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Case study

Temperature development in a modern municipal solid waste incineration (MSWI) bottom ash landfill with regard to sustainable waste management

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Abstract

Municipal solid waste is treated in incineration plants to reduce the volume, the toxicity and the reactivity of the waste. The final product, municipal solid waste incineration (MSWI) bottom ash, was considered as a material with a low reactivity, which can safely be deposited in a MSWI bottom ash landfill, or which can be used, e.g. in road construction after further treatment. However, temperature measurements in MSWI bottom ash landfills showed temperatures up to 90°C, caused by exothermic reactions within the landfill. Such high temperatures may affect the stability of the flexible polymer membrane liner (FML) and may also lead to an accelerated desiccation of the clay barrier. At the beginning of this study it was uncertain whether those reported results would be applicable to modern landfills, because the treatment techniques in MSWI and landfills have changed, bottom and fly ash are stored separately, and the composition of the incinerated waste has changed significantly since the publication of those results.

The aim of this study was to gain detailed knowledge of temperature development under standard disposal conditions in relation to the rate of ash disposal, the variation of layer thickness, and the environmental conditions in a modern landfill.

Temperatures were measured at nine levels within the body of a landfill for a period of nearly 3 years. Within 7 months of the start of the disposal, a temperature increase of up to 70°C within the vertical centre of the disposal was observed. In the upper and central part of the landfill this initial temperature increase was succeeded by a decrease in temperature. The maximum temperature at the time of writing (May 2000) is about 55°C in the central part of the landfill. The maximum temperature (45.9°C) at the FML was reached 17 months after the start of the deposition. Since then the temperatures decreased at a rate of 0.6°C per month.

Temperature variation within each individual layer corresponds to the temperature of the underlying layer and the overall surface-to-volume ratio of the landfill. The temperatures in the uppermost

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layer are significantly influenced by the ambient temperatures.

Keywords: Bottom ash; Temperature development; Municipal solid waste incineration; Landfill

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1. Introduction

In OECD countries and the US, 15–20% of municipal solid waste is treated by incineration [1]. Municipal solid waste incineration (MSWI) aims to reduces the volume, the toxicity and the reactivity of the waste. Although the volume of the waste is reduced by about 90%, the residues (bottom ash, fly ash) still amount to roughly 17 Mt per year world-wide [2]. This amount is expected to double within the next 10 or 15 years [3]. Bottom ash, which is the object of this study, represents about 80% of the residues and contains various substances that may pose a threat to groundwater quality [2–4].

Assessing the potential pollution risks of the residues is essential since bottom ash has increasingly been used as building material or has been deposited in landfills with poor landfill liner systems in Europe and in other countries during the last decade [5]. In the US, bottom ash was commonly landfilled without processing, even though metals and other materials can be recovered by magnetic separation and screening [6]. In some European countries (e.g. Germany, The Netherlands and France) bottom ash is partly reused (about 60%) in road construction or as raw material for the ceramic and cement industry [7–9], whereas in Switzerland almost 100% of the bottom ash is disposed in landfills [6].

Until the 1970s, bottom ash was believed to be almost inert, but since then several studies have shown that a number of exothermic reactions occur in this material [10–15]. Other studies have shown that exothermic reactions may cause a temperature increase in the landfill of up to 90°C [16,17] which may constitute a major hazard to the flexible polymer membrane liner (FML) and the mineral clay layer. Temperatures above 40°C may affect the stability of the FML (made of high-density-polyethylene (HDPE)) due to depolymerisation and oxidation. Sudden ruptures of the FML may follow [18]. Due to a diffusive transport of water and water vapour along the temperature gradient in the mineral clay layer, the clay barrier may desiccate and fail to retain leachate [19–21]. Johnson et al. [22] observed a rapid increase in bottom ash landfill discharge following rainfall. Within 1–4 days, approximately 50% of precipitation discharged in response to a rain event.

Due to their limited time scale, published studies on exothermic reactions [23–26] have to be considered as a 'snapshot', hence giving no information on the long-term development of the landfill temperatures. Moreover, many of the basic conditions have changed since then. The incineration technique has been improved and the composition of the municipal waste has changed. For instance, the heating value of domestic waste increased from 6000 to 8000 kJ/kg over the last two decades caused by recycling activities and an augmented share of plastic contents in domestic waste [27]. In contrast to former landfills, fly ashes nowadays are stored in underground repositories, and ferromagnetic scrap metal of a diameter >16 mm is usually separated out by a magnetic separator. With these changes the mineralogical and chemical composition of the deposited residue has changed as well, thus putting the extrapolation of published results to state-of-the-art landfills under question.

The present study aims to provide data on the long-term development of the temperatures within a recent bottom ash landfill under normal disposal conditions.

2. Experimental

2.1. Bottom ash description

The bottom ash in this study was produced by MSWI in Ingolstadt in the south of Germany (MVA Ingolstadt/Germany). The incinerator (installation year 1996) operates at temperatures between 850 and 1200°C. The incineration capacity of each furnace is roughly 11 Mg/h and the material remains in the combustion chamber for about 1 h. Following incineration, the bottom ash is quenched in a water basin. After this quenching process, the bottom ash is temporarily stored in piles up to 2 m in height at an open dump site for 1–3 weeks, in order to reduce the reactivity [28]. Prior to deposition in the landfill, magnetic materials are removed. The grain size distribution of the bottom ash (Fig. 1), determined according to DIN 18123 [29], shows a badly sorted material with grain sizes from silt to gravel.

The determined bulk density has a mean value of $2.13 \pm 0.15\,\mathrm{Mg/m^3}$. The geotechnical water content (weight of water in a sample relative to the oven dry weight of the sample, expressed as percentage, DIN 18121 [30]), measured after a 3 weeks storage period, ranges from 8 to 15% by weight.

