Assessment of internal condition of waste in a roofed landfill

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Abstract

Recently, roofed landfills have been gaining popularity in Japan. Roofed landfills have several advantages over non-roofed landfills such as eliminating the visibility of waste and reducing the spread of offensive odours. This study examined the moisture balance and aeration conditions, which promote waste stabilisation, in a roofed landfill that included organic waste such as food waste. Moisture balance was estimated using waste characterization and the total amount of landfilled waste. Internal conditions were estimated based on the composition, flux, and temperature of the landfill gas. Finally, *in situ* aeration was performed to determine the integrity of the semi-aerobic structure of the landfill.

With the effects of rainfall excluded, only 15% of the moisture held by the waste was discharged as leachate. The majority of the moisture remained in the waste layer, but was less than the optimal moisture level for biodegradation, indicating that an appropriate water spray should be administered. To assess waste degradation in this semi-aerobic landfill, the concentration and flow rate of landfill gas were measured and an *in situ* aeration test was performed. The results revealed that aerobic biodegradation had not occurred because of the unsatisfactory design and operation of the landfill.

Keywords: Roofed landfill, food waste, moisture balance, landfill gas, *in situ* aeration test.

1. Introduction

Recently, the number of roofed landfill sites has increased in Japan. The first roofed landfill was built in July 1998, and as of 2010, 54 roofed landfills had been constructed or were under construction, accounting for approximately 2% of municipal solid waste (MSW) landfill sites (NPO·LSCS, 2009).

In a roofed landfill, the landfill area is enclosed by a roof and walls so that waste is not visible from the outside. The roof is either fixed after closure or removable. The latter type is used for landfills that are partitioned into several compartments, where a roof is moved from a closed area to the next active area. Eleven roofed landfills in Japan have a removable roof. The fabric of the roof is a translucent plastic membrane or steel folded plate. The landfill volume is relatively small, generally ranging from 1900 m^3 to 311,200 m^3, and there are only five roofed landfills in Japan that have a volume of 100,000 m^3 or larger. In Japan, a high percentage of MSW is incinerated, and thus landfilled waste consists mainly of incombustibles and incineration residues. Of the 54 roofed landfills, food waste is landfilled in only two sites.

The increasing popularity of roofed landfills stems from increasing awareness by residents and local governments of the advantages of this type of landfill. Roofed landfills 1) avoid the dirty image associated with landfills since waste is not visible from surrounding areas, 2) prevent the scattering of waste and dust and the spread of offensive odours, 3) produce a low and constant volume of leachate by controlling moisture input (cutting off natural rainfall and spraying regulated amounts of water), and 4) allow for easy use if the landfill is constructed underground or if the roof is constructed with concrete (Toge et al.,2004; Nagumo, 2004).

In roofed landfills, water supply is the key factor to promote stabilization. Otsuka et al. (2008) studied the removal of salt from several landfills containing different types of waste. The removal rate was correlated with the liquid/solid (L/S) ratio, and a macroscopic model was developed to determine the optimal precipitation rate. Ishii et al. (2004) performed experiments on the leaching of total organic carbon from incineration residue using a cylindrical acrylic column. The intensity and frequency of spraying water were modified to determine optimal conditions. Hasegawa et al. (2010) used a 20 m^3 lysimeter packed with incineration residue to determine the accumulated L/S ratio to meet effluent standards for biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total nitrogen (TN). Nagata et al. (2004) and Kohinata et al. (2008) studied the leaching behaviour of organic matter (BOD, COD, TN) and inorganic matter (Ca, Cl, and electrical conductivity). Nagata et al. (2004) recirculated leachate in four experimental tanks packed with incineration residue. On the other hand, Kohinata et al. (2008) performed their studies in three real-scale landfills and measured the concentration of landfill gas and the waste temperature.

Most studies on roofed landfills have focused on incombustible waste and incineration residue, and there has been no previous report of a roofed landfill in which organic waste is deposited. However, because of the advantages described above, roofed landfills are expected to be attractive in other countries where mixed waste is landfilled without incineration or recycling of the organic fraction. Therefore, studies on roofed landfills with organic waste will be helpful for future use of this type of landfill.

This study examined a roofed landfill containing organic waste (including food waste). Landfill regulation in Japan obligates operators to monitor water quality of treated leachate discharging into environment and groundwater upper and lower point of landfill as environmental monitoring. Only after closure, landfill gas emission, temperature of landfilled waste, and leachate quality before water treatment are added in monitoring list for terminating aftercare. Therefore, data on monitoring internal condition of landfills is very limited.

In this study, the moisture balance and aeration conditions, which are the most important factors for promoting waste stabilization, were emphasized.Moisture balance was estimated based on waste characterization and the amount of waste landfilled, and internal conditions were estimated based on the composition, flux, and temperature of landfill gas. Finally, *in situ* aeration was performed to determine the integrity of semi-aerobic structures in the landfill.

