. Figure 7 shows

the relationship between OFR and $\text{TOC}_{\text{solid}}$ reduction, with pH of leachate (at day 65) as parameter. The range of OFR by natural ventilation (amount of oxygen introduced to a semi-aerobic landfill by convection and diffusion flow) previously reported by the authors (Asakura et al., 2010) in the same experiment is also shown in Fig. 7. $\text{TOC}_{\text{solid}}$ reduction of MOW and MIW was large at high OFR. Ritzkowski and Stegmann (2003) also reported that $\text{TOC}_{\text{solid}}$ can be reduced by aeration. As the plot for MIW is a convex, the acceleration of $\text{TOC}_{\text{solid}}$ reduction could be effected at an OFR that is lower than the OFR by natural ventilation. On the other hand, as the plot for MOW is a concave, a higher OFR than that by natural ventilation is required.

The addition of compost decreased the pH of the leachate. One of the reasons is that organic matter in the added compost acted as a buffer (Garcia-Gil et al., 2004). However, in this study, we found that the effect of increasing OFR on decreasing pH was larger than that of compost addition. The increased IC_{solid} probably neutralized the filled samples. Furthermore, as regards the amount of compost added in this study, $\text{TOC}_{\text{solid}}$ reduction in the run of compost addition (MOW) was less than that of MIW. Therefore, although leachate neutralization could be effected by compost addition, $\text{TOC}_{\text{solid}}$ reduction became rather small. $\text{TOC}_{\text{solid}}$ reduction could be accelerated by increasing OFR, rather than by adding compost.

Furthermore, the oxygen concentrations of MIW were relatively low compared with those of MOW during the aeration test below 10^1 OFR. Therefore, compost addition reduced oxygen consumption. The results indicate that TOC in MSWI residue and incombustible waste could be decomposed more easily than that in compost. Compost contains stable organic matter, such as humic substances (Garcia et al., 1991). Hamamura et al. (2009) pointed out that a larger amount of stable organic matter was

1 contained in compost made from sewage sludge than in compost made from food waste.
2 Piccolo et al. (1999) have shown that hydrophobic domains in humic substances prevent
3 the microbial activity associated with water. Therefore, it is possible that humic
4 substances in compost prevent the decomposition of TOC in MSWI residue and
5 incombustible waste. When organic matter is used to neutralize waste layer containing
6 mainly MSWI residue and increase microbial activity, the use of compost having a high
7 content of humic substances should be avoided.

8
9 Fig. 7 here
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12 **5. Conclusions**

13 In this study, efficiencies of neutralization and organic matter decomposition in
14 MSWI residue using aeration and compost addition were evaluated. The main findings
15 are as follows.

- 16 1. Total organic carbon (TOC) reduction in the waste layer is large at high oxygen
17 flow rate (OFR).
- 18 2. To effectively accelerate TOC reduction in waste layer to which compost is
19 added, high OFR exceeding that by natural ventilation is required.
- 20 3. Although leachate neutralization could be effected by compost addition, TOC
21 reduction in the waste layer became rather small.

22 From the above, TOC reduction in the waste layer could be accelerated by
23 increasing OFR, rather than by adding compost. It is possible that humic substances in

compost in MSWI residue and incombustible waste prevent the decomposition of TOC in MSWI residue and incombustible waste. When organic matter is used to neutralize waste layer containing mainly MSWI residue and increase microbial activity, the use of compost having a high content of humic substances should be avoided.

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Table 1. Properties of waste samples

	Unit	MOW ^a	MIW ^b
MSWI residue	Vol %	47.6	50.0
Shredded municipal bulky solid waste	Vol %	19.0	20.0
Shredded industrial incombustible solid waste	Vol %	28.6	30.0
Compost	Vol %	4.8	0.0

^aMixed organic waste, ^bMixed inorganic waste

Table 2. Properties of filled mixed samples in columns

			MOW	MIW
Column size	Inner diameter	cm	10.0	
	Height	cm	34.8	
	Volume for waste layer (V_{waste})	cm ³	2733	
Filling condition	Dry weight	g-dry	2873	2912
	Dry bulk density	g-dry/mL	1.1	1.1
	Porosity	–	0.50	0.51

