CONSIDERATION OF LANDFILL LINER TEMPERATURE

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SUMMARY: The observed temperature of landfill base liners is discussed. Typically the temperature ranged from 35 to 45°C. In some cases the temperature increased very quickly, whereas in others it built up gradually. The temperature at the base of the Tokyo Port Landfill is modeled and predicted to be over 30°C for 30 years. A sensitivity analysis examining factors affecting the base temperature shows that both aerobic or anaerobic decomposition could result in the high base temperatures of over 35°C and that the infiltrated water flux could also greatly affect the base temperature.

1. INTRODUCTION

A rise in landfill temperature has been observed in many landfills. This has generally been considered to be a consequence of the heat generated by biodegradation or the heat of hydration of incinerated residues (ash) and generally has not been a matter of concern. However, landfill temperature will affect the chemical, physical and biological processes in the landfill and, in particular, may have a significant impact on the service life of components of any engineered barrier system. A rise in liner temperature will cause antioxidant depletion in a geomembrane, potential desiccation in clay liners beneath a geomembrane, and an increase diffusion and/or moisture movement through liners (Rowe 1998; Rowe *et al.* 2003).

This paper discusses the observed temperature of landfill liners and then seeks to model the temperature at the base of the Tokyo Port Landfill using a numerical heat transfer model. A sensitivity analysis is performed to assist in evaluating how biodegradation and the infiltrated water flux from the surface to the base in the landfill could influence liner temperature.

2. PUBLISHED DATA RELATING TO LANDFILL LINER TEMPERATURE

A few studies (Collins 1993, Tokyo Metropolitan Government 1996, Barone *et al.* 2000, Klein *et al.* 2001) report the temperature of landfill liners and these are summarized in Figure 1. The data shows two temperature trends. In some cases, the temperature rises quickly. In others the

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temperature rises gradually.

Tokyo Metropolitan Government (1996) and Klein *et al.* (2001) showed that landfill temperature of liners in Japan and Germany rose quickly after the commencement of landfilling.

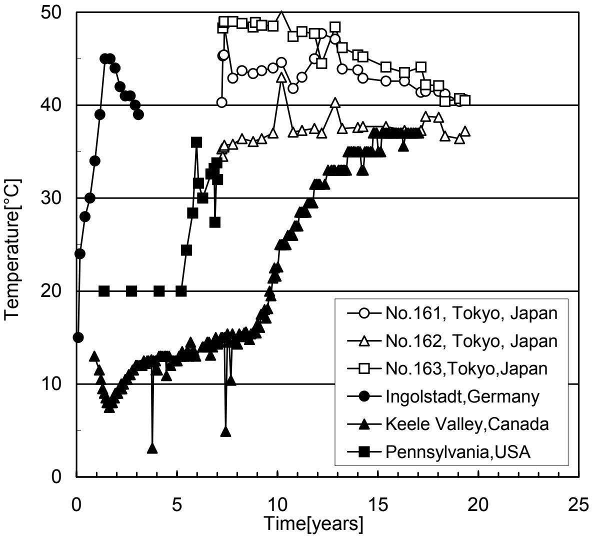


Figure 1. Observed temperatures around landfill liners

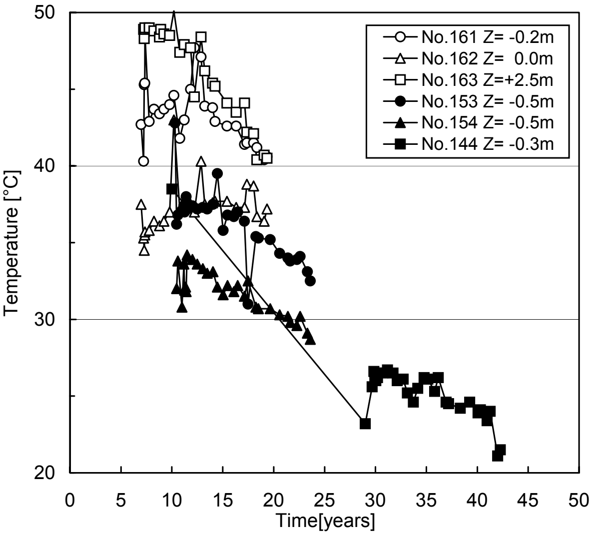


Figure 2. Observed temperatures around the landfill liner at the Tokyo Port Landfill