Although the bottom ash studied is a very inhomogeneous material, it is in general comparable with other MSWI bottom ashes investigated elsewhere [12,31] although there

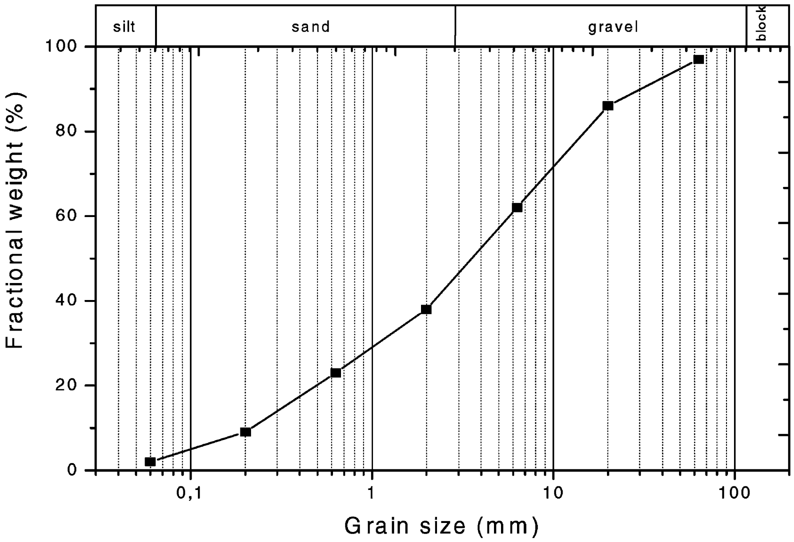

Fig. 1. Grain size distribution of the examined MSWI bottom ash as a function of fractional weight.

Table 1
Bottom ash composition (wt.%)

	Melting products and ashes	Metals	Ceramic	Stones	Glass	Organic waste
This study	82	8	2	1	6	1
Lichtensteiger (1996)	85	5	2	1	5	2
Reichelt (1996)	67	4	4	–	17	–

is a significant variation in the fraction of glass in the bottom ash, caused by increased recycling in municipal solid waste (Table 1).

The thermal conductivity of the investigated bottom ash ranges from 0.23 (dry) to 1.27 W/m K (saturated). It was determined with the thermal conductivity instrument TK04 (TeKa, Berlin/Germany). The samples were taken prior to deposition. The value for the deposited bottom ash at a water content between 10 and 20% by weight ranged between 0.5 and 0.6 W/m K.

2.1.1. Disposal site

The bottom ash landfill investigated in this study is located near Ingolstadt. The measured average ambient temperature in this area is 15°C, with a recorded maximum and minimum of 33 and -8°C during the observation period (June 1997–June 2000). The measured annual precipitation in this period was between 800 and 1000 mm with a maximum between May and July. The driest period was January–April. The summer rains tend to occur in short events with a high intensity.

The geology at the landfill location comprises fluvial and alluvial sediments. The elevation of the water table is approximately 2 m below the base of the landfill. The groundwater flows south towards the river Danube, which flows in an easterly direction approximately 800 m south of the landfill.

The landfill was constructed above ground adjacent to a hill side. The base of the landfill is a 0.6 m thick mineral clay layer, covered by a 2.5 mm FML made of HDPE. Between the FML and the bottom ash is a gravel drainage layer (16–32 mm grain size). The leachate is transported to a communal waste water treatment plant. Two geotextiles separate the bottom ash from the drainage layer and the drainage layer from the FML. A schematic of the test site is given in Figs. 2 and 3. The levelled ground directly below the clay liner consists of sand and gravel. Therefore the capillary rise of water from the ground water into the mineral clay layer may be hampered, leading to a forced desiccation.

Approximately 19,000 m^3 of bottom ash are deposited in the landfill per year at discrete and irregular intervals. The landfill is subdivided into four separated disposal sectors (Fig. 3) [32]. Sectors I–III were already completely filled at the start of the study. Sector IV was filled with bottom ash during the study period. The MSWI fly ash is stored elsewhere in a hazardous waste disposal site. Sector IV, where the sensors are located, has a filled surface area of 16,500 m^2 and a total bottom ash capacity of approximately 100,000 m^3. The sensors are located in the centre of sector IV, so no influence from the other sectors is to be expected. The surface of sector IV has not yet been covered or cultivated, so there is direct contact between the deposited bottom ash and the atmosphere.

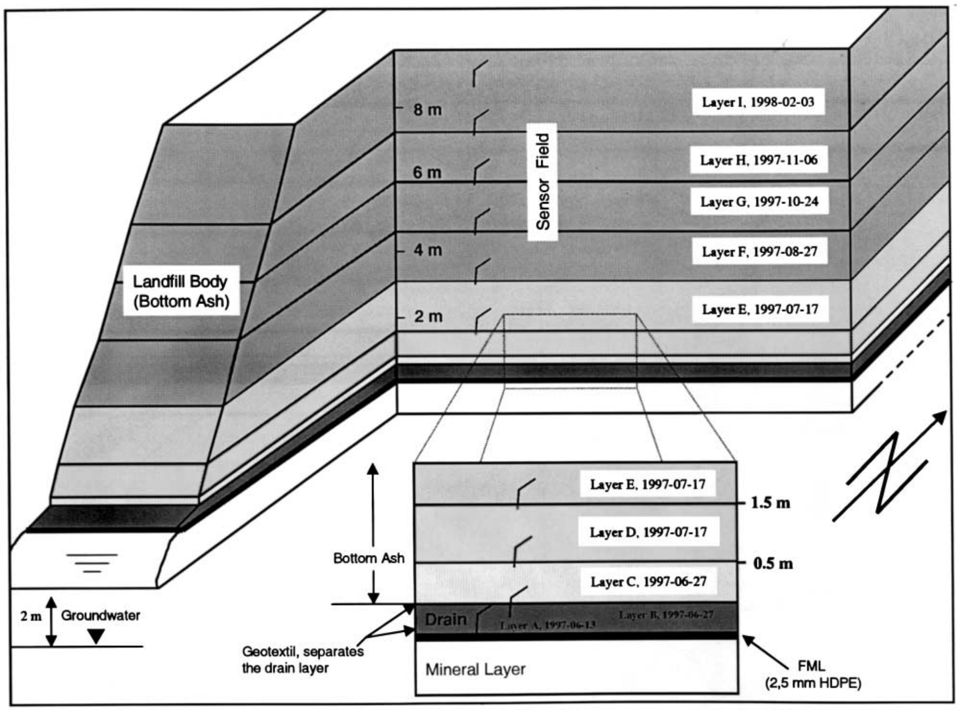

Fig. 2. Schematic cross section through the bottom ash landfill in Ingolstadt (Germany) showing locations of the temperature sensors installed within discrete layers (A–I).