1 Table 3. Characteristic changes of mixed samples by aeration

			Mixed organic waste (MOW)					Mixed inorganic waste (MIW)						
Aeration by		—	—	syringe	syringe	pump	pump	—	syringe	syringe	pump	pump		
		mL-air/d	—	5.0×10 ¹	5.0×10 ²	7.2×10 ⁴	4.3×10 ⁵	—	5.0×10 ¹	5.0×10 ²	7.2×10 ⁴	4.3×10 ⁵		
Air/oxygen flow rate		m ³ -air/(d·m ³)	—	3.8×10 ⁻³	3.8×10 ⁻²	5.5×10 ⁰	3.3×10 ¹	—	3.8×10 ⁻³	3.8×10 ⁻²	5.5×10 ⁰	3.3×10 ¹		
		mol-O ₂ /(d·m ³)	—	1.7×10 ⁻¹	1.7×10 ⁰	2.5×10 ²	1.5×10 ³	—	1.7×10 ⁻¹	1.7×10 ⁰	2.5×10 ²	1.5×10 ³		
			Original	After aeration				Original	After aeration					
Moisture content		%	15.2	24.9	19.6	19.8	18.5	13.4	18.6	22.3	21.4	20.9		
Particle density		kg/L	2.1	2.3	2.2	2.3	2.2	2.2	2.2	2.3	2.4	2.2		
Loss on ignition		%	9.3	6.7	8.7	7.4	7.7	7.2	5.3	6.2	4.9	6.2		
Carbon _{solid}	TOC _{solid}	%-C	4.1	3.9	4.0	3.8	3.7	2.6	2.4	2.2	2.1	2.0		
	IC _{solid}	%-C	1.1	1.2	1.2	1.4	1.9	1.2	1.4	1.6	1.9	2.4		
Original & inflow	Solid	TOC _{solid}	kg-C/m ³	—	42.6	42.6	42.6	42.6	—	28.1	28.1	28.1	28.1	
		IC _{solid}			11.9	11.9	11.9	11.9		12.8	12.8	12.8	12.8	
	Gas	CH ₄			<0.1	<0.1	<0.1	<0.1		<0.1	<0.1	<0.1	<0.1	<0.1
		CO ₂			<0.1	<0.1	1.3	7.6		<0.1	<0.1	1.3	7.6	
	Subtotal (A)				54.5	54.5	55.7	62.0		40.9	40.9	42.2	48.5	
Carbon balance	Solid	TOC _{solid}	kg-C/m ³	—	41.3	41.9	40.3	38.5	—	25.4	23.1	21.9	21.8	
		IC _{solid}			12.4	12.3	14.9	20.2		14.8	17.2	19.8	25.3	
	Gas	CH ₄			<0.1	<0.1	<0.1	<0.1		<0.1	<0.1	<0.1	<0.1	<0.1
		CO ₂			<0.1	<0.1	0.3	2.0		<0.1	<0.1	0.3	1.1	
	Leachate	TOC			0.9	0.9	0.2	0.2		0.6	0.5	0.1	0.1	
		IC			<0.1	<0.1	<0.1	<0.1		<0.1	<0.1	<0.1	<0.1	
	Subtotal (B)				54.7	55.1	55.8	61.0		40.7	40.8	42.1	48.4	
	Total outflow (gas & leachate) (C)				1.0	0.9	0.6	2.3		0.6	0.6	0.4	1.3	
TOC _{solid} reduction		kg-C/m ³		1.3	0.8	2.3	4.1		2.7	5.0	6.2	6.3		
Outflow rate (C) / (A)		%	—	1.8	1.7	1.1	3.7	—	1.4	1.4	1.0	2.6		
Balance (B) / (A)		%		100	101	100	98		100	100	100	100		