At the 35m high Tokyo Port Landfill municipal refuse was placed directly on the surface of a natural clayey liner. Figure 2 shows landfill temperatures around the liner for both the Tokyo Port (No. 161-163) and two other landfills (No.144, No.153, and No.154) in Tokyo. In most cases, the temperatures were high 7-10 years after the beginning of landfilling and then declined. At location No.163 the maximum temperature rose to 50°C. There is evidence of landfill temperature above ambient temperature for more than 40 years.

At the landfill in Ingolstadt, Germany (Klein *et al.* 2001), municipal solid waste incinerator bottom ash was placed to a thickness of about 9m over a composite (geomembrane over clay) liner system. Here the temperature of the geomembrane rose to 46°C (Figure 1) and the maximum temperature in the waste was 85°C.

Barone *et al.* (2000) and Koerner (2001) showed that some landfill liner temperatures in Canada and U.S.A. rose slowly 5~10 years after the beginning of landfilling.

The Keele Valley Landfill near Toronto operated between 1983 and 2002. Up to 65m of municipal waste was placed on a sand protection layer above the clayey liner in Stages 1 and 2 (1983 to 1988) when the landfill drainage system consisted of French drains spaced at 65 m. Here the temperature above the clay liner remained relatively constant until a significant leachate mound began to develop at which time the temperature increased slowly and rose to 37°C. Liner temperatures are still low at newer sections of the landfill where there is a coarse gravel leachate collection blanket and, as yet, no significant leachate mounding.

At a landfill in Pennsylvania up to 50m of waste was placed above a leachate collection and composite liner system. The temperature at the composite liner was constant at 20°C for about 5 years; however it then rose to 35°C and subsequently fluctuated.

The data from these four landfills shows different trends that may be the result of different rates of heat generation by decomposition of organic wastes or chemical reactions associated with hydration of bottom ash in the landfills.

Figure 3 shows the landfill liner temperatures versus the maximum waste temperatures in the landfill. An additional data point for the Hannover Landfill, Germany (Collins 1993), has been added to Figure 3. The landfill temperatures around liners tend to be below 50°C, whereas maximum waste temperatures are over 50°C.

Figure 4 shows average landfill liner temperatures versus the period during which the temperature was over 30°C. For example, the temperature at location No.163 of the Tokyo Port Landfill was over 30°C from 7 to 20 years after landfilling and the average temperature during this period is 46°C. Most of the average temperatures were over 30°C for more than 5 years.

Heibrock (1997) predicted cracking of a clay liner in 20 years with a temperature at the top of the liner of 40°C. Rowe (1998) shows that diffusion coefficient and hydraulic conductivity in a liner at 35°C are 100% and 80% higher (respectively) than at 10°C. Such thermal effects on the liner systems should be considered in the landfill design.

