Evaluation of air injection and extraction tests in a landfill site in Korea: implications for landfill management

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Abstract Air extraction and injection were evaluated for extracting hazardous landfill gas and enhancing degradation of organic materials in a landfill in Korea. From the pilot and full-scale tests, the following results were obtained. The pressure radii of influence varies with direction (anisotropy). A smaller oxygen radius of influence compared with the pressure radius of influence was observed in the landfill where the oxygen consumption rate was relatively high. This was in contrast to a petroleum-contaminated site, where the oxygen radius of influence was estimated to be larger than the pressure radius of influence. The increase in the pressure radius of influence was relatively small compared with the increase in air injection rate. When air was injected at a flow rate of 1 pore volume, the air temperature inside the landfill material increased by up to 20 °C because of a calorific reaction. It was also observed that the air-extraction system recovered landfill gas (LFG), and also enhanced aerobic degradation of landfill materials. Methane oxidation occurred during the continuous air injection, which was supported by a decrease in the CH_4/CO_2 ratio. Oxygen consumption rate for the air injection was larger than that for the LFG extraction. Furthermore, the intermittent air injection appeared less effective in landfill stabilization than the continuous injection when they are applied to an active younger landfill with larger oxygen consumption rates, whereas the reverse is the case when applied to an aged landfill.

Keywords Aeration · Korea · Landfill · Methane oxidation · Oxygen consumption

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Introduction

Over the last several years, concern has grown regarding the release of potential air pollutants from landfills. Control of gas movement is primarily used to prevent outgas from damaging plants and property, or from causing injury to human health. Methane (CH_4) generated in landfills kills vegetation and displaces oxygen from the root zone. Furthermore, methane accumulates in buildings and, if its concentration exceeds a lower explosive limit of 5%, there may be a gas explosion (Campbell 1996; Stegmann 1996). Landfill gas (LFG) collection systems remove the landfill gas under a vacuum from the landfill or the surrounding soil formation. These systems use gas-recovery wells and vacuum pumps to provide migration control and/or the recovery of methane for use as an energy source. A pipe network is built to interconnect the wells and the blower equipment. When the primary purpose is migration control, the recovery wells are constructed near the perimeter of the landfill. Depending on site conditions, these wells may be placed in the waste itself, or in the soil immediately adjacent to the landfill. The location of the recovery wells depends on the site characteristics, including type of soil formation and type of waste in the landfill.

Solid waste initially decomposes aerobically. The primary gas product is carbon dioxide (CO_2). As oxygen is depleted, facultative and anaerobic microorganisms will predominate. These microorganisms continue to produce carbon dioxide, but the process proceeds into anaerobic decomposition, in which methane and carbon dioxide are produced in approximately a 60/40 ratio. In addition, other compounds are produced and additional chemicals are released into the air surrounding the landfill by volatilization.

The main components of LFG after relatively short times after disposal are 55±5% of CH_4 and 45±5% of CO_2

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(Rettenberger and Stegmann 1996). These concentrations remain relatively constant, whereas higher methane concentrations can be observed in an older landfill. A change in LFG composition within the landfill will take place when oxygen enters into the landfill (Stegmann and others 2000). Oxygen may enter the landfill by natural diffusion from the atmosphere, but this is limited to the uppermost part of the landfill. If a substantial vacuum is created within the landfill by extensive gas extraction, and/or forced air injection occurs, air enters the landfill; this accelerates waste decomposition and inhibits methane generation in the influenced area.

Landfills can produce severe environmental impacts via secondary pollution, such as landfill gas and leachate. Even after a landfill has stopped accepting new solid wastes, there will be continuous LFG production, sometimes for an additional 20–30 years (Augenstein and Pacey 1991). The methane gas generated, besides being an environmental threat, represents a potential explosion hazard. Closed landfills should be treated using proper technologies to recover landfill space and environment. The landfill stabilization phases are mainly composed of initial methanogenic and stable methanogenic phases, which are relatively longer periods of degradation (Christensen and Kjeldsen 1989). Reduction of these periods can offer some important advantages in the management of landfills, including enhanced land usage and minimized long-term liabilities.

Some aeration technologies may be applied to minimize the period of the anaerobic degradation, which changes landfill conditions from anaerobic to aerobic. The air-based remedial technologies, such as air injection and LFG extraction, which have been widely used in the remediation of petroleum-contaminated soil, may be applicable to landfills to achieve early stabilization. In this study, the feasibility of aeration processes was evaluated for extraction of hazardous gas and/or enhancement of degradation of organic materials in a landfill in Korea.