2. Landfill description

2.1 Structure of the landfill site

Figure 1(a) shows a general view of the studied landfill. The landfill covers an area of 27,000 m^2 and is divided into four compartments. The first compartment was used from October 2007 to August 2010, after which the roof was moved to the second compartment which was in use as of 2012. The roof is made of translucent plastic membrane, which allows for sun penetration to the landfill. This landfill has the second largest capacity among roofed landfills in Japan and is scheduled to be used until 2017.

The leachate collection and drainage pipe is made of perforated high-density polyethylene (HDPE). The diameter of the main pipe is 40 cm and the branch pipe is 20 cm. There are 12 branch pipes placed at intervals of 20 m in every compartment. The gas vent is made of perforated polyethylene pipe 20 cm in diameter. Six pipes are placed in each side at intervals of 20 m, but there is no gas vent in the centre of the compartment.

The internal arrangement is shown in Figure 1 (b). The leachate collection and drainage pipe was covered with a protective layer (0.5 m depth). Collected leachate is drained gravitationally through the HDPE pipe (25 cm in diameter) to the leachate pit, where the leachate is automatically pumped to the regulating reservoir when leachate levels are increased and treated at the leachate treatment system. The volume of the regulating reservoir is 1300 m^3. This landfill is designed as a semi-aerobic landfill in which gas vents and leachate collection pipes are interconnected. Air is introduced from the lower end of the leachate collection pipe by natural convection (Matsufuji et al., 2007). In addition, perforated polyethylene pipes (diameter 10 cm) are placed horizontally on the top of every waste layer to connect gas vents on the two sides. The length of the horizontal perforated pipe is 3240 m.

2.2 Landfill operation

There are a total of five layers, each with 2 m of solid waste (excluding the top layer). To improve the aeration of waste, a 250-mm layer of scallop shells was placed around the horizontal perforated pipe. No intermediate cover was placed over the waste.

As shown in Table 2, food waste is disposed of in this landfill. To reduce the odour, indoor air is vacuumed by a blower (50 m^3/min) connected to gas vents at side B. Collected air is deodorized using an activated carbon tower (biological deodorization is expected) and discharged to the atmosphere. The blower was operated 200–300 hours every month from April 2008 to August 2010. Additionally, 27 roof fans (200 m^3/min) were installed at the top of the roof to ventilate air. The total number of active fans fluctuates according to the temperature. Typically, seven fans are active in summer and four are active in winter.

The leachate treatment system is composed of biological treatment, coagulating sedimentation, filtration, and activated carbon adsorption. The leachate is circulated to the landfill in 68% of roofed landfills. However, in this landfill leachate is discharged to the environment. The geomembrane liner at the bottom consists of a double polyethylene sheet and a single bentonite sheet.

2.3 Closure of the first compartment

The first compartment was filled with waste in August 2010. Prior to that, closure work was initiated. In July 2010, two thirds of the top area was covered with a capping sheet, which is impermeable to water but permeable to air. Water sprinklers (40 cm in diameter) were placed at intervals of 2 m to spray 0.28 m^3/min. Movement of the roof started on 5 August 2010 and was completed 13 days later. In October 2010, the other one third of the capping sheet and water sprinkle pipe were finalized and completed in one day. The final cover with a depth of 1.5 m was constructed between November 2010 and June 2011.

2.4 Monitoring of the first compartment

Moisture and temperature in the waste layer were monitored in this landfill using a SM200 soil moisture sensor (Delta-T Devices) and Chino MC1000 series handheld digital thermometer. Figure 2 shows the locations of the sensors. Gas vents are numbered from G1 to G12.

Figure 3 illustrates the changes in temperature and moisture, with average values of each month plotted. Sensors were installed as landfilling operations proceeded in the order of S1 to S8. S1–S4 and S5–S8 are located in the centres of the second and fourth waste layers, respectively. This landfill is equipped with a leachate leak detection system. When a leak is detected, waste is excavated to repair the liner defect. Before September 2009, repair work was not completed and very low temperature and moisture levels were recorded several times. Excluding these irregular changes, temperature and moisture were stable for more than half a year.

The temperature of S1 to S4 changed independently. S1 increased gradually until the beginning of 2009 and maintained a high temperature of approximately 55°C. S3 had high temperature of 60°C until early 2009, which decreased to 30°C by September 2009. S4 was approximately 40°C, slightly lower than S1 and S3, and the behaviour of S2 was similar to that of S4. These differences in temperature can be explained by landfill operations. Because waste was landfilled layer by layer, S1 and S3 were originally located at depths of 1 m from the surface, allowing for the diffusion of air to promote aerobic biodegradation. In April 2009, however, a leak was detected between S2 and S3, and the excavated waste (to repair the liner defect) was placed on S3. In S4, waste was placed vertically from the second layer to the third layer. Therefore, diffusion of air was reduced by the thick layer of waste on S3 and S4, and the temperature decreased due to limited aerobic biodegradation. S5 and S6 maintained a temperature of 45^{o}C, whereas S7 and S8 were 30^{o}C. Unlike the other areas, waste was piled up to the fifth layer on S5 and S6, reducing air diffusion.