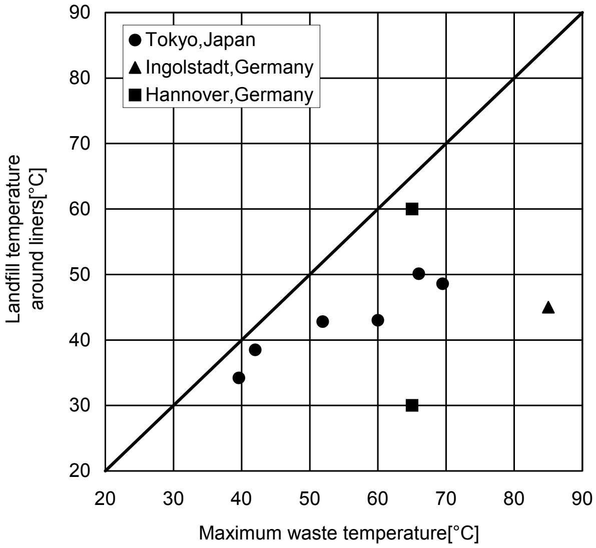


Figure 3. Landfill temperatures around liners versus maximum waste temperatures

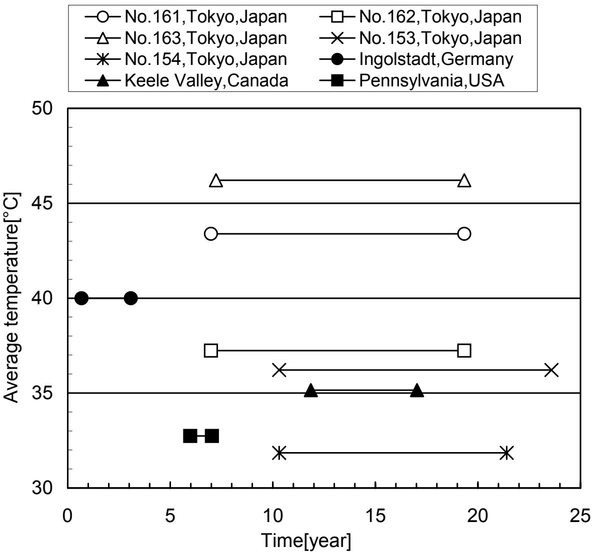


Figure 4. Average landfill liner temperatures and period that temperature was above 30°C

3. SIMULATION OF A LANDFILL TEMPERATURE AROUND LINERS

Yoshida *et al.* (1997, 1999) developed the method for calculation of temperature distribution in a landfill and applied it to calculating of the temperature of the Tokyo Port Landfill. Calculated temperatures were in relatively good agreement with observed temperatures.

This paper focuses on the simulated landfill temperature around the liner at location No.163 of the Tokyo Port Landfill. Some parameters are revised from those previously reported and consideration of leachate mounding in the landfill and new temperature simulations are reported. The results from a sensitivity analysis are also presented.

3.1 Energy equation in a landfill

A one-dimensional heat transport equation is given by (Yoshida *et al.* 1997):

$$C_e \rho_e \frac{\partial \theta}{\partial t} = k_e \frac{\partial^2 \theta}{\partial z^2} - C_w \rho_w v_z \frac{\partial \theta}{\partial z} + Q_b \qquad (1)$$

where t : time [s], z : position in space[m], θ : temperature [°C], C_e : specific heat of waste [J/(kg°C)], ρ_e : apparent density of waste [kg/m^3], k_e : effective thermal conductivity of waste [J/(ms°C)], C_w (=4184) : specific heat of water [J/(kg°C)], ρ_w : density of water [kg/m^3], v_z: infiltrated water flux[m/s], and Q_b : rate of heat generation [J/(m^{3}s)],

The rate of heat generation with biological decomposition is given by:

$$Q_b = (-\Delta H_b) R_b \qquad (2)$$

where ΔH_b : heat of biological decomposition [J/mol-landfill gas], R_b: gas production (or consumption) rate [mol-landfill gas/(m^{3}s)]

3.2 Scenarios and parameters for simulations

The parameters are generally similar with those used in previous paper (Yoshida *et al.* 1999) and only the revised parameters are discussed here. Figure 5 illustrates a waste cell model wherein 2m thick waste layers are placed every 2 months until the height of the landfill reaches 30m. The last waste cell was 1m thick and covered by 2.5m of final soil cover giving a total landfill thickness of 33.5m constructed over a period of 32 months from the beginning of landfilling.

Each fresh cell of waste is exposed to the air and is assumed to have a 1m thick aerobic zone at the surface and an underlying anaerobic zone. When the next fresh cell is placed on the former cell, the aerobic zone in the former cell becomes anaerobic.

Landfill layers consist of unsaturated zones above the water table and saturated zones below the water table. Thermal and geotechnical properties are estimated as shown in Table 1. Water levels in the landfill fluctuated as shown in Figure 6. The base of the landfill was essentially impermeable and there was no leachate collection system so that leachate naturally drained from inside the landfill to the area surrounding the landfill.