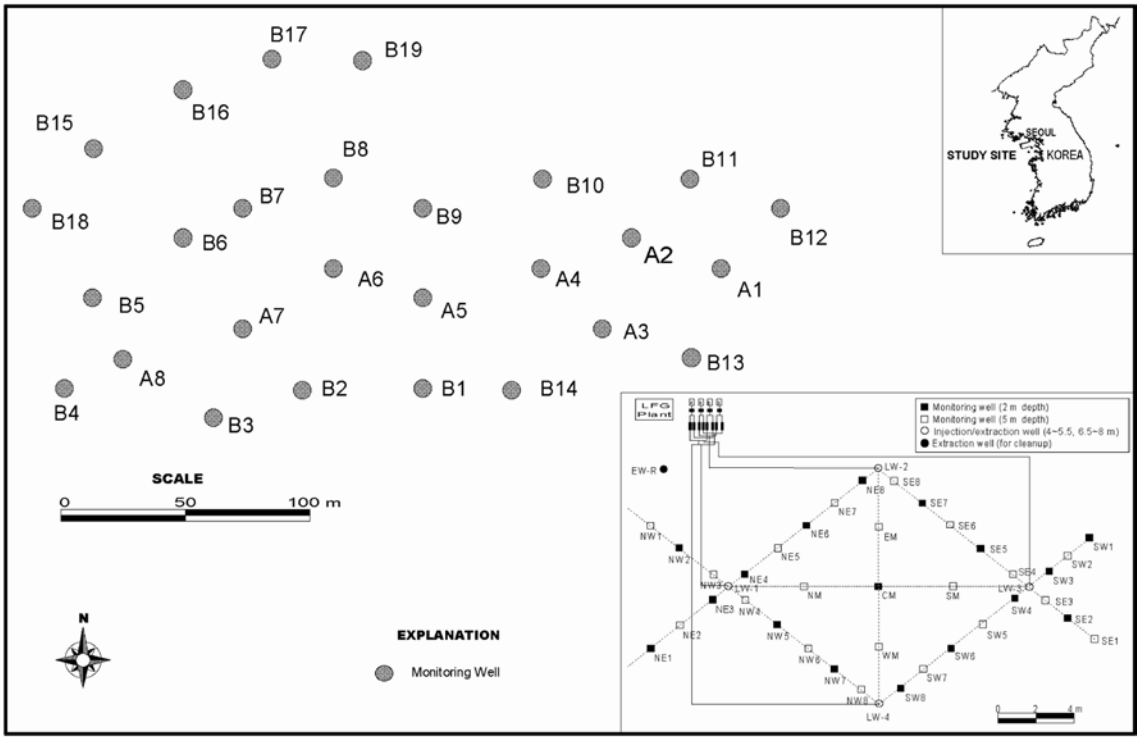
Materials and methods

The landfill under study is 5 km west of Seoul, Korea (Fig. 1). The landfill has a surface area of approximately 222,480 m^2 and a 590,000 m^3 volume of waste. The landfill was in operation from February 1990 to December 1992. The average composition of the solid wastes dumped at this site was 60% biowastes, 17% industrial wastes, and 23% construction wastes.

The equipment for the experiments was set up at areas where decomposition was in progress. The equipment included a blower system for injection and extraction. Injection and extraction wells and monitoring wells were constructed. The injection and extraction systems were designed to apply various kinds of injection/extraction methods. Two types of monitoring wells were constructed at different depths (2 and 5 m) and these were equipped to measure gas pressure, landfill gas and oxygen concentrations, and air temperature.

The injection experiment was conducted first, to prevent any problems that may arise during the extraction. A portable infrared meter (GA94, Geotechnical Instruments) was used for the LFG analysis.

Fig. 1
Location of the study site and layout of the test wells



Results of pilot scale tests

Background LFG composition and gas pressure

The LFGs of the landfill under study were investigated before air injection and extraction tests. The gas sample was collected after extracting a volume of gas in the observation wells. Measured gas concentration, pressure, and temperature at the landfill are summarized in Table 1. The extent of biological reactions may change with time because the interior of the landfill is a kind of biological reactor. So the preliminary measurements of LFG composition before the tests was conducted to understand the gas transport characteristics and to use the measurements as background data.

To a certain extent, the gas pressure within the landfill varies according to location and depth (see Table 1). In this landfill, the gas pressure at a depth of 5 m is 30–50 mm H_2O, but at a depth of 2 m it is below 2 mm H_2O. The large difference in gas pressure is because of the intermittent cover layering, which means that horizontal gas flow is dominant in the landfill. The horizontal flow characteristics should be considered when the LFG extraction and air injection are applied, and extraction or injection depth are decided.

The increase in the internal pressure is a result of the production of gas and increase in temperature within the landfill. The pressure increase plays a vital role in the emission of the LFG to the atmosphere. It can be said that the pressure of the landfill at a depth of 2 m is more readily released than that at 5 m.

Radius of influence

In general, the radius of influence is the distance from the injection or extraction point at which a pressure change of 0.25 cm H_2O (or 0.1 inch H_2O), or about 10% of the injection or extraction pressure, is observed (USACE 1995; Suthersan 1997; Toy 1997; Lee and others 2002). Because the performance of air extraction is highly affected by the pressure distribution, a pressure radius of influence should be estimated. Nevertheless, the distance to which an effective oxygen concentration is transmitted should also be considered in the air injection. Figure 2 shows the radius of influence at this landfill. The pressure radius of influence is greater than that based on oxygen propagation; furthermore, it varies with the monitoring direction, which would indicate anisotropic characteristics within the landfill body. If a monitoring well is located within the radius of influence of an air injection or vapor-extraction well it will experience an increase in oxygen concentration after a time lag from the start of air injection or pumping. A radius of influence for an air-injection system can also be estimated based on observed oxygen concentration at the monitoring point in an oxygen-consuming condition. Because most landfills are under oxygen-limiting conditions, some of the oxygen supplied will be consumed by respiration of indigenous microorganisms during air transmission. Therefore, the observed oxygen concentrations at the monitoring points were lowered. This phenomenon should be considered when determining the effective radius of influence with oxygen.

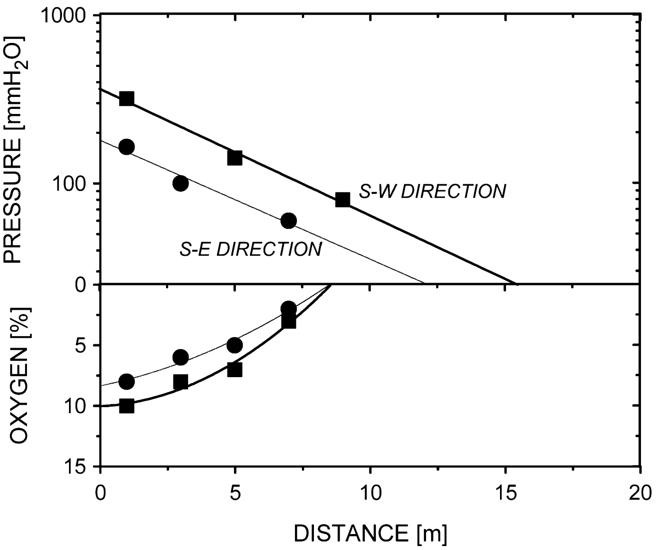


Fig. 2
Radii of influence with respect to pressure and oxygen at the landfill

Change in flow rate and pressure

Injection or extraction rates and pressures are the most important factors in the system design. Stabilized gas pressures at the monitoring wells are shown against flow rate in Fig. 3a. The rise in pressure at the monitoring wells was not directly proportional to an increase in the flow rate. The radius of influence estimated from the pressure measurements varies with flow rate. As the flow rate increases, the pressure at the wellhead and the radius of pressure influence also increase. However, the degree of the increase in the radius of influence was relatively small compared with that in the flow rate.