As mentioned in 2.3, this landfill is constructed as a semi-aerobic landfill, and horizontal perforated pipes were placed on top of every waste layer. If the semi-aerobic structure is functioning properly, the temperature should be constantly high. Although the behaviour of S2 was not precisely explained, temperature was dependent only on oxygen diffusion from the atmosphere, and oxygen supply through gas vents and horizontal pipes was not significant.

Figure 4 shows the amount of leachate. As mentioned in 2.2, the amount of leachate was measured when it was pumped from the pit to the regulating reservoir in the leachate treatment facility. After closure of the first compartment, leachate from the second compartment was collected together at the pit. The amount of leachate was approximately 200 tons per month in July 2010 and increased significantly after the roof was moved. After the roof was moved, rainfall permeated the landfill and increased the leachate between August 2010 and October 2010. The thick final cover was put in place in November 2010. The weight load not only lead to compaction of waste, but also increased hydraulic pressure in void space of waste, which resulted in leachate generation.

As shown in Figure 3, the temperature and moisture content of S7 and S8 increased suddenly from January 2011. Although the timing is not identical to the increase in leachate in Figure 4, it was likely caused by rain and the added moisture of activated aerobic biodegradation. This suggests that the moisture content was not sufficiently high for the aerobic microorganisms in the organic waste landfill.

3. Moisture balance

Although volumetric moisture contents were continuously measured by sensors, gravimetric moisture content is helpful to estimate moisture balance and to better understand the condition of waste in the landfill. In this section, moisture balance is discussed based on the amount and characterization of waste and leachate generation in the first compartment.

3.1 Composition of landfilled waste

Solid waste in the first comportment is summarized in Table 1. In the municipality which owns this roofed landfill, waste paper, beverage cans, glass, and PET bottles are recovered, but other household waste is landfilled, including food waste. In addition to waste from commercial and business sectors, industrial waste is also disposed of in this landfill (In Japan, sewage sludge is categorized as industrial waste, not municipal waste.)

To estimate the moisture contained in the waste, MSW compositions are assumed as shown in Table 2. Composition data were obtained from the composition analysis performed by the municipality in 2005. In both household waste and business and commercial waste, food waste accounts for the largest percentage.

3.2 Moisture content of waste

The moisture content of each component in Table 2 was estimated based on previously reported values. Waste samples for composition analysis are usually taken from a waste storage pit in an incinerator, but the composition in Table 2 was determined for waste collected from households. In this case, the moisture content of each component differs from those measured for well-mixed waste taken from an incinerator pit by minimizing moisture transfer between components. Therefore, literature values obtained using similar sampling methods were selected. Waste samples were collected from collection points for categories a (Japan Waste Management Association, 2006) and c (Tokyo Institute of Cleaning, 1992) in Table 2. For category b (Matsuo et al., 2011), paper and plastic constitute a separate collection category of mixed paper and plastics. Furthermore, food waste in plastic bags was sampled from the combustible waste category to determine the actual moisture content.

The average value of moisture content was used, except for food waste for which the range of the moisture content was considered because of the large percentage of food waste both in household waste and business and commercial waste. Regarding industrial waste, sewage sludge was sampled and moisture content was determined in triplicate to be 81%. The same value was assumed for business and commercial sludge. For all other waste, water content was neglected because of minor amount.

Estimated moisture contents were 36.5–47.9% for household waste, 28.5–39.4% for commercial and business waste, and 78.6% for industrial waste.

3.3 Moisture content in the first compartment

The landfill has a water sprinkler, but the sprinkler had not been used during the landfilling operation. Therefore, water held by waste and the weight of dry waste can be calculated in the following manner:

$$W = \Sigma \text{ waste amount} \times \text{moisture content} - \Sigma \text{ leachate amount} \tag{1}$$

$$M = \Sigma \text{ waste amount} \times (1\text{- water content}) \tag{2}$$

$$\text{Average moisture content} = W / (W+M) \tag{3}$$

The values calculated using data in Tables 1 and 2 and Figure 4 are W = 22,197–27,324 tons, M = 32,487–27,353 tons, discharged leachate = 3215 tons, and average moisture content = 37.0–46.8%. Of the total moisture input into the landfilled waste, 85% was held in the landfill and only 15% was discharged as leachate.

3.4 Relationship between volumetric and gravimetric moisture content

To confirm the accuracy of the above estimation, moisture contents were compared with the values measured using the sensor. Gravimetric moisture content and volumetric moisture content are defined by equations in Figure 5, and their relationship can be expressed as Eq. (4):

$$\theta=\rho_T \times \omega \qquad (4)$$

in which θ: volumetric moisture content, ω: gravimetric moisture content, and ρ: wet bulk density.