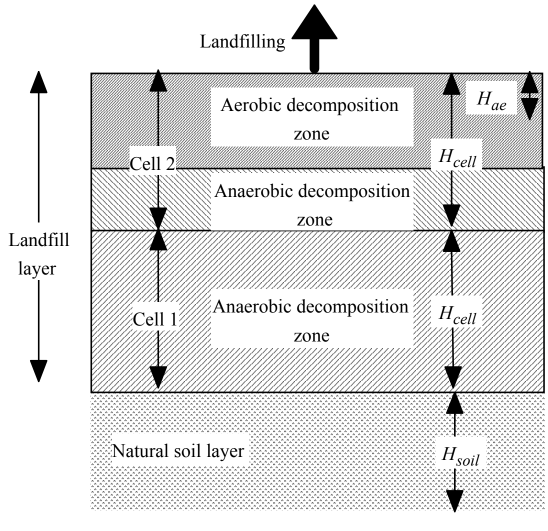


Figure 5. Schematic diagram of the landfilling of waste cells

Table 1 Properties used in simulation of Tokyo landfill case

Parameters	sign	units	value
Landfill layer(unsaturated)			
Water content	w	[%]	28.9
Apparent density	ρ_e	[kg/m^3]	1157
Specific heat	C_e	[J/(kg)]	1939
Effective thermal conductivity	k_e	[J/(ms)]	0.35
Landfill layer(saturated)			
Water content	w	[%]	42.3
Apparent density	ρ_e	[kg/m^3]	1424
Specific heat	C_e	[J/(kg)]	2363
Effective thermal conductivity	k_e	[J/(ms)]	0.96
Natural soil layer			
Water content	w	[%]	9.1
Apparent density	ρ_e	[kg/m^3]	1800
Specific heat	C_e	[J/(kg)]	1109
Effective thermal conductivity	k_e	[J/(ms)]	0.86
Aerobic decomposition			
Depth of aerobic zone	H_{ae}	[m]	1.0
Rate of methane production	Ro	[mol-O$_2$/(m^{3}s)]	10^{-5}
heat generation	ΔH_o	[kJ/(mol-O$_2$)]	460×10^3
Rate of heat generation	Q_{ae}	[J/(m^{3}s)]	4.67
Anaerobic decomposition			
Rate of methane production	R_m	[mol-CH$_4$/(m^{3}s)]	5×10^{-6}
heat generation	ΔH_m	[J/(mol-CH$_4$)]	43.5×10^3
Rate of heat generation	Q_{an}	[J/(m^{3}s)]	0.218
Total gas generation	V_m	[mol-CH$_4$/m^3]	1298
Duration of decomposition	$t_{an}=V_m/R_m$	[year]	8.2
The depth of landfill	H	[m]	33.5
The depth of natural soil layer	H_{soil}	[m]	30
Air annual average temperature	θ_a	[° C]	15
Natural soil temperature	θ_o	[° C]	15
Initial temperature of waste cell	θ_o	[° C]	15
Infiltrated water flux	v_z	[mm/d]	2.0
Excessive drainage flux of leachate	v_e	[mm/d]	0.05-0.08
Heat transfer coefficient	h	[J/(m^{2}s)]	10

Infiltrated water flux through the saturated zones, v_{sat} is assumed to decrease linearly towards the base and become zero at the base.

$$v_{sat} = v_z \times z / H_{water} \qquad (3)$$

where v_z : infiltrated water flux [m/s], H_{water}: water level above the base [m], z: distance above landfill base [m].

v_{sat} is zero during the increase of water level because all infiltrated water is accumulated in the saturated zones and not drained from the landfill. On the other hand, v_{sat} is greater than v_z during the decrease of water level because the excess leachate is being drained from the landfill.

$$v_{sat} = v_z + v_e \qquad (4)$$

where v_e: excess leachate drainage flux [m/s]