Table 1
Summary of characteristics of the study landfill including gas pressure, temperature, methane (CH_4), carbon dioxide (CO_2), oxygen (O_2), and flow rate

Location	Observed depth[a] (m)	Pressure (mm H_2O)	Temperature (°C)	Methane (%)	Carbon dioxide (%)	Oxygen (%)	Flow rate (l/h)
"K" landfill	2[b]	1.6±0.5[c]	39.2±1.9	57.2±1.6	42.8±1.6	0.0±0.0	2.8±11.6
	5	45.7±16.3	38.9±1.8	58.2±1.3	41.8±1.3	0.0±0.0	81.7±21.8

[a] Depth below ground surface
[b] Number of observation points is 23
[c] Mean ± standard deviation

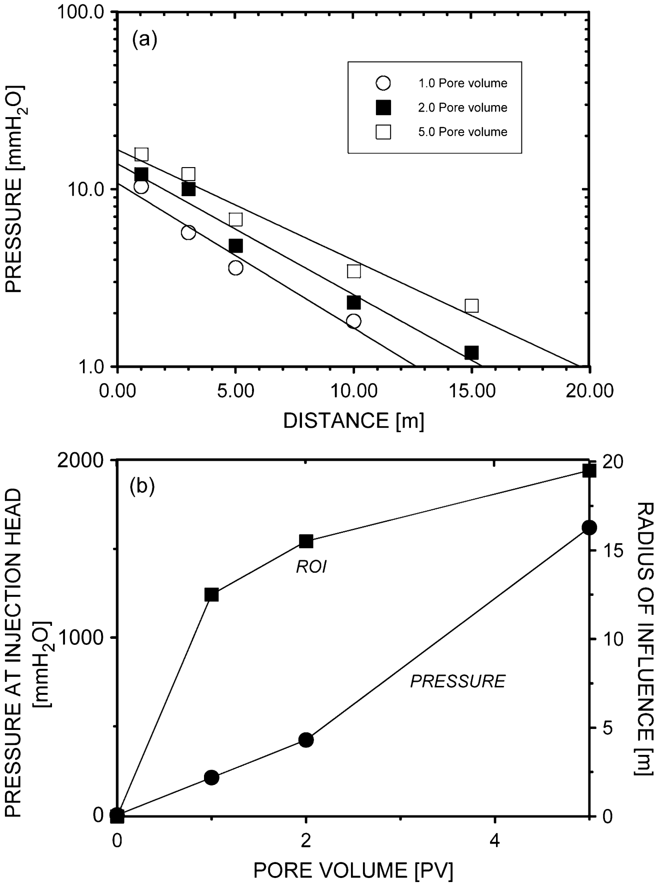


Fig. 3a, b
Changes in pressures and radius of influence during air injection

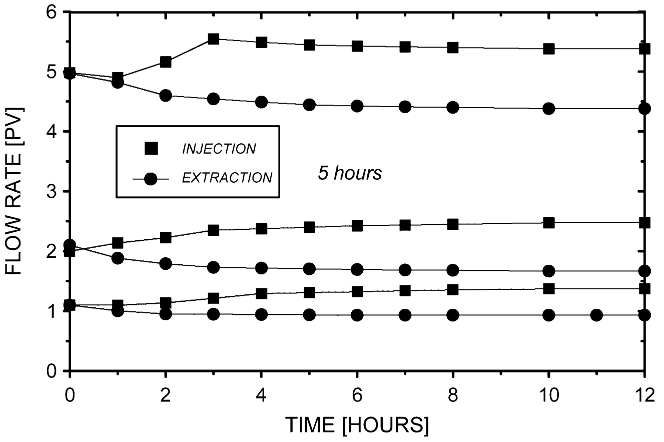
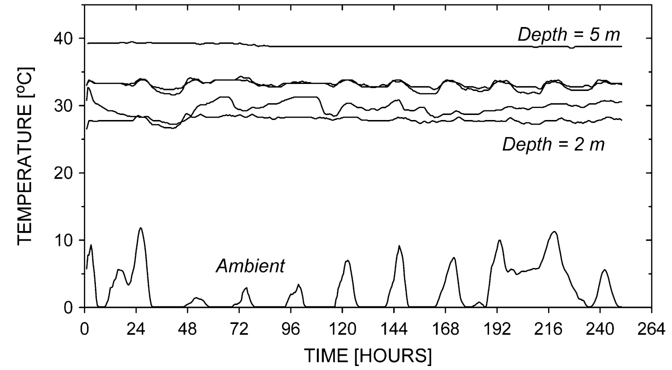


Fig. 4
Changes in flow rate during air injection and extraction

(a) Background



(b) During air injection

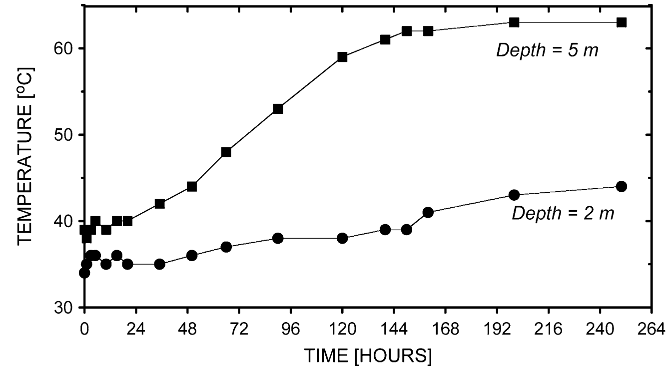


Fig. 5
Results of air temperature monitoring: **a** background, **b** during air injection

The pressure increases linearly up to a small flow of 2 pore volumes, which satisfies Darcy's law, but the pressure increases as a curve when the flow is higher, which is a so-called slip phenomenon (Fig. 3b). Efficiency of the pressurization was lower in extraction than in injection at higher flow rates. Therefore, a larger flow appeared comparatively efficient in extraction and a smaller flow rate was effective in injection. In this study, the effective flow rates were estimated as 5 and 1 pore volumes for extraction and air injection, respectively.