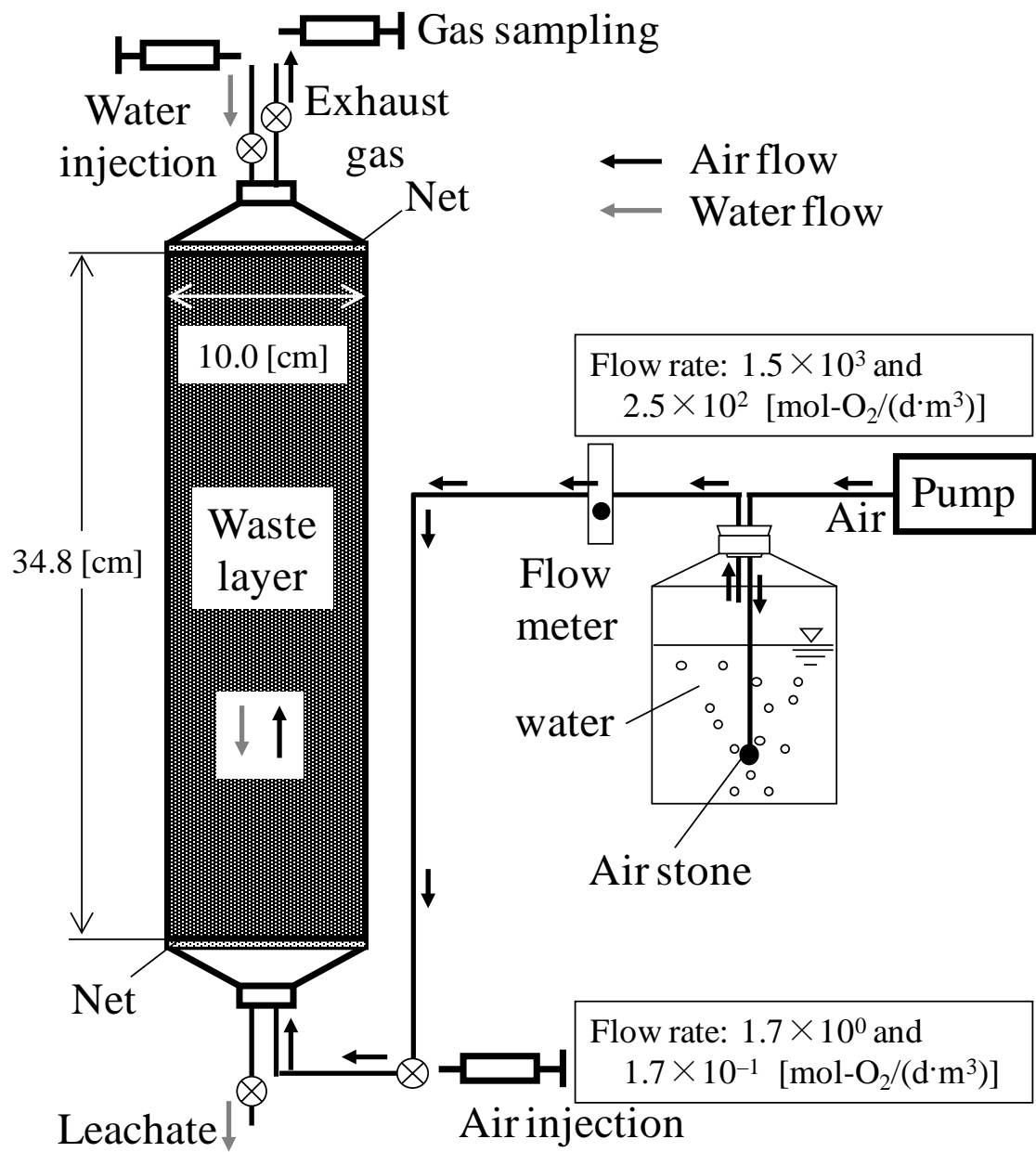


Figure 1. Schematic diagram of aeration apparatus

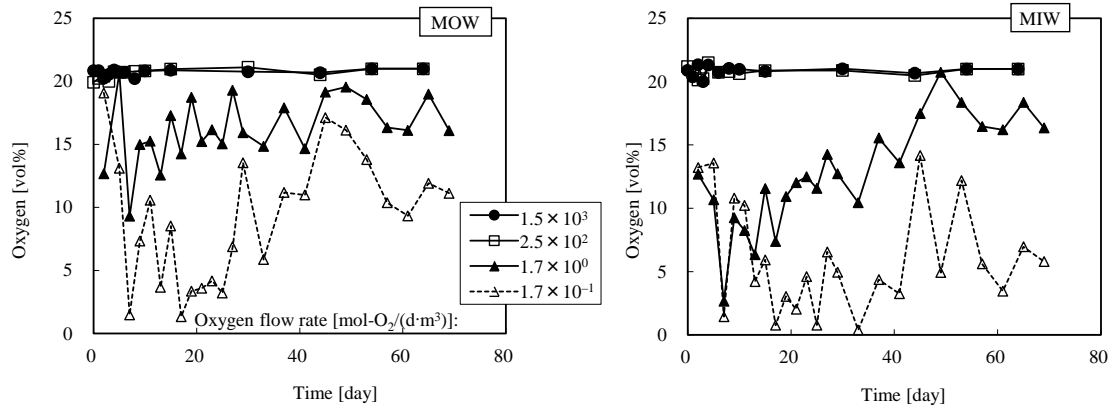


Figure 2. Changes in concentration of oxygen in exhaust gas

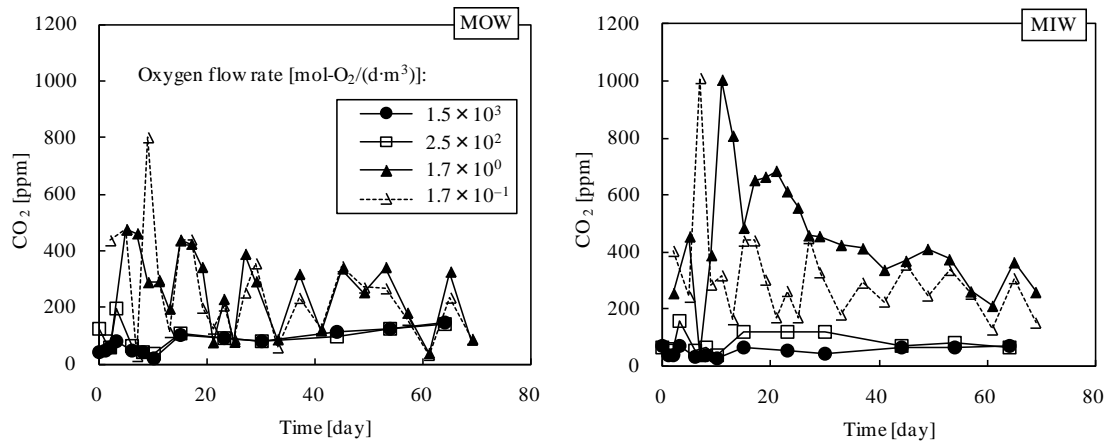