2.1.2. Materials

Temperatures were recorded using Pt-100 temperature sensors (R + S Components, Moerfelden, Germany, measurement range from −200 to +300°C with an error of 0.3%) embedded directly into the bottom ash. The sensors were installed at the top of each layer before the deposition of a new layer (except of sensors in layer I which was placed in the middle of the layer, 9 m above drain, see Table 2, Fig. 2), thus reflecting the temperature development under ordinary disposal management conditions. Each of the nine discrete layers was equipped with two sensors, placed at a horizontal spacing of approximately 1 m.

The bottom ash was deposited in irregular time intervals (depending on bottom ash amount in the MSWI). The ash remained piled for 1–3 weeks on the landfill before it was levelled flat to 150 cm thick layers by dredging. The bottom ash piles were located in the eastern part of sector IV and in sector III. Bottom ash was not compacted and no temporary liner was used to cover the landfill between deposits. There has been no other activity in the test field area during the measurement period.

Data were recorded using a DL2e data logger (Delta-T-Devices, Cambridge, UK) at intervals of maximum 24 h. Additionally, in order to detect any temperature fluctuations, data were recorded at intervals of 1 h from 6 April to 13 April 2000. The following climatic

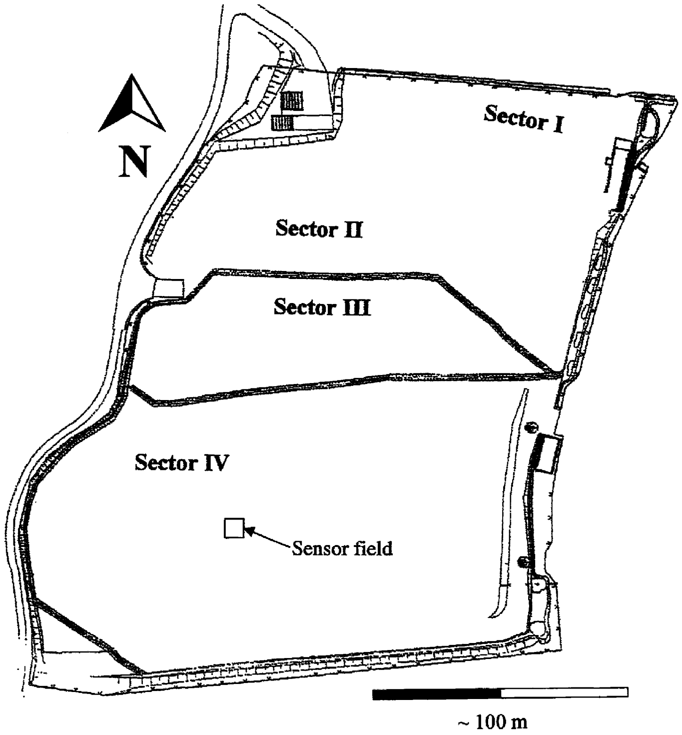

Fig. 3. Schematic section of the bottom ash landfill in Ingolstadt (Germany) showing locations of the temperature sensor field and the four landfill sectors.

Table 2
Bottom ash depositing parameters during the installation of the test field and the corresponding temperature gradients during the first 50 days of depositing

Layer	Localization within the landfill	Date of depositing	Ambient temperature (°C)	Temperature of the underlying layer (°C)	Average temperature gradient (°C per day)
A	at the FML	13 June 1997	24	8.5	0.14
B	in the drain	27 June 1997	22	17.5	0.16
C	0.5 m above drain	27 June 1997	22	21.2	0.23
D	1.5 m above drain	17 July 1997	26	32.5	0.4
E	3.0 m above drain	17 July 1997	26	36.4	0.4
F	4.5 m above drain	27 August 1997	27	51.8	0.71
G	6.0 m above drain	24 October 1997	7	68.7	1.02
H	7.5 m above drain	1 November 1997	15	69.1	0.99
I	9.0 m above drain	3 February 1998	−1	67.5	Climatic changes

parameters were recorded daily using equipment provided by Delta-T-Devices (Cambridge, UK): Air temperature, air humidity, solar radiation, and rainfall. Data are available over a time period of 36 months from June 1997 to June 2000.

2.1.3. Heat transport

Heat is transported in the bottom ash landfill mainly by two ways. First, there is a conductive heat transport from one layer to each other. The second way is a convection heat transport from the bottom ash to the atmosphere.

The conductive heat transport j can be calculated with the thermal conductivity of the bottom ash λ and the temperature difference between two landfill layers $(T_2 - T_1)$

$$j = \lambda(T_2 - T_1) \tag{1}$$

The convection heat transport from the bottom ash to the atmosphere Φ is defined as the product of the temperature difference from the bottom ash to the atmosphere $(T_{\mathrm{S}} - T_{\mathrm{L}})$, the surface A, the time period Δt and the thermal coefficient α_{C} (6.2 $\mathrm{W/m^2\,K}$ for the bottom ash surface)

$$\Phi = \alpha_{\mathrm{C}} A (T_{\mathrm{S}} - T_{\mathrm{L}}) \Delta t \tag{2}$$

3. Results

3.1. Temperature development

The development of the temperatures (daily mean) in the different layers of the field site is given in Fig. 4. The mean temperature difference between the two sensors in each layer was between 0.1 and 0.5°C with an average of 0.24°C.