As shown in Fig. 4, the extraction and injection rates were initially 1, 2, and 5 pore volumes at extraction and extraction wells. As extraction time passed, the flow rates decreased slightly, but remained nearly constant after 5 h of operations. There was an opposite tendency for the injection mode. When air was injected, the injection flow initially increased by a little and later became constant at different flow rates.

Change in temperature during air injection

The subsurface air temperatures at the monitoring wells before the tests are shown in Fig. 5a for depths of 2 and 5 m. The ambient air temperature was low and it showed a daily fluctuation of 10 °C. However, the air temperature within the landfill was very high. It was just slightly affected by variations in the atmospheric temperature at a depth of 2 m, but the temperature was almost constant at a depth of 5 m.

Preheated air to 40 °C was injected by the blower at a depth of 5 m and a flow rate of 1 pore volume. Changes in temperature at the observation well 5 m away were monitored at depths of 2 and 5 m (Fig. 5b). The rise in temperature was large at a depth of 5 m, but only a slight rise in temperature was observed at a depth of 2 m. The air temperature in the landfill started to rise perceptively after

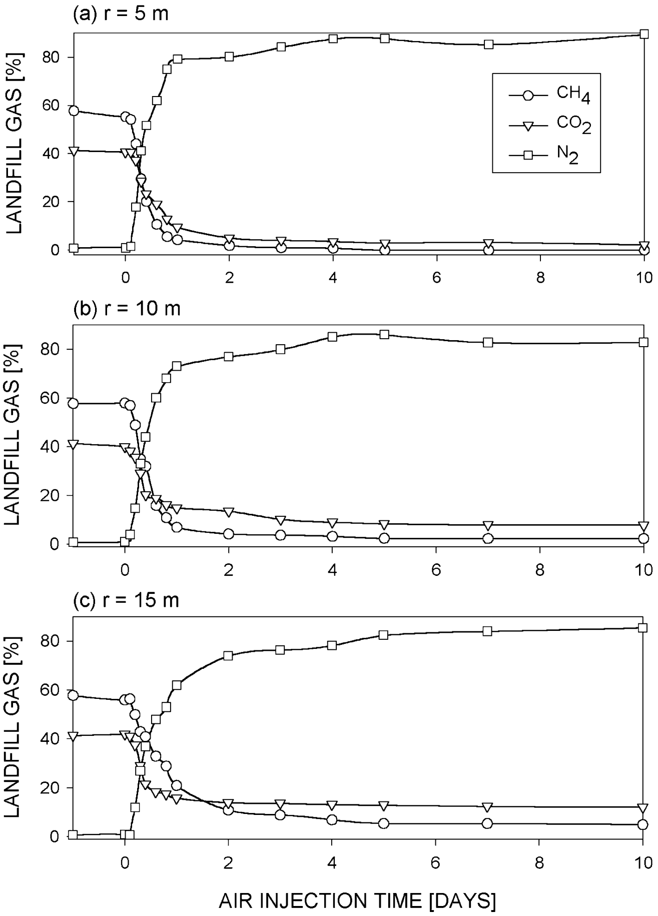


Fig. 6a–c
Changes in landfill gas concentration during air injection

2 days of air injection and reached approximately 60 °C at a depth of 5 m after 5 days.

The oxygen transmitted to the interior of the landfill changed the conditions to aerobic, and this caused a calorific reaction. It raised the temperature of the interior of the landfill. This rise in temperature is important evidence demonstrating the change of the interior of the landfill to aerobic conditions.

Air injection and methane oxidation

Change in LFG concentration because of the air injection with a flow rate of 1 pore volume, with initial concentrations of 60% CH_4 and 40% CO_2, was examined. Nitrogen gas, a relatively stable substance, was used to identify air propagation with distance. The N_2 curve, used as an indicator of the time required for the air propagation, shows a rapid transmission of the injected air (Fig. 6). Nitrogen gas was propagated to 10 m within 1 day and to 15 m within 2 days, which means that the injected air was transmitted to 15 m within 2 days. Concentrations of CH_4 and CO_2 decreased immediately as the air was injected, but the decrease in CO_2 was less than that of CH_4. This was derived from the change of the landfill conditions from methanogenic (anaerobic) to aerobic in which the CH_4 production was suppressed. The smaller decrease in CO_2 concentration was considered an effect of CO_2 production as CH_4 oxidized. Furthermore, the percentage of nitrogen increased to over 80%, which was a result of methane oxidization.

Methane can be oxidized by methane-consuming bacteria (methanotrophic) by the following reaction (Kjeldsen 1996):

$$CH_4+2O_2= CO_2+2H_2O + \text{Heat}\,(890\ \text{kJ/mol},\ CH_4) \qquad (1)$$

The reaction shows that a volume, or pressure, reduction takes place: 3 mol of gas transformed to only 1 mol (plus water). Owing to volume reduction, the concentration of nitrogen in the soil gas can exceed the normal concentration in air. Nitrogen enrichment is probably the most apparent indicator of methane oxidation (Bergman and others 1993; Kjeldsen 1996). The increase in nitrogen concentration during air injection is demonstrated in Fig. 6. A decrease in the CH_4/CO_2 ratio over time at a specific location or condition can be used as an indicator of methane oxidation (Kjeldsen 1996). Many researchers have studied the influence of methane oxidation on methane emission through the top covers of landfills. In contrast, only a few have studied the influence of methane oxidation on the migration of landfill gas and air injection. In general, the average CH_4/CO_2 ratio in most landfills is 1.86 (Kjeldsen and Fischer 1995). In this landfill, the average CH_4/CO_2 ratio was initially 1.5 and decreased to 0.9–0.4 with time and distance from the injection well during air injection.

The numbers of heterotrophic and methanotrophic microorganisms were investigated by collecting soil and waste samples (Table 2). The number of the microorganisms was sufficient for methane oxidation. The temperature rose greatly during methane oxidation to a temperature of over 70 °C, which was higher than the thermophilic degradation temperature ($\sim$60 °C) by composting. This was one piece of evidence for methane oxidation. In addition, the temperature of the gas escaping through a crack to the landfill surface showed an abnormal value above 90 °C, which is further evidence for methane oxidation.