Figure 3. Changes in concentration of CO₂ in exhaust gas

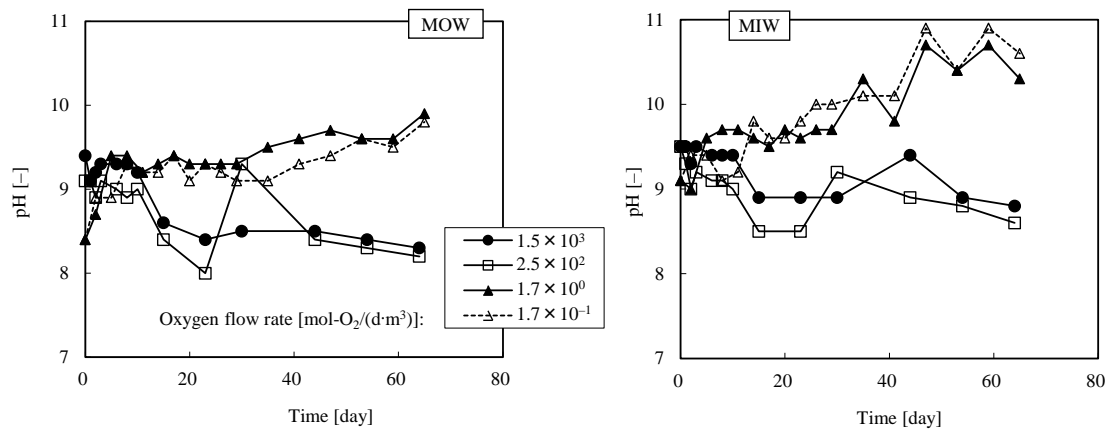


Figure 4. Changes in pH of leachate

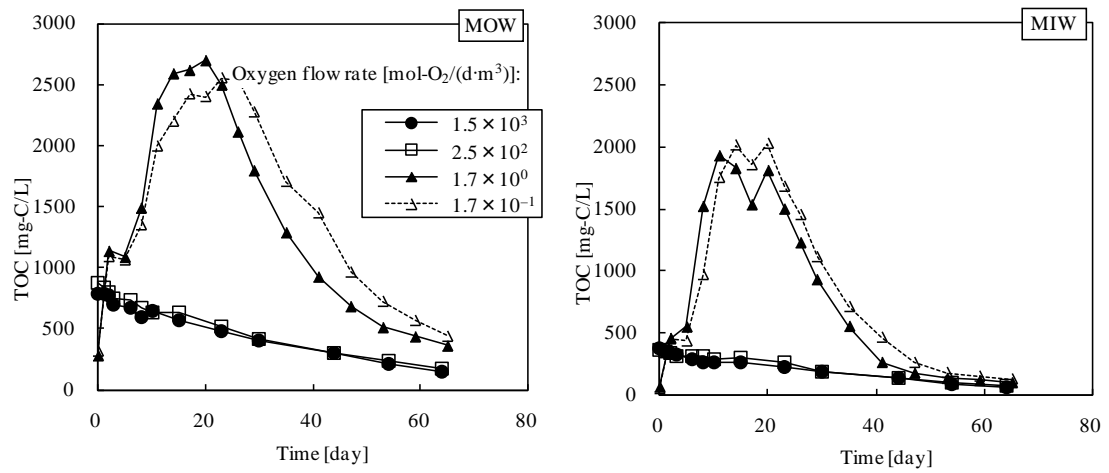


Figure 5. Changes in TOC in leachate