In every layer the temperature development started with an increase immediately after deposition. During the next 2.8 ± 0.3 months, the bottom ash temperatures increased by about 75°C, depending on the layer position. The average rate at which the temperatures rose was between 0.16 and 1.02°C per day (Table 2).

In layers A and B (FML and drain) the initial temperature rise (0.14°C per day in layer A and 0.16°C per day in layer B during the first 4 weeks) was followed by a levelling off for the next 2 months. Afterwards a second increase of temperatures, now at a rate of 0.065 ± 0.005°C per day was observed. The maximum temperature (45.9°C in layers A and B) was reached 17 months after the deposition of these layers. Subsequently, the temperatures in layers A and B decreased at a rate of 0.6°C per month (layer A), respectively 0.54°C per month (layer B). The temperature increase in these two layers is a result of the temperature increase in the bottom ash layers deposited above them and the heat flux from these layers. The gravel in the drainage (layer B) and the FML (layer A) do not generate their own heat.

Layer C (the lowest bottom ash layer) showed an initial temperature increase of up to 44°C (at a rate of 0.25°C per day) during the first 2 months of storage. The temperature increase showed a first levelling off after a storage time of 18 days. After depositing layer D, layer C showed a renewed small rise in the gradient of temperature increase. This

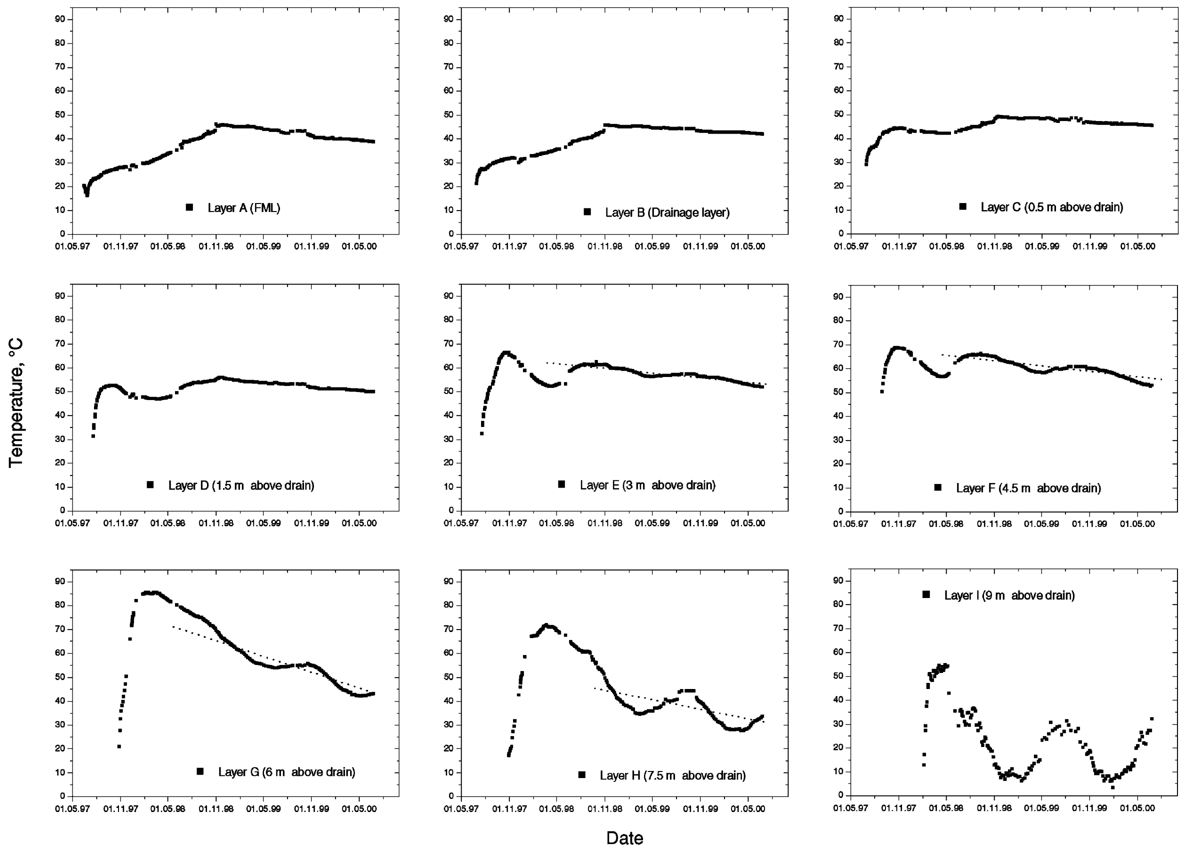

Fig. 4. Recorded temperatures in the various landfill layers. The different factors, explaining the variation of the temperatures are given in the text.

increase was followed by a 6 month temperature decrease (0.36°C per month). With a second temperature increase, this layer reached its maximum after 14 months of storage time (49°C for layer C). From that time temperatures decreased at an overall rate of 0.3°C per month.

Layer D showed a similar temperature development with an initial temperature increase of 0.35°C per day. It reached its maximum temperature after 14 months of storage time (56°C) and decreased then with an rate of 0.3°C per month.

In layers E–G, the temperature development after the initial increase (with its maximum at 87°C in layer G) shows an oscillation with a period of approximately 12 months. The monthly average temperatures (dotted line in Fig. 4) decline at a rate of 0.3°C per month in layers E and F and 0.9°C per month in layer G.

Layer H shows a similar temperature development. After a storage time of 80 days, the temperature increase in layer H levelled off. By depositing layer I, the temperature in layer H rose again for the next 50 days and reached its maximum with 72.2°C. The trend in this layer indicates a decline of temperatures at the rate of 0.6°C per month.