Oxygen was transmitted together with air, but most of the injected oxygen was consumed during air transmission and the observed concentration at the monitoring wells was small. The oxygen concentrations were about 5, 4, and 1% at distances of 5, 10, and 15 m, respectively (Fig. 7). The CH_4 concentrations were about 1, 2.4, and 5% at distances of 5, 10, and 15 m, respectively. The oxygen consumption rate in this area was very large. The supplied oxygen content at 5 m distance during air injection was 17%: 12% was consumed, 5% left. The supplied and consumed oxygen concentrations were calculated based on the measured nitrogen concentrations. The supplied oxygen content at 15 m distance was 3%: 2% was consumed, therefore 1% was left. The magnitude of oxygen propagation, unlike nitrogen, was smaller because of oxygen consumption during transmission. Therefore, the effective radius of influence based on observed oxygen concentration would be relatively small.

The oxygen-consumption rate in the air injection system was larger than that in the LFG extraction system (Figs. 7 and 8). Therefore, the air-injection system appears to be more effective in landfill stabilization than extraction,

Table 2
Number of microorganism in air-injected landfill

Distance[a] (m)	Depth[b] (m)	Temp. (°C)	WC[c] (%)	pH	Microbiological analysis		
					Heterotrophs (CFUs/gdw)	Methylotrophs (MPN index/ 100 ml)	Methanotrophs (CFUs/ ml)
5	2	68.5	28.9	7.84	2.39×10^7	$\geq1.6\times10^4$	4.6×10^4
5	5	69.7	14.7	8.56	1.29×10^7	1.3×10^3	5.0×10^4
10	2	53.7	26.8	7.72	1.28×10^7	$\geq1.6\times10^4$	2.8×10^4
10	5	54.9	16.8	6.22	1.32×10^7	$\geq1.6\times10^4$	1.43×10^4
15	2	22.8	23.5	7.94	9.25×10^6	$\geq1.6\times10^4$	3.15×10^5
15	5	31.9	27.0	6.85	5.62×10^7	1.6×10^4	3.99×10^5

[a] Distance from the injection well
[b] Sampling depth below the ground surface
[c] Water content

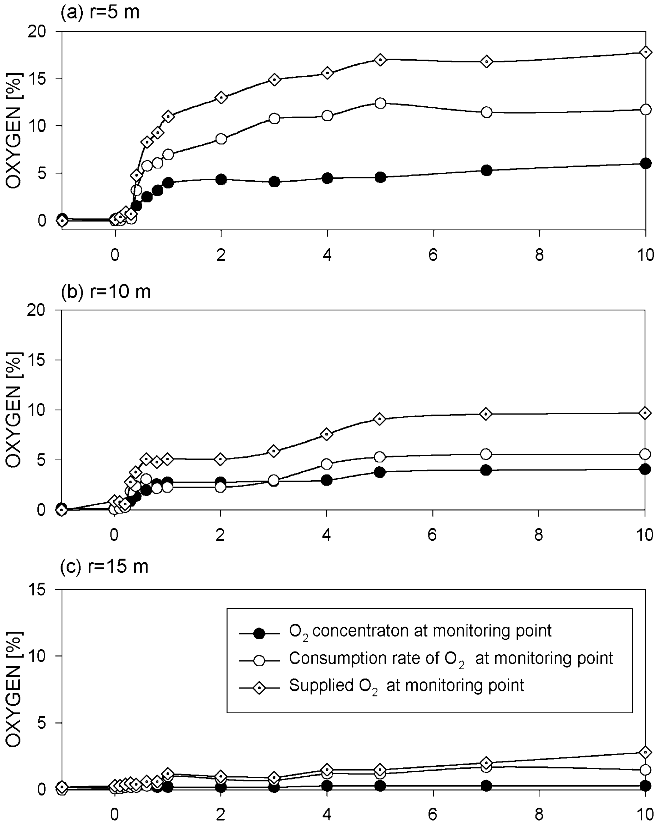


Fig. 7a–c
Oxygen concentration and consumption rate at monitoring point during air injection

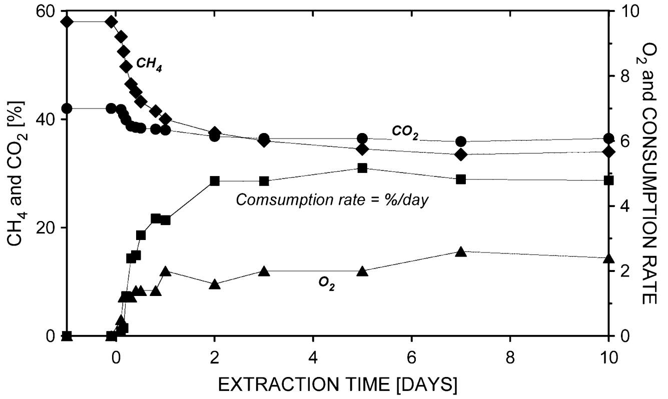


Fig. 8
Landfill gas concentrations and oxygen consumption rate during air extraction

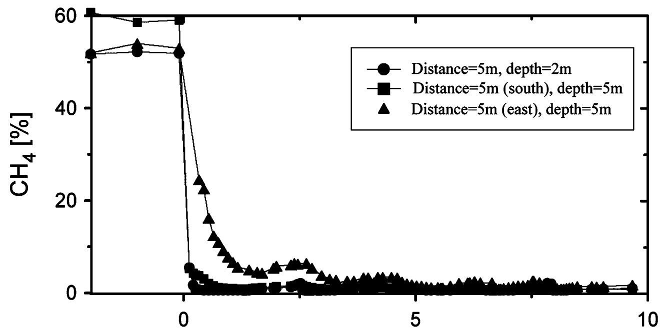
especially for an active landfill. In addition, the oxygen concentration measured at the monitoring well didn't appropriately reflect air propagation in the landfill because some oxygen in air would be consumed during transmission. As organic components from municipal solid waste degenerate under anaerobic conditions to generate methane gas, air injection will cause methane oxidation, which minimizes emission of CH_4.