The first compartment had a volume of 64,750 m^3, of which 12,176 m^3 was occupied by the protective layer, horizontal perforate pipe, scallop shells, and final cover. Because 54,677 tons of waste was disposed of, the wet bulk density was calculated as 54,677 / (64,750–12,176) = 1.04 t/m^3, which is similar to the published value of 0.7–1.48 t/m^3 (Japan Society of Civil Engineers, 2004). By substituting the measured volumetric moisture content (36–45% in Figure 3) and the bulk density in Eq. (4), gravimetric moisture content was estimated to be 34.6–43.3%. This range is consistent with the range of 37.0–46.8% given in section 2.4; both ranges are lower than the optimal composting moisture content of 50–60% (Fujita, 2002). As mentioned in section 2.4, the moisture content was not sufficiently high for aerobic microorganisms and thus appropriate water spray should have been supplied.

4. Gas characteristics

4.1 Objectives of gas measurement

This landfill was designed as a semi-aerobic landfill, which is thought to promote waste stabilization. When aerobic biodegradation occurs, organic waste can be transformed to gas and exit through the gas vent. Therefore, landfill gas was sampled at gas vents to determine the gas composition, which could reflect the internal state of the waste on 7 July 2011. To measure the gas velocity, concentration, and temperature, a hot wire anemometer (Kanomax 6531), a portable gas analyzer (GA2000Plus, Geotechnical Instruments) and CHINO Handy-Logger thermometers were used, respectively.

4.2 Gas concentration in the gas vent

Gas concentrations in the gas vents from G1 to G6 (see Figure 2) are shown in Figure 6. Because the gas vents were covered (there are 15 holes with diameters of 1 cm), the covers were removed one day prior to measurement.

Figure 6 shows the correlations between oxygen and nitrogen and between carbon dioxide and methane. In the left figure, the line indicates the ratios of oxygen and nitrogen in the air (79% nitrogen, 21% oxygen), which should be kept when air is diluted by landfill gas. The ratio of oxygen in the gas vent was slightly lower than that in the air, which may have resulted from aerobic decomposition. Since oxygen consumed by aerobic decomposition is converted to carbon dioxide, the ratio of carbon dioxide on the right side of the figure includes the increase in CO_2 generation by aerobic biodegradation. Meanwhile, H_2S was measured as 14–85 ppm, with an average of approximately 40 ppm.

4.3 Gas velocity and temperature in the gas vent

Kim et al. (2010) reported that the oxygen/nitrogen concentration ratio of landfill gas was much less than that in the air, and that the gas velocity released from the gas vent was in the range of 0.3 to 1.2 m/s. These results suggest that a large mass of oxygen is consumed by aerobic biodegradation. The fact that the gas temperature was 30^{o}C higher than the environment also supports the occurrence of aerobic biodegradation. Kim et al. (2010) examined a landfill in which gas vents were installed after closure and not connected to the leachate collection pipes.

The present study found a minor decrease in oxygen concentration, and the velocity at the gas vent exits was only 0.08–0.43 m/s. The gas temperature ranged from 17–24^{o}C, while the atmosphere temperature ranged from 28–31^{o}C. The gas temperature was lower than the atmosphere temperature. These values for landfill gas and the monitoring observations shown in Figure 3 indicate that the semi-aerobic structure was not functioning properly at the studied landfill.

5. *In situ* aeration test

5.1 Procedure

To evaluate the possibility of forced aeration for waste stabilization, *in situ* aeration was performed. When air is injected, all flowing gas should be measured for total concentration and flux to determine the mass balance. Therefore, the gas extraction method was applied. As shown in Figure 7, three of the gas vents located in side B were connected to a blower which was used for odour control (see 2.2). To maximize aeration of waste by vacuuming, nine other vents were scheduled to be closed. However, when the *in situ* aeration test was initiated on 14 October 2011, other vents were open to measure the volume of gas collection in the pipe network. The gas velocity in the gas extraction pipe (diameter: 30 cm) was measured, and gas concentration was determined. A Marunisayiensu L-Pitot tube and Kanomax 6531 anemometer were used to measure the gas velocity.

5.2 Extracted gas

Figure 8 shows the flow rate of vacuumed gas in the main pipe. The flow rates in gas vents which connected with the main pipe are also shown. When gas extraction was initiated, some leakage points were found around the pipe joints, requiring repair work. Although the total flow rate of three gas vents was lower than the flow rate in the main pipe, gas could be extracted through the gas vents. The flow rate of the extracted gas was almost half of the maximum ability of the blower (50 m^3/min).

5.3 Gas concentration

If all gas vents are connected, air should be vacuumed from vents kept open during the aeration test. As shown in Figure 9, CH_4 and CO_2 were detected at relatively high concentrations in all gas vents. Moreover, H_2S was detected up to 304 ppm in open gas vents. That is, when gas is extracted from gas vents at one side in the landfill, landfill gas flows out from gas vents at the other side. This suggests that the gas vents do not form a network of aeration pipes.

Even if the gas vents are not connected, gas extraction can collect landfill gas from the waste layer and supply air for aerobic biodegradation. However, gas extracted by the blower contained minor amounts of CO_2 at 0.1% and no CH_4. During seven days of *in situ* aeration tests, the concentrations of CO_2 and CH_4 did not increase. Air might have collected only in the void spaces formed in the landfill, reducing the probability of *in situ* aeration of the waste layer.