At the top of the landfill, layer I, the initial increase was followed by a rapid decrease and a following oscillation with a period of 12 months. The minimum temperatures were reached during winter, the maximum temperatures during summer. The temperature curve also shows an oscillation with a shorter period (24 h) reflecting the daily ambient temperature fluctuation (Fig. 5).

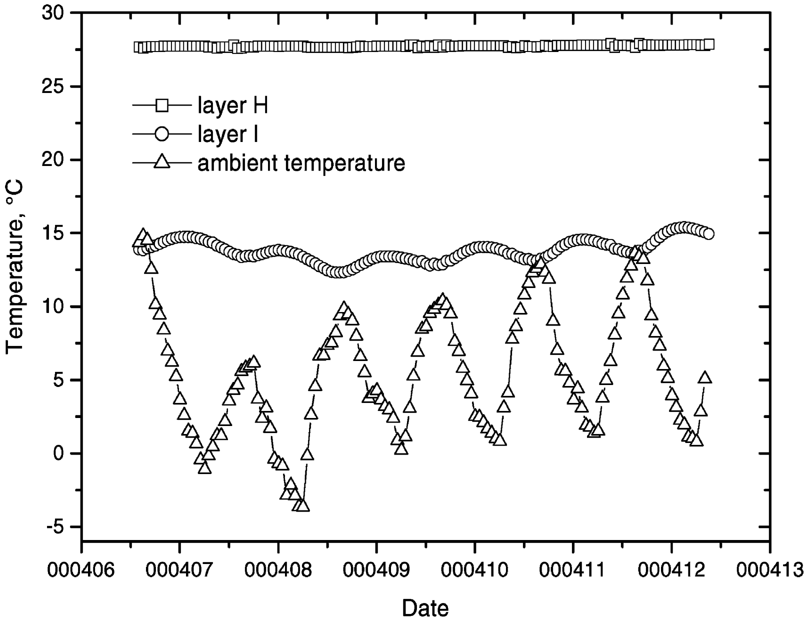

Fig. 5. Influence of measured daily temperature fluctuations (recorded for 1 week at intervals of 1 h) on selected bottom ash layers.

Three years after deposition, temperature development in the upper layers shows an overall decrease with a seasonal component. The lower layers in the lower landfill follow this overall trend, but they do not show the seasonal influence.

4. Analysis

There are several factors which are suspected to influence temperature development. A simplified description of the temperature change (ΔT) within a representative elemental volume (REV) leads to Eq. (1) as the sum of heat production (E_{exo}) due to exothermic reactions minus the heat consumption from endothermic reactions (E_{end}) plus external input (F_{in}) minus heat loss (F_{out}).

$$\Delta T = E_{\mathrm{exo}} - E_{\mathrm{end}} + F_{\mathrm{in}} - F_{\mathrm{out}} \tag{3}$$

Within this equation, the amount of exothermic and endothermic reactions is unknown. The heat exchange to and from the REV is a function of the temperature gradient, the thermal conductivity and the convection heat transfer between the REV and its environmental (e.g. other bottom ash REV, drain, atmosphere). On the field scale, each layer is considered as a REV.

The key factors influencing the temperature development thus can be defined as

1. the temperature gradient to the underlying layer or, if there is no underlying layer, the ground of the landfill,
2. the temperature gradient to the ambient temperature or, if another layer is on top of the REV, the temperature gradient to the upper layer,
3. the thermal conductivity between the REV and its environment,
4. the convection heat transfer from the bottom ash to the atmosphere,
5. the ratio between heat production and the heat flux at the boundaries of the REV, which is expected to be a function of the surface-to-volume ratio of the REV,
6. the effect of the precipitation as transport and reaction medium.

In the following section, the effects of these factors will be assessed semi-quantitatively based on the measurements of temperature development.

4.1. Temperature at the bottom of each layer

There is a positive correlation ($R^2 = 0.983$, $N = 6$) between the temperature gradient from the next deposited bottom ash layer to the underlying layer (at the time of depositing the next layer) and the rate of temperature increase in the newly deposited layer (Fig. 6). This effect is based on an addition of the internal generation of heat in each bottom ash layer (layers A and B do not generate their own heat) and the heat conduction from the underlying layer.

The highest rate of increase (temperature increase per day, see Table 2) was observed in layer G, where the temperature of the underlying layer (layer F) had reached a temperature of almost 69°C when layer G was deposited. The lowest rate was observed in layer C, where

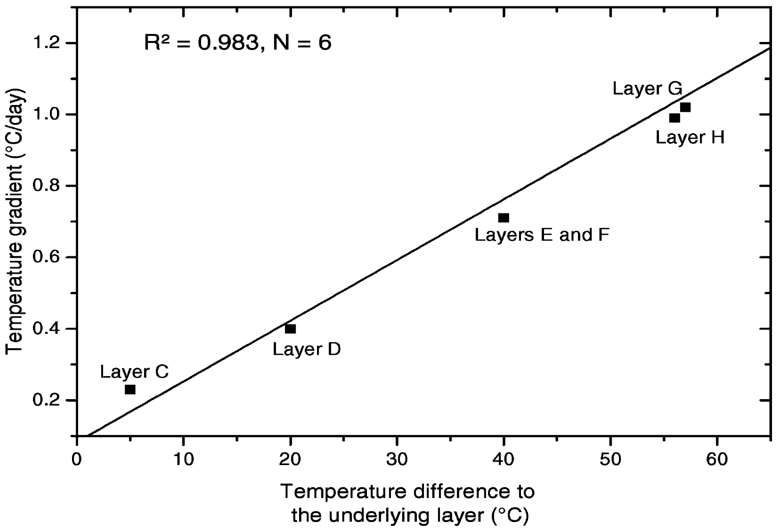

Fig. 6. Calculated gradient of temperature increase of the different layers vs. the temperature of the underlying layer in time of depositing the next one (shown is the regression line).

the underlying layer, which does not generate heat at all, had a temperature of only 21°C (see Table 2).