A cyclic injection operation at the same site was evaluated (Fig. 9). The oxygen level rose with injection time. The calculated oxygen-consumption rate was less than that in continuous operation. There was rapid CH_4 disappearance and gradual CO_2 disappearance. When the injection was halted, CH_4 concentrations rebounded by a small amount, whereas a comparatively large amount of CO_2 rebounded. Based on these results, in an active landfill that has a large oxygen consumption rate, an intermittent air injection appeared less effective than continuous operation. However, in an aged landfill that has a lower oxygen consumption rate, the cyclic operation appeared more effective and economical (Lee 2000).

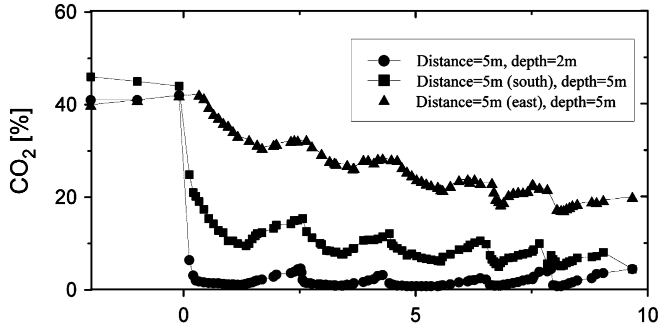
LFG change during extraction

LFG extraction was performed with a flow rate of 5 pore volumes. The change in LFG concentration in the landfill is shown in Fig. 8. The CH_4 concentration at the extraction well showed a marked decrease from 58 to 40% in the early stages and to below CO_2 levels after 2.5 days of extraction. The CO_2 concentration showed a slight decrease. Oxygen concentration increased slightly from 0 to 2.5%. The increase in oxygen concentrations during extraction was attributed to air intrusion through the surface into the body of the landfill. The estimated oxygen consumption rate, based on a nitrogen balance calculation, averaged 5% per day. Intruded air and oxygen consumption will change the LFG composition and the oxygen levels in the landfill. A reduction in the activity of methane-generating bacteria and oxygenation of methane by the intruded air resulted in a reduction in methane concentrations in the extracted LFG.

(a) Methane



(b) Carbon dioxide



(c) Oxygen

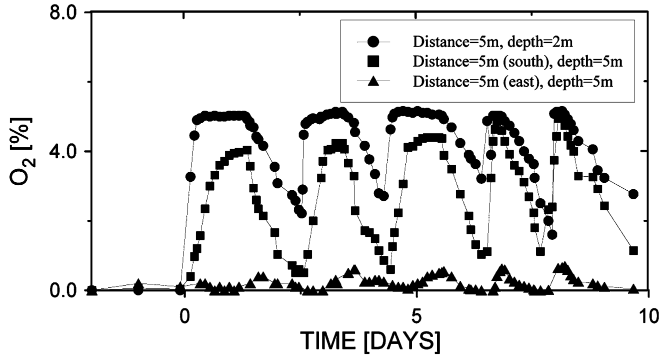
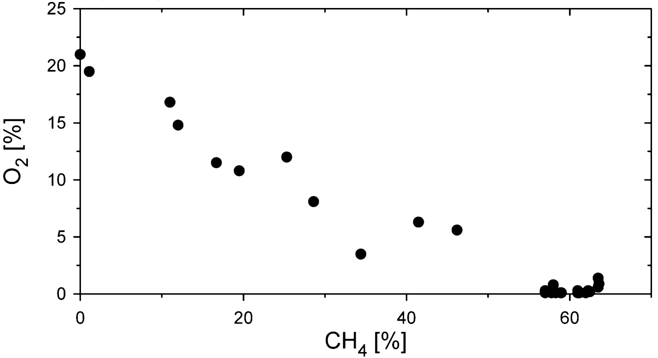
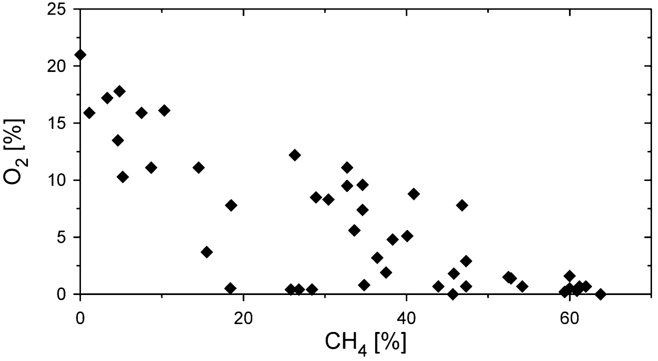


Fig. 9
Changes in landfill gas concentration during a cyclic operation

(a) Early period



(b) During extraction



(c) After extraction stop

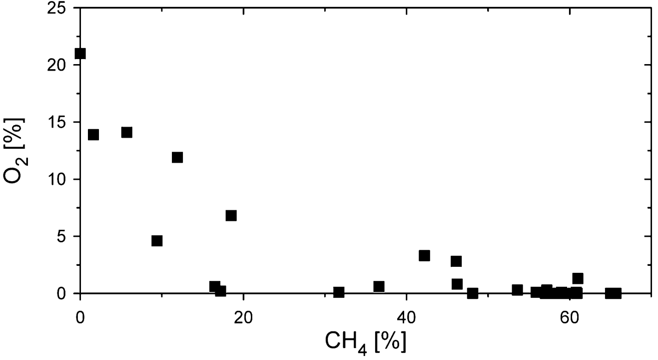


Fig. 10
Relationship between methane (CH_4) and oxygen (O_2): **a** early period, **b** during extraction, **c** after extraction had stopped

An increase in the aerobic bacteria and methane oxidation resulted in the maintenance of CO_2 concentrations. Therefore, it was inferred that the extraction of LFG recovered LFG as well as enhanced the aerobic stabilization of the landfill in a similar manner to soil vapor extraction (SVE) for a petroleum-contaminated soil (Lee and others 2001).

Results of full-scale application

A full-scale LFG extraction was conducted to evaluate the feasibility of landfill stabilization and LFG utilization. The LFG extraction system was composed of 27 wells (see layout in Fig. 1). The gas collection and treatment plant, which had been established in 1999 at this site, was able to extract landfill gas at a maximum rate of 20 m^3/min. Recently, the operating conditions have been examined to evaluate the feasibility of the system for energy utilization.