6. Summary and conclusion

The main findings obtained from this study will be useful for future landfill design and operation, and are as follows:

1) The studied landfill is a semi-aerobic landfill, in which gas vents and leachate collection pipes form a pipe network to supply outside air by natural convection. In the surveyed landfill, there are 12 gas vents at the side of the landfill, but they have several bends (see Figure 1(b)) which could be clogged by the waste loading. Vertical gas vents located at the centre of a landfill would be effective for natural convection, but there were no vertical gas vents installed in this landfill. The lower end of a leachate collection pipe is usually open to the atmosphere to “breathe” air, but in this case it was placed in a closed pit. Overall, the structure of the studied semi-aerobic landfill is not appropriate.
2) The greatest advantage of a roofed landfill is the ability to control moisture content by diverting rainfall. This reduces the chances of leachate build-up in the landfill and overflow of leachate to the outside during the rainy season or during an occasional heavy rain. In the studied landfill, however, moisture content was lower than the optimal level for biodegradation because no moisture was added. Appropriate water spray should have been provided.
3) The final cover was placed just after the first compartment was filled. According to the monitoring data, aeration was mainly provided by diffusion from the surface of

the landfill. Therefore, prompt placement of the final cover was not a good decision for aerating the waste. The thick soil layer might have reduced the void space by compaction and make aeration of waste more difficult.

4) The internal conditions of waste in the landfill could be estimated by monitoring temperature and moisture, and by measuring the concentration of landfill gas. The analysis indicates that appropriate procedures (such as spraying water, placing vertical gas vents, and placement of a final cover) should have been performed.

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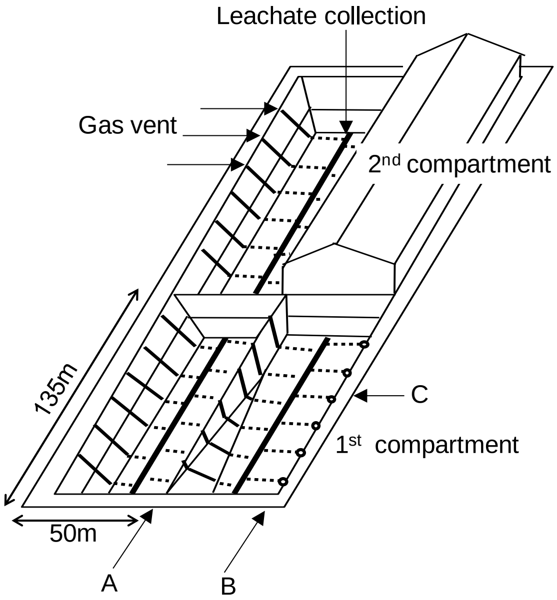
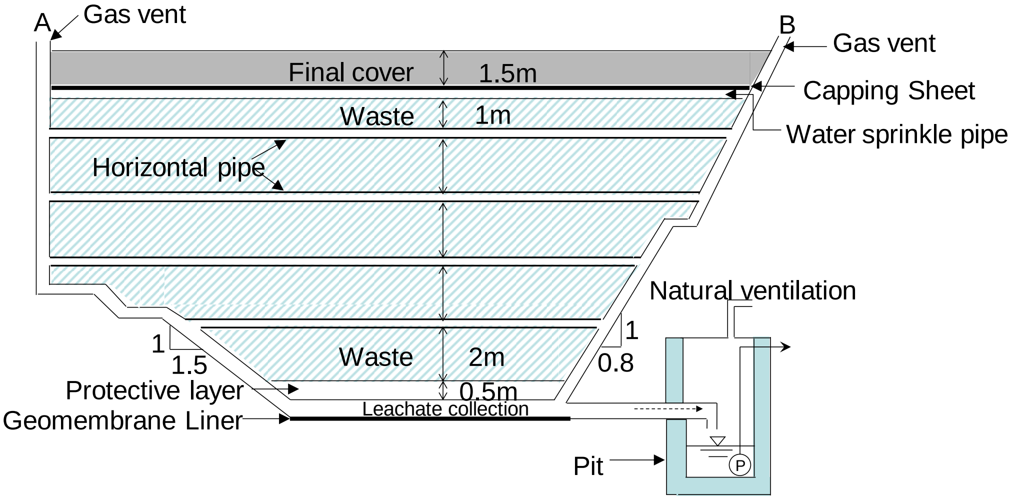