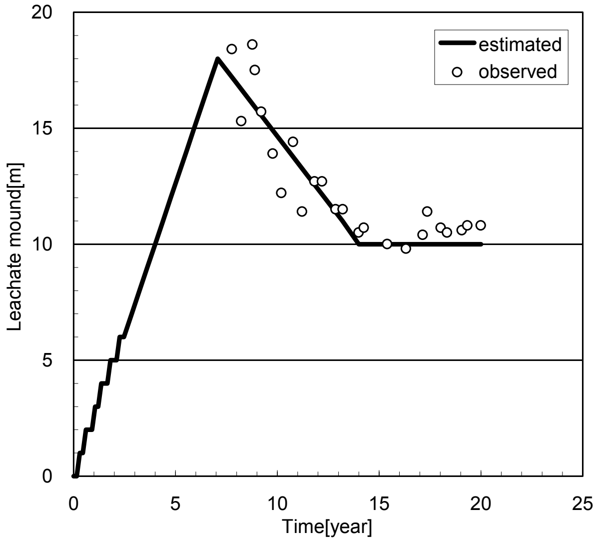
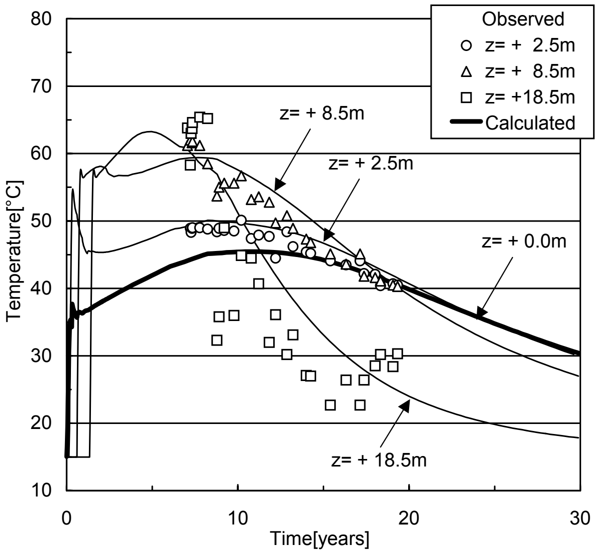


Figure 6. Leachate mound in the Tokyo Port Landfill

3.3 Numerical results

Figure 7 shows the observed and calculated temperature distributions. Figure 8 shows the observed and calculated temperature at various locations above and below the landfill base (z=0).



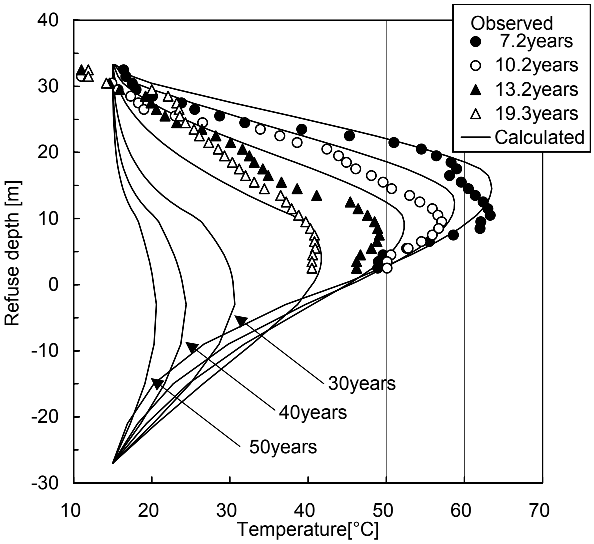


Figure 7. Observed and calculated temperatures in the Tokyo Port Landfill

Figure 8. Observed and calculated temperatures in the Tokyo Port Landfill

They are in relatively good agreement except in the upper zone. The simulated temperatures rise quickly after the beginning of waste placement as a result of aerobic decomposition at the surface of the cells. They then decrease temporally and rise again as a result of anaerobic decomposition.

The observed and calculated temperatures at 2.5m above the base are in good agreement. The base temperature rises steadily and reaches to the peak, 45°C, and decreases more slowly than the upper zone temperatures in Figure 8. The temperature near the base is over 30°C for more than 30 years. This suggests that landfill liner temperature may remain high for a long time once is heated.

3.4 Sensitivity analysis

The sensitivity analysis simulations of the base temperature of the Tokyo Port Landfill are shown in Figure 9. The cases examined are as follows:

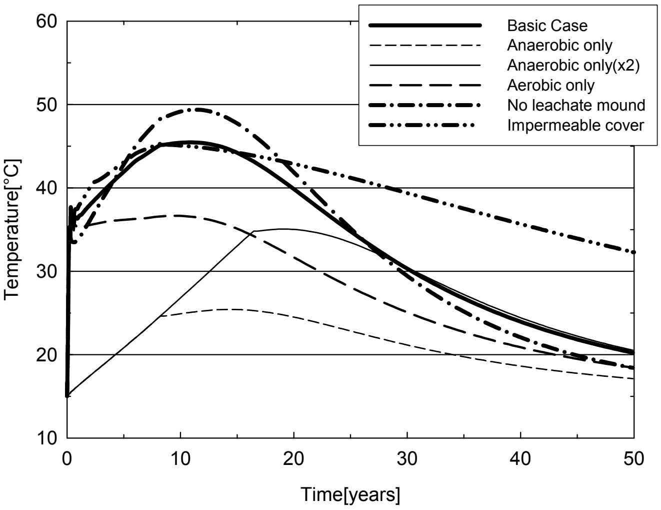


Figure 9. Sensitivity analysis of the base temperature in the Tokyo Port Landfill

(1) Only anaerobic decomposition occurs in the landfill

If there is no aerobic decomposition at the beginning of landfilling, the maximum base temperature only reaches 25°C. The waste cell model of the Tokyo Port Landfill has the potential to generate 50 L-LFG/kg-waste of landfill gas. McBean *et al.* (1995) refer to 100-300 L-LFG/kg-waste for U.S. municipal refuse based on theoretical estimates. If the base temperature is calculated for 100 L-LFG/kg-waste, denoted as Anaerobic only (x2) in Figure 9, the maximum base temperature rises to 35°C (similar to that observed at the liner at the Keele Valley and Pennsylvania landfills discussed earlier).

(2) Only aerobic decomposition occurs in the landfill

The maximum base temperature reaches to 37°C. It is over 30°C for 20 years even if the heat generation occurs for only 2 years during landfilling.

(3) No leachate mound

It is assumed that leachate collection systems are installed in the landfill and the infiltrated water into the landfill is perfectly drained from the bottom, consequently there is no leachate mound in the landfill. The maximum base temperature rises to 50°C as a result of heat transport by the infiltrated water flux from the surface to the base in this case. However this is not consistent with field observations in the post 1989 portions of the Keele Valley landfill or the Pennsylvania landfill where there are operating leachate collections systems and no significant leachate mound, as discussed earlier, demonstrating that other factors (such as the rate of filling) will also have a significant effect on base temperature. The rate of landfilling at the Tokyo landfill (assumed here) was very fast compared to that for most North American landfills.

(4) Impermeable landfill cover is placed on the landfill

It is assumed that the impermeable landfill cover is placed on the landfill and then the infiltrated water flux becomes zero. The maximum base temperature reaches to 45°C. It is over 30°C for 60 years due to the slow rate of heat loss from the landfill by heat conduction. It appears that heat loss by leachate drainage is important for the decreasing the landfill liner temperature.

These sensitivity analysis simulations imply that:

(1) either aerobic or anaerobic decomposition can result in base temperatures over 35°C; and

(2) the infiltrated water flux may affect on the base temperature.

4. CONCLUSIONS

This paper has examined landfill liner temperatures based on data from the literature and has also presented the results of simulations and sensitivity analysis relating to the base temperature at the Tokyo Port Landfill. Based on this work it is concluded that:

(1)The observed landfill liner temperatures are often between 35 to 45°C. In some cases the temperature rose quickly, whereas the other cases the temperature gradually increased with time. These differences may be as a result of the different rates of landfilling, types of waste, water infiltration and consequent rates of heat generation by decomposition of organic wastes, the effect of leachate mounding, and/or the different rate of chemical reactions observed in bottom ash landfills.

(2)The observed temperatures tended to be below 50°C, whereas the maximum waste temperatures in the landfill were over 50°C. Liner temperatures were generally over 30°C for more than 5 years and in some cases for many decades. Thus thermal effects on the liner systems such as ageing of plastics (geomembranes), potential for cracking of clay liners, and an increase in the diffusion coefficient and hydraulic conductivity should be considered in the landfill design.

(3)The simulations of the base temperature of the Tokyo Port Landfill predicted that the base temperature would be over 30°C for more than 30 years and that the subsequent decrease would be slow.

(4)The sensitivity analysis of the base temperature showed that either aerobic or anaerobic decomposition alone could result in the high base temperatures of over 35°C and that the infiltrated water flux could significantly affect base temperature.

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