4.2. Ambient temperatures

There is a statistically significant correlation ($R^2 = 0.788$, $N = 522$) between the temperatures in the top layer (layer I) and the ambient temperature (Fig. 7). This effect is observed to be less pronounced with increasing depth in the landfill. Layers E to H show an oscillation in bottom ash temperature after having reached their maximum temperatures. This oscillation has a period of approximately 12 months and reflects the annual ambient temperature development with a delay of 28 days for layer H, 58 days for layer G, 82 days for layer F and 112 days for layer E. This growing delay reflects the thermal buffer capacity of the bottom ash.

4.3. Surface-to-volume ratio

Heat flux (Φ) from the bottom ash towards the cooler air is an important factor influencing the thermal development in the landfill.

With an upwards conductive heat transport in layer I of 2–35 W/m^2 (with an average of 15 W/m^2) and an average convection heat transport of 70–250 W/m^2 (with an average of 105 W/m^2) from the heated bottom ash of layer I to the air during the first 200 days of deposition, the addition of each new layer hampers the heat exchange between the bottom ash and the atmosphere.

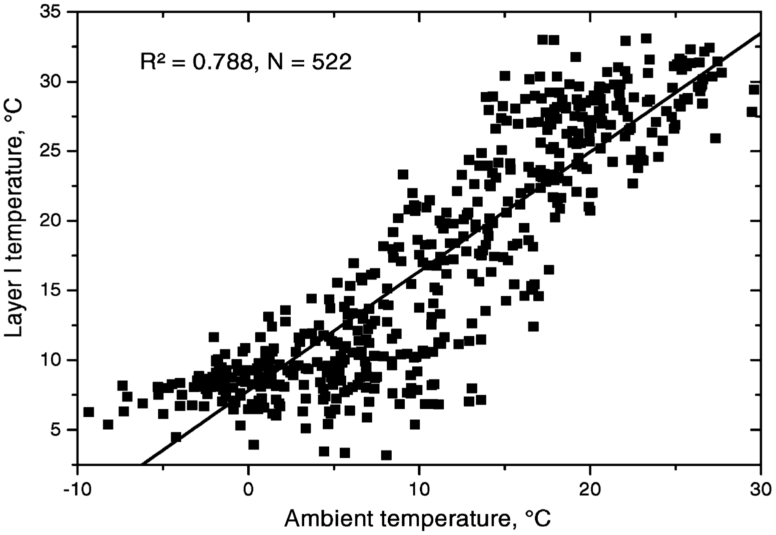

Fig. 7. Recorded ambient temperature plotted vs. recorded temperature in layer I (shown is the regression line).

There is a correlation ($R^2 = 0.987$, $N = 4$) between the surface-to-volume ratio (s/v) and the maximum temperature in the observed volume. The maximum temperature increases with decreasing s/v (Fig. 8) from 50°C (layer C) to 87°C (layer G) (see Table 2).

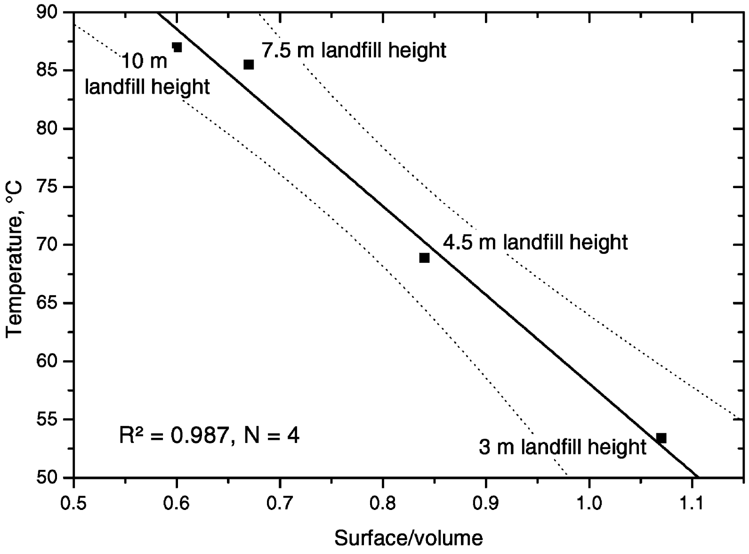

Fig. 8. Calculated surface-to-volume ratio of the growing landfill vs. the maximum temperatures in the middle of each volume at the given landfill height (shown is the regression line).