(a) Plan view of general arrangement



(b) Cross-sectional view at C

Figure 1 Schematics of studied landfill

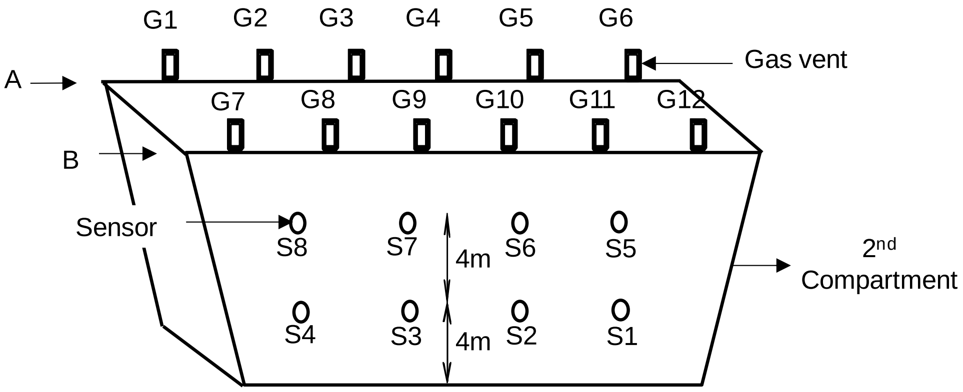
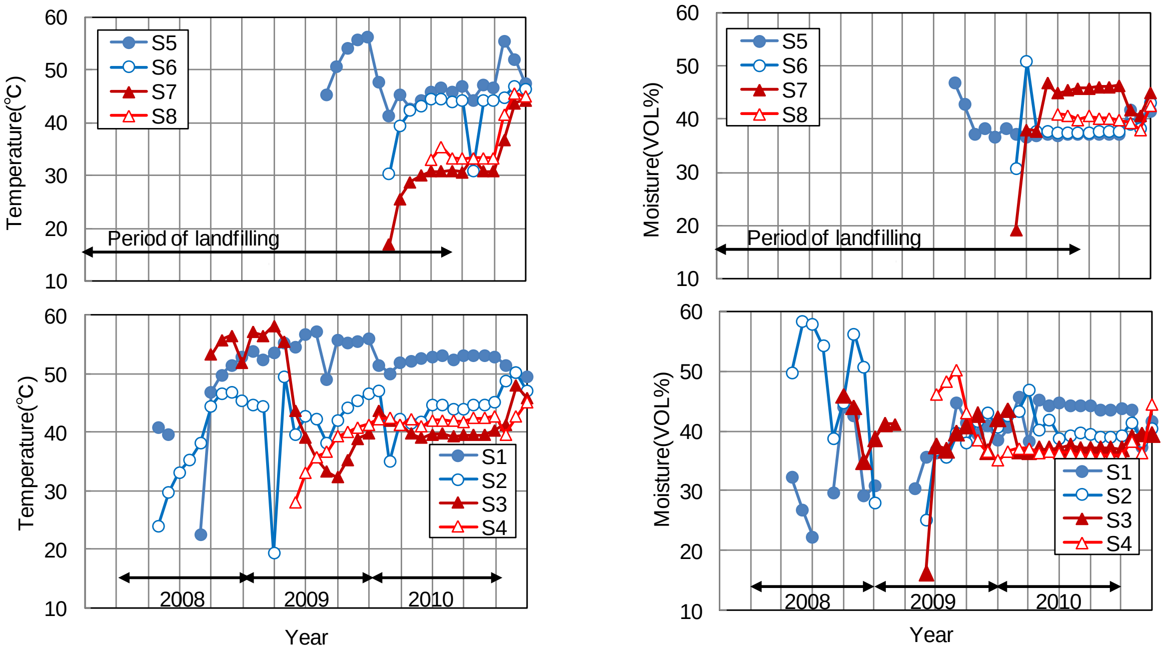


Figure 2 Location of sensors



(a) Temperature of first compartment (b) Moisture of first compartment

Figure 3 Temperature and moisture of first compartment

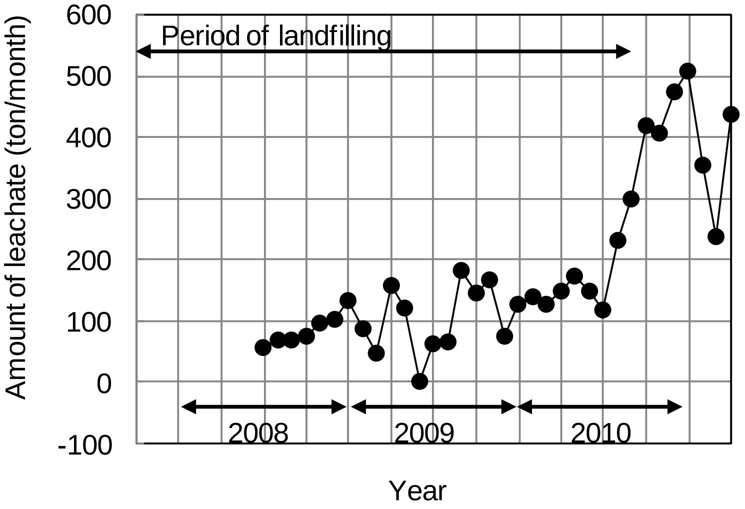


Figure 4 Leachate production

	Mass	Volume
Air	Ma	Va
Water	Mw	Vw
Solid	Ms	Vs

Moisture content

$$\text{Volumetric } \theta = \frac{Vw}{Vs + Vw + Va}$$

$$\text{Gravimetric } \omega = \frac{Mw}{Ms + Mw + Ma}$$

$$\text{Wet bulk dencity } \rho_T = \frac{Ms + Mw + Ma}{Vs + Vw + Va}$$

in which Ma=0, Mw=$\rho_w \cdot$Vw, ρ_w=1

Unit : M(ton), V(m^3), ρ(ton/m^3)