The results showed that the initial methane content was about 60% in LFG and no detectable oxygen was present. Average LFG generation was about 10 m^3/min. The practical LFG extraction rate was 9–12 m^3/min and the extracted LFG gas was composed of 39–56% CH_4 and 3–5% O_2, which indicated that there was air ingress during the extraction. Therefore, LFG extraction at a greater rate than natural production caused air inflow from outside, which resulted in the dilution of methane concentration and an increase in oxygen concentration. This is a positive aspect for landfill stabilization, but a negative aspect for LFG utilization. During the early period of extraction in October 1999, LFG had a methane content of about 60%. Presently, there is some evidence of air ingress, probably because of the LFG extraction, as indicated by a lower methane content (Fig. 10).

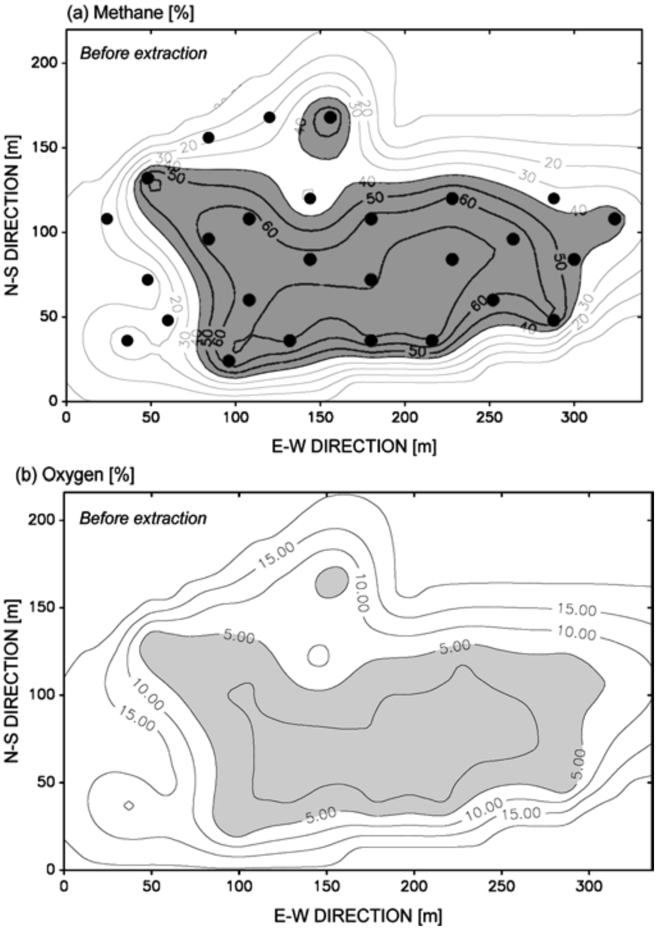


Fig. 11a, b
Distribution of methane and oxygen at initial stage of extraction (October 1999)

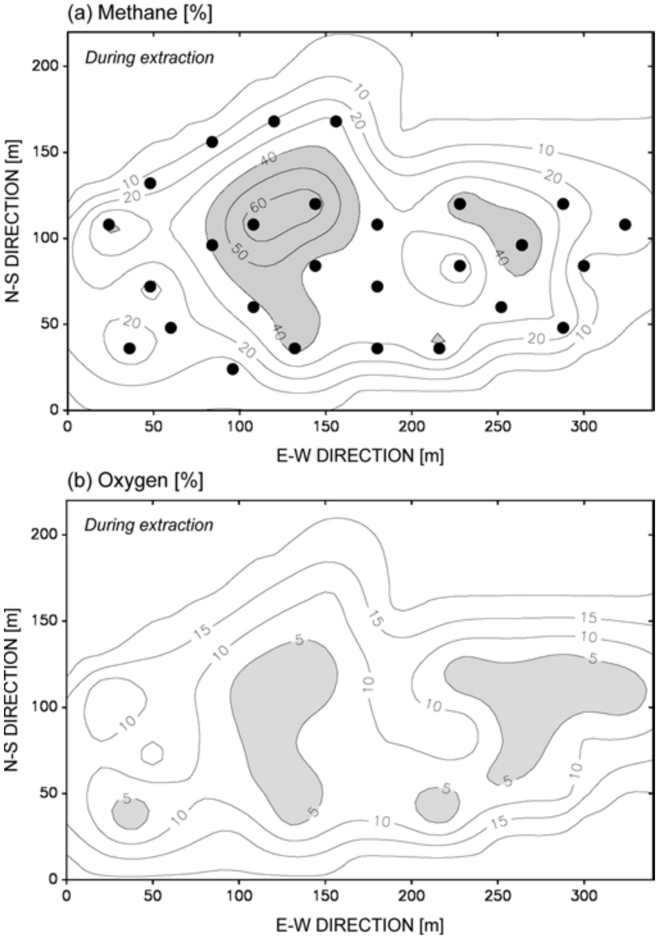


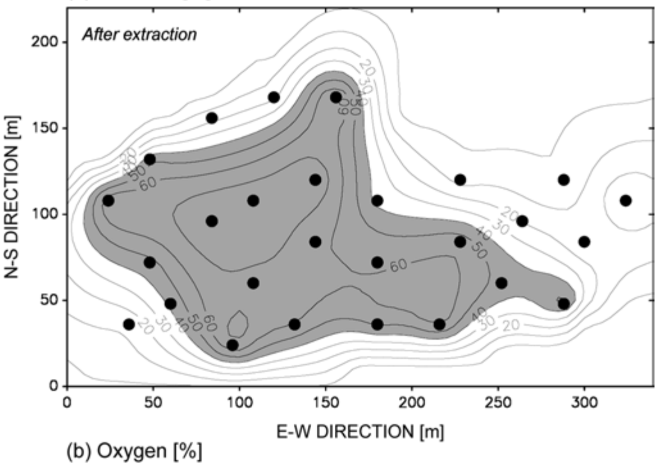
Fig. 12a, b
Distribution of methane and oxygen during mid-extraction (January 2000)