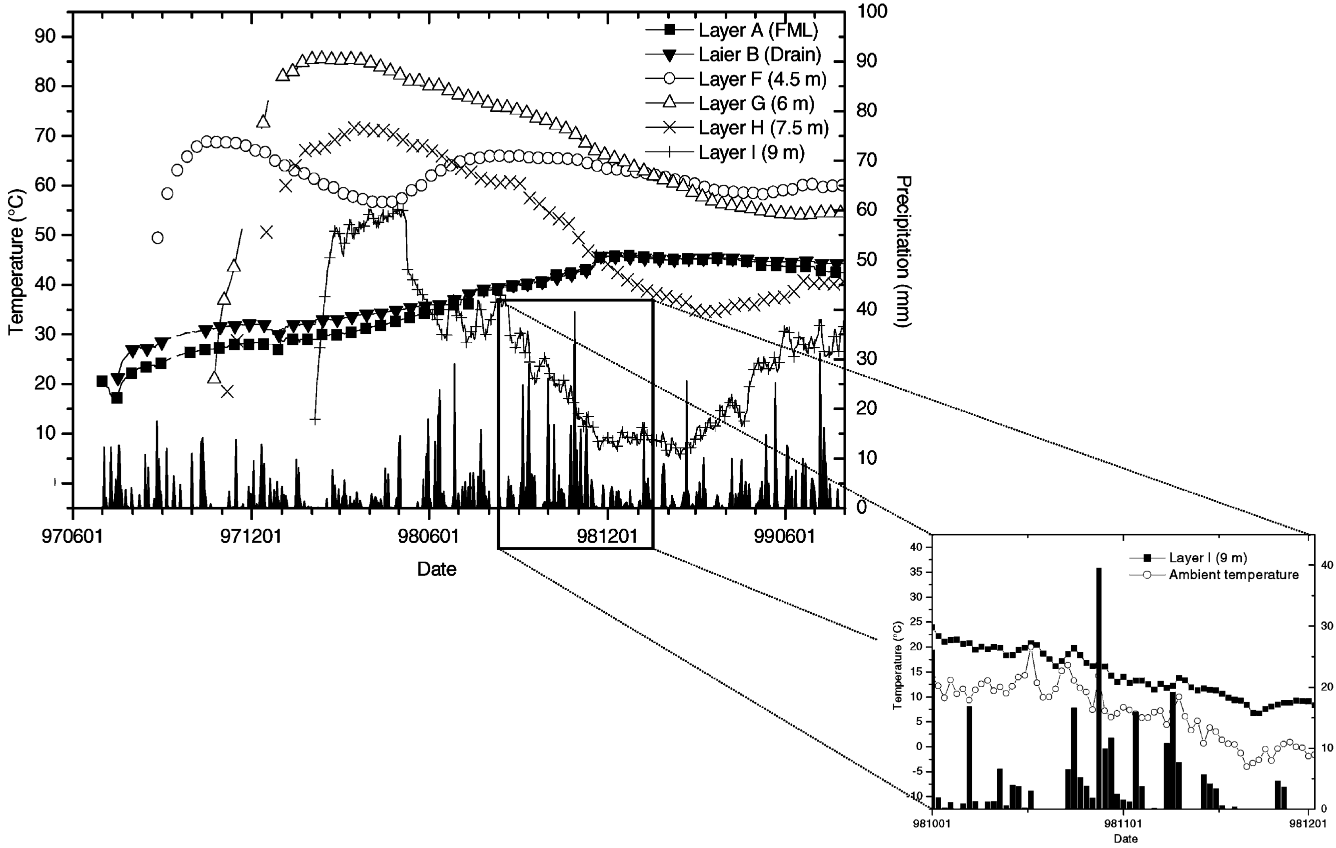

Fig. 9. Temporal change of bottom ash temperature in selected layers and precipitation intensity.

4.4. Precipitation

Rainwater seeping through the landfill body influences the temperature in two ways. First, it is a transport medium and contributes to the heat exchange. Second, it is a reaction medium and contributes to the heat production.

Although we observed that rainfall passes through the landfill within days (there is a direct discharge responding to rain events), precipitation seeping through the landfill body was not observed to have a significant effect on temperatures in the bottom ash (Fig. 9).

Seeping water passing the landfill showed a temperature increase regardless of the intensity of the rainfall of approximately 11.5°C. This is equivalent to an heat extraction of only 0.1 W/m^3 bottom ash from the landfill.

Even after an intensive period of rain (e.g. 85 mm within 6 days, 25 October 1998 until 11 November 1998) there was no observable influence on temperature development in the landfill body and on the temperature of the leachate. The temperature decrease in layer I during this rain period is mainly caused by ambient temperature fluctuations (Fig. 9). A dry period in spring (26 March 1999 until 30 May 1999, 120 mm within 70 days) also appears to have caused no change in the temperature development. Precipitating waters seeping through the landfill body, exhibited only a negligible cooling effect.

5. Conclusions

The monitoring of the temperatures in a MSWI bottom ash landfill over a 3-year-period showed a maximum temperature of 87°C 3 months after disposal followed by a decrease over the next 33 months. Temperatures at the FML reached a maximum of 45.9°C after 17 months. Subsequently, the temperature decreased at a rate of 0.6°C per month. We estimate that the temperature in this layer will stay in the critical region above 40°C (depolymerisation and oxidation in the FML, desiccation of the mineral clay layer) for the next year. These temperatures may jeopardise the integrity of the liner through depolymerisation of the HDPE and desiccation of the clay layer, resulting in leachate escaping into the groundwater.

From the temperature development, it can be seen that the main temperature increase due to the exothermic reactions have a time scale of 2–3 months, after which the reaction activity decreases. This suggests that the bottom ash should be stored in thin layers or small cones (which have a favourable s/v ratio) for at least 3 months prior to the final disposal.

The disposal should be given a significant amount of time to react before the next layer is deposited, since the temperature of the underlying layer controls the initial temperature development of the actual layer. From our investigations, it can be concluded that the disposal of the next layer should not start before the maximum temperatures of the underlying layer have been reached and the temperatures and the heat production in the underlying layer are decreasing again significantly. At the present stage of the experiments, we estimate that the time before depositing a new layer should be approximately 3–5 months.

If that time lag in the filling procedure is not possible, other cooling measures (e.g. reinjection of landfill leachate) have to be brought forward, since the precipitation shows a negligible cooling effect. In any case, if a sustainable liner system imperviousness has to be guaranteed, the capping and recultivation of the landfill, which will hamper any heat, gas, water or vapour exchange between bottom ash and atmosphere should be done only after the reactions within the landfill have reached a minimum and no further temperature rise is to be expected (at least 1 year after the final deposition of the bottom ash). A premature recultivation may lead to an additional temperature increase within the landfill body unless the exothermic reactions have decreased significantly.

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References

[1] European Environment Agency, Dangerous Substances in Waste, Technical report No. 38 (2000), http://themes.eea.eu.int/toc.php?toc=39332.

[2] H.U. Hartenstein, M. Horvay, Overview of municipal waste incineration industry in West Europe (based on the German experience), J. Hazard. Mater. 47 (1996) 19–30.

[3] J.M. Chimenos, M. Segarra, M.A. Fernández, F. Espiell, Characterisation of the bottom ash in MSWI, J. Hazard. Mater. 64 (1999) 211–222.

[4] C.C. Wiles, Municipal solid waste combustion ash: state of the knowledge, J. Hazard. Mater. 47 (1996) 325–344.