Figure 5 Relationship between volumetric and gravimetric moisture content

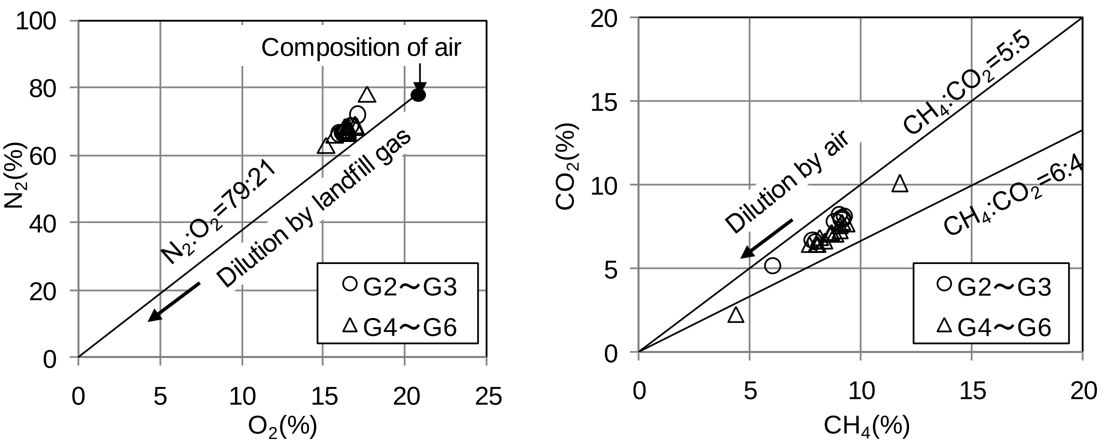


Figure 6 Gas concentration observed at gas vents (7, July, 2011)