As shown in Fig. 11, it is evident that there is a substantial landfill area where the oxygen content is below 5%. During the LFG extraction, LFG showed methane content with a range of 20 to 60%. The oxygen content was inversely related to methane content. The larger increase in oxygen content corresponds to the lower methane content.
Figure 12 shows that the landfill area that produced more than 40% of methane (which is the lowest concentration for the use of LFG) decreased significantly, and concentration of oxygen increased. On the other hand, when LFG extraction was temporarily ceased, the concentration of available oxygen was less than 3% and methane concentration was 60% in the LFG. As shown in Fig. 13, the methane content recovered to values observed at the initial period of LFG extraction.
Currently, after 8 years have elapsed since the cessation of landfill operations, the amount of natural landfill gas production has sharply decreased. A plan for the use of LFG from the closed landfill appears feasible on a small scale if LFG is extracted at a rate less than natural production. With regard to efficiency, it appears less economical to extract LFG just after landfill closure, but this is helpful for the stabilization of the landfill. Because LFG extraction carries the economic burdens of treatment and maintenance problems, the injection method is efficient in stimulating landfill stabilization. However, the effect of LFG surface emissions by air injection on air pollution or human health should be evaluated.

Effect of LFG extraction on landfill gas composition

To investigate the effects of LFG extraction on air intrusion and the composition of LFG, the gas-generation rate was estimated using the Scholl Caynon model (Cossu and others 1996). As a consequence of LFG extraction at a rate of 10 m^3/min, methane concentrations decreased while oxygen concentrations increased (Fig. 14). It was estimated that methane production would cease in 2001 because of an excess of available oxygen from aerobic conversion of the landfill by continuous LFG extraction. According to this result, if LFG, produced at a rate of 8.4 m^3/min, is extracted at 10 m^3/min, the concentrations of methane and oxygen will be approximately 40% and 2–3%, respectively. This agrees well with the result of LFG extraction at the landfill. It was found that the use of LFG would not be possible if the extraction of LFG continues at the present rate. Therefore, to use LFG, the stabilization plan by LFG extraction should be modified. Based on the modeling calculation, there will be no problems with the

(a) Methane [%]



(b) Oxygen [%]

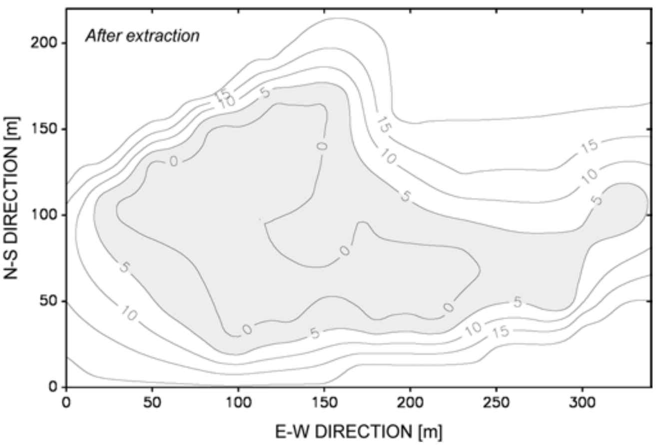


Fig. 13a, b
Distribution of methane and oxygen after extraction had stopped (January 2000)

use of LFG if it is extracted at a rate not exceeding 10 m^3/min at present, but less than natural production.

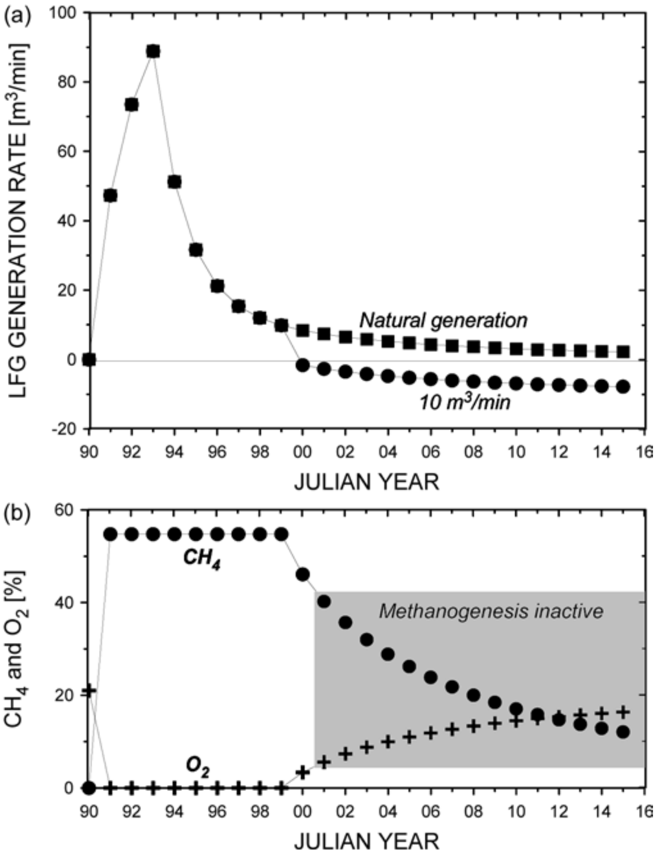


Fig. 14a, b
Landfill gas generation (*upper*) and changes in methane and oxygen concentrations (*lower*)

Summary and conclusions

This study evaluated air extraction and injection for extracting hazardous landfill gas and/or enhancing degradation of organic materials in a landfill in Korea. For these purposes, the pilot and full-scale tests were performed. From the pilot tests, the anisotropic characteristics of air flow in the landfill were found. In addition, a pressure radius of influence greater than that of oxygen was observed, which was derived from respiration of bacteria during air transmission. This oxygen consumption should be considered for the system design. In the air-injection test, methane oxidation was detected, which was supported by a decrease in the CH_4/CO_2 ratio, enrichment of nitrogen gas, and abnormally high temperatures of escaping gas. Air extraction as well as air injection induced oxygen ingress. Cyclic air injection appeared not to be feasible for a landfill whose oxygen consumption rate was large. From the full-scale test and model calculation, an extraction rate of 10 m^3/min at present or less than the natural gas production was reasonable for stabilization and LFG utilization for this landfill.

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