[5] A.E. Chandler, J. Hartlen, Municipal solid waste incinerator residues, Studies in Environmental Science 67, Elsevier, Amsterdam, 1997.

[6] D.H. Komilis, R. Stegmann, The effect of municipal solid waste pretreatment on landfill behaviour: a literature review, Waste Manage. Res. 17 (1999) 10–19.

[7] O. Hjelmar, Disposal strategies for municipal solid waste incineration residues, J. Hazard. Mater. 47 (1996) 345–368.

[8] J. Pera, Use of incinerator bottom ash in concrete, Cement Concrete Res. 27 (1) (1997) 1–5.

[9] E.R. Berg, J.A. Neal, Municipal solid waste bottom ash as Portland cement concrete ingredient, ASCE J. Mater. Civil Eng. 10 (1998) 168–173.

[10] C.A. Johnson, Chemische Eigenschaften und Langzeitverhalten der Müllschlacke (Chemical properties and long-term behaviour of MSWI bottom ash). Deponierung fester Rückstände aus der Abfallwirtschaft — Endlagerqualität am Beispiel Müllschlacke, Ittingen/ Schweiz (1993) 35–52.

[11] C.A. Johnson, S. Brandenberger, P. Baccini, Acid neutralizing capacity of municipal waste incinerator bottom ash, Environ. Sci. Technol. 28 (1995) 142–147.

[12] T. Lichtensteiger, Müllschlacken aus petrologischer Sicht (MSWI bottom ash from the petrologic view), Geowiss. 14 (1996) 173–179.

[13] J. Yan, Neutralising process of MSWI bottom ash in a flow ash system, Sci. Total Environ. 227 (1999) 1–11.

[14] J. Yan, L. Moreno, The neutralization behaviour of MSWI bottom ash on different scales and different reaction systems, Waste Manage. 19 (5) (1999) 339–347.

[15] S. Dugenest, MSWI bottom ash: characterization and kinetic studies of organic matter, Environ. Sci. Technol. 33 (1999) 1110–1115.

[16] T. Lichtensteiger, Langzeitverhalten von Schlacken in Deponien (Long-term behaviour of MSWI bottom ash). VDI-Bildungswerk, Seminar 43-76-03, 16./17.3.92, (1992) München.

[17] M. Turk, Inkrustationen in Entwässerungssystemen von MVA-Schlacke- und Klärschlammproben (Incrustations in MSWI bottom ash landfill drainage systems and sewage mud), Müll und Abfall 9 (1996) 587–594.

[18] C. Dittmar, K.M. Gottheil, T. Mossotter, Kombinationsdichtungen für Deponien- Versuche zum Verhalten unter thermischer Belastung (The influence of temperature stress on the mineral and polymer liners below landfills), Z. dt. geol. Ges. 141 (1990) 364–368.

[19] U. Holzlöhner, Austrocknung und Rißbildung in mineralischen Schichten der Deponiebasisabdichtung (Drying out of mineral liners below landfills), Wasser und Boden 5 (1992) 289–293.

[20] P. Döll, Austrocknung von Kombinationsdichtungen unter Deponien mit Wärmeentwicklung (Drying out of mineral liners below landfills under the influence of temperature gradients), Müll und Abfall 5 (1998) 295–302.

[21] H. Stoffregen, Rißgefährdung von Kombinationsdichtungen durch temperatur-abhängige Austrocknung (Desiccation risk of mineral and polymer liners below landfills under the influence of temperature gradients), Müll und Abfall 1 (1999) 29–35.

[22] C.A. Johnson, A. Richner, T. Vitvar, N. Schittli, M. Eberhard, Hydrological and geochemical factors affecting leachate composition in MSWI bottom ash. Part I: the hydrology of landfill Lostdorf, J. Contam. Hydrol. 33 (1998) 361–376.

[23] S. Dugenest, MSWI bottom ash: characterization and kinetic studies of organic matter, Environ. Sci. Technol. 33 (1999) 1110–1115.

[24] C. Zevenbergen, L.P. van Reeuwijk, J.P. Bradley, R.N.J. Comans, R.D. Schuiling, Weathering of MSWI bottom ash with emphasis on the glassy constituents, J. Geochem. Explor. 62 (1–3) (1998) 293–298.

[25] J. Meima, The leaching of trace elements from MSWI bottom ash at different stages of weathering, Appl. Geochem. 14 (1999) 159–171.

[26] C. Zevenbergen, R.N.J. Comans, Geomechanical factors controlling the mobility of major elements during weathering of municipal solid waste incinerator (MSWI) bottom ash, Stud. Environ. Sci. 60 (1994) 179–194.

[27] J. Morris, Recycling versus incineration: an energy conservation analysis, J. Hazard. Mater. 47 (1996) 277–293.

[28] J.J.U. Staketee, L.G.C.M. Urlings, in: J.J.M. Goumans, H.A. Van der Sloot, T.G. Aalbers (Eds.), Environmental Aspects of Construction with Waste Materials, Elsevier, Amsterdam, 1994, p. 233.

[29] DIN 18 123-5. Bestimmung der Korngrößenverteilung durch Sedimentation (grain size distribution) DIN 18 123 Ausgabe 4/1983 Abschnitt 5, Berlin/Köln (1983).

[30] DIN 18121. Wassergehalt — Bestimmung durch Ofentrocknung (water content — determination with oven drying), Teil 1, Berlin/Köln (1976).

[31] J. Reichelt, Mineralogische Aspekte bautechnischer und umweltrelevanter Eigenschaften von Müllverbrennungsschlacken (Mineralogical aspects, technical and environmental properties of MSWI bottom ash), Veröffentlichungen des Institutes für Straßen- und Eisenbahnwesen der Universität Karlsruhe (TH) 47 (1996).

[32] AEW-Plan, Tekturplan Schlackedeponie Großmehring (MSWI bottom ash landfill building plan), Ausbau Abschnitt 4. München, Zweckverband Müll-verbrennungsanlage Region Ingolstadt (1988).