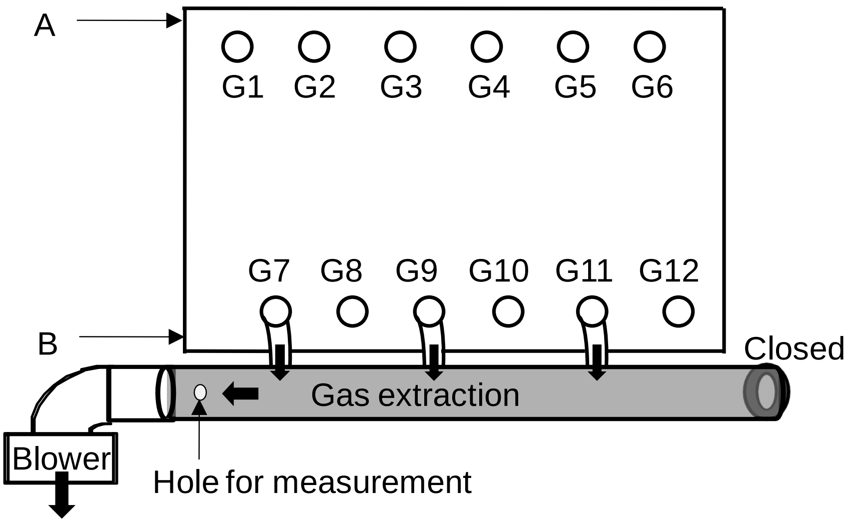


Figure 7 Layout of gas extraction system

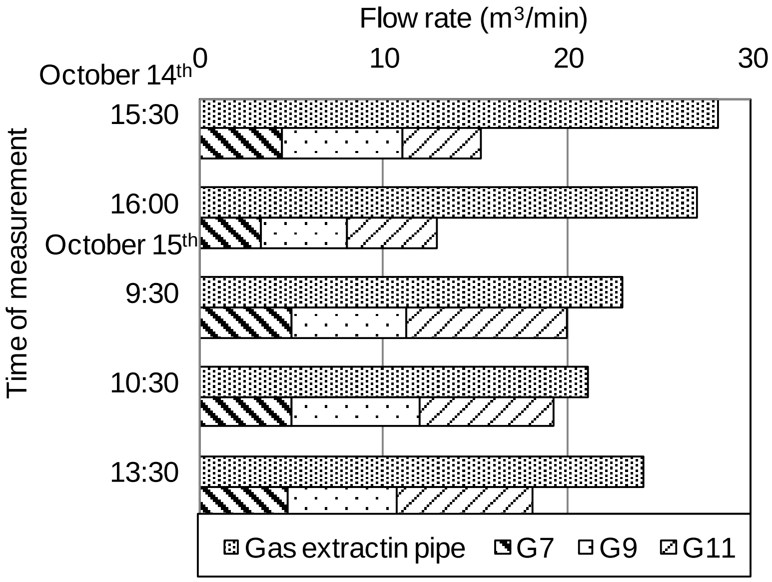


Figure 8 Flow rate at collected gas vents and gas extraction pipe

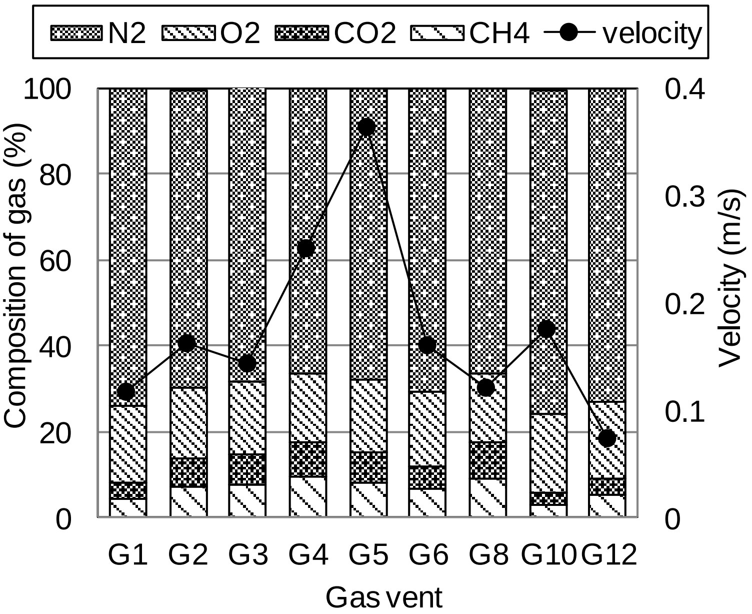
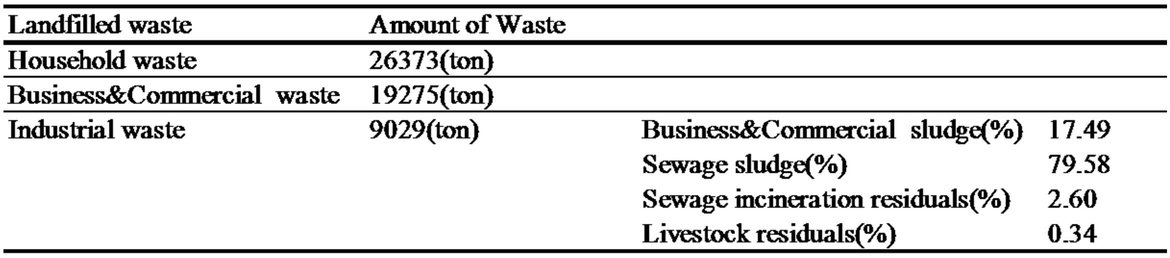


Figure 9 Gas velocity and composition at opened gas vents

Table 1 Total waste amount of first compartment



Landfilled waste	Amount of Waste		
Household waste	26373(ton)		
Business&Commercial waste	19275(ton)		
Industrial waste	9029(ton)	Business&Commercial sludge(%)	17.49
		Sewage sludge(%)	79.58
		Sewage incineration residuals(%)	2.60
		Livestock residuals(%)	0.34

Table 2 Waste component and assumed moisture

Waste component		Composition(%)		Moisture(%)			Assumed value(%)
		Household waste	Business&Commercial waste	a	b	c	
Waste Papers	News paper	6.43	4.39	8.9	6.2		8.9
	Magazines	0.28	0.54	5.2	3.1		5.2
	Corrugated cardboard	4	2.31	7.6	7.7		7.6
	Paper bag	0.52	0.22	5.8	5.7		5.8
	Other papers	4.19	5.39	7.2			7.2
Containers and pakages	Aluminum can	0.17	0.47			8.52	8.52
	Steel can	0.57	1.62			3	3
	Glasses	1.69	2.12			1.99	1.99
	Reusable glass bottle	0	0.15				
	Plastics	13.46	12.92	1			1
Combustibles	Food waste	47.41	35.19	69.6	81.8	70.6	70-80
	Office paper	0.18	2.51	6.3			6.3
	Waste paper	14.3	15.4	6.8		13.63	6.8
	Textile	1.55	4.28	3.34		9.13	3.34
	Wood	1.66	1.2	34.5		20.25	34.5
	Other combustible	0.52	1.19			48	48
Incombustibles	Polyvinyl chloride	1.18	0.84	0.3			0.3
	Rubber and leather	0.14	0.35	5.4		5.42	5.42
	Expanded polystyrene tray	0	0.08				
	Flexible plastics	0.18	0.28			9.71	9.71
	Rigid plastics	0.64	3.08			1.52	1.52
	Pottery and glass	1.3	1.07			1.3	1.3
	Metal	0.75	2.91			3.38	3.38
	Other incombustible	1.3	1.58			7.59	7.59