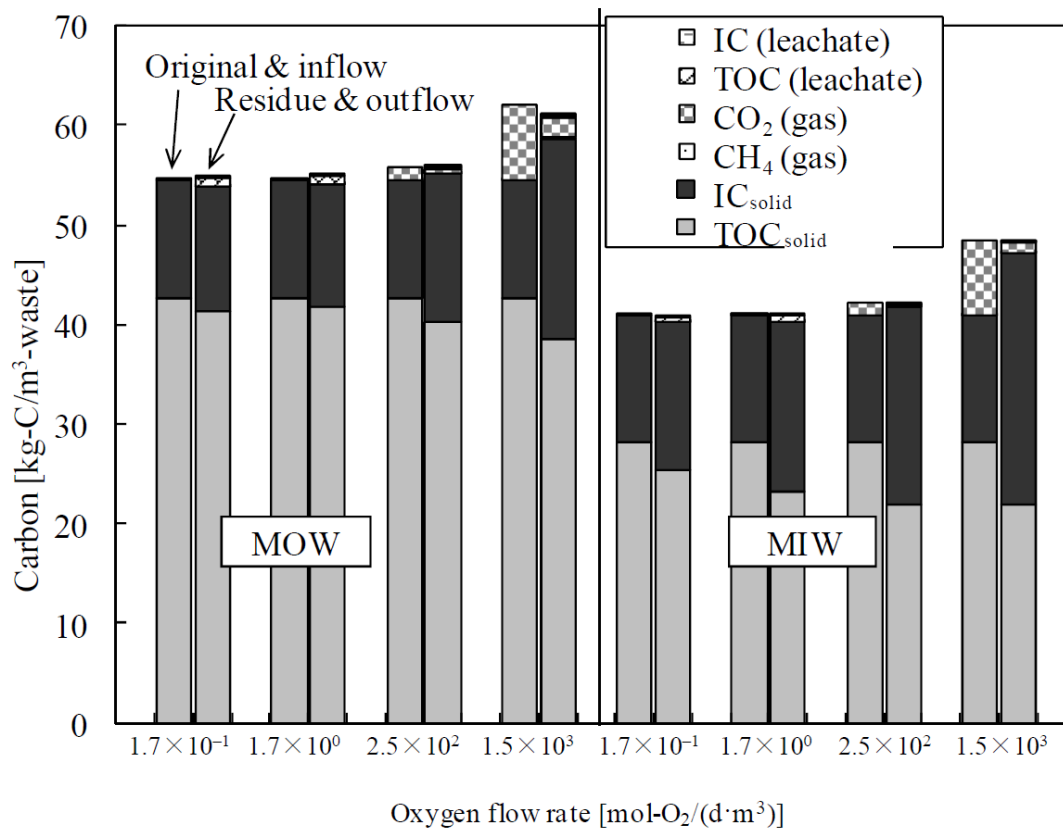


Figure 6. Carbon balance

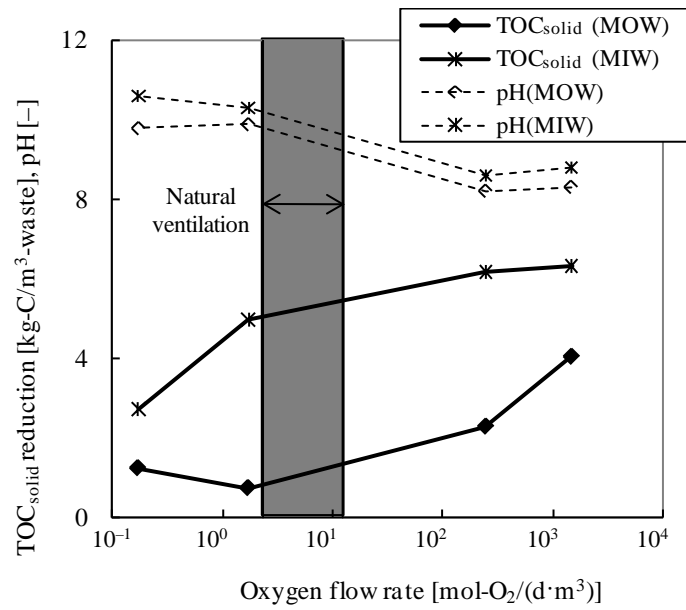


Figure 7. Relationship between oxygen flow rate and TOC_{solid} reduction, with pH of leachate as parameter (at day 65)