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Numerical modelling of the generation and transport of heat in a bottom ash monofill

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Abstract

Municipal solid waste is incinerated to reduce its volume, toxicity and reactivity. Several studies have shown that the resulting bottom ash has a high exothermic capacity. Temperature measurements in municipal solid waste incineration (MSWI) bottom ash landfills have found temperatures up to 90 °C. Such high temperatures may affect the stability of the landfill's flexible polymer membrane liner (FML) and may also lead to an accelerated desiccation of the clay barrier. The purpose of this study was to gain detailed knowledge of temperature development under several disposal conditions in relation to the rate of ash disposal, the variation of layer thickness, and the environmental conditions in a modern landfill. Based on this knowledge, a simulation was developed to predict temperature development. Temperature development was simulated using several storage periods prior to the deposition and several modes of emplacement. Both the storage time and the mode of emplacement have a significant influence on the temperature development at the sensitive base of the landfill. Without a preliminary storage of the fresh quenched bottom ash, high temperatures at the bottom of a landfill cannot be avoided.

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

1. Introduction

Until the 1970s, bottom ash from municipal solid waste incineration was believed to be almost inert, but since then several studies have shown that many exothermic reactions may cause a temperature increase of up to 90 °C in the landfill [1].

High temperatures at the bottom of a landfill may affect the stability of the landfill liner system (flexible membrane liner, polymer membrane liner (FML) and mineral clay layer).

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Temperatures above 40 °C may damage the stability of the FML (made of high-density-polyethylene, HDPE) due to depolymerisation and oxidation [2]. Due to 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 [3,4]. In order to prevent thermal damages to the liner system, it is necessary to minimise the temperatures in the landfill. There are several factors such as the storage time prior to the deposition and the surface-to-volume ratio influencing the temperature development in a landfill [1]. The most important reactions that cause a temperature increase in the stored bottom ash are the corrosion of iron and aluminium, the hydration of lime (CaO) and the carbonation of portlandite ($Ca(OH)_2$) [5–7]. Table 1 shows the identified reactions. Speiser [8] has pointed out that the corrosion of iron is followed by carbonation of portlandite which are the most relevant heat sources in bottom ash material.

Assessing the thermal capacity of the residues is essential since bottom ash has been deposited in landfills with poor landfill liner systems in Europe and in other countries during the last decade [7]. In the US, bottom ash was commonly landfilled without processing, even though metals and other materials can be recovered by magnetic separation and screening [9]. In some European countries (e.g. Germany, The Netherlands and France) approximately 60% of the bottom ash is reused in road construction or as raw material for the ceramic and cement industry [10–12], whereas in Switzerland almost 100% of the bottom ash is disposed in landfills [9].

Although the exothermic reactions in bottom ash are well known, their speed and the amount of heat released are still unknown. Klein et al. [1] have shown that the main temperature increase due to the exothermic reactions has a time scale of 2–3 months. Speiser [8] calculated an average specific heat production of 5.3 $W\,m^{-3}$ of the bottom ash material during the first 2 years of deposition. The released energy in this period amounts to 313–331 $MJ\,m^{-3}$. The bottom ash investigated in this study is comparable to a common bottom ash analysed in the EU [6].

The objective of this work was to develop a numerical model incorporating basic concepts from chemistry and physics to simulate the spatial and temporal distribution of heat in a bottom ash landfill. This objective was accomplished in two steps: (1) the observation of the temperature development in a bottom ash landfill under several modes of emplacement, and (2) the development of a heat generation and transport model and validation of this with the data obtained from field experiments. This numerical simulation provides the possibility of

Table 1
Exothermic reactions in bottom ash materials [5–7]

Reaction	Enthalpy of reactions, ΔH ($kJ\,mol^{-1}$)
$2Al + 6H_2O \leftrightharpoons 2Al(OH)_3 + H_2\uparrow$	−422
$FeS + (9/4)O_2 + (5/2)H_2O \leftrightharpoons Fe(OH)_3 + H_2SO_4$	−921
$CaO + H_2O \leftrightharpoons Ca(OH)_2$	−65
$Ca(OH)_2 + H_2CO_3 \leftrightharpoons CaCO_3 + 2H_2O$	−111
$Ca(OH)_2 + CO_2 \leftrightharpoons CaCO_3 + H_2O$	−120
$Ca(OH)_2 + SiO_2 \leftrightharpoons CaH_2SiO_4$	−140
$CaH_2SiO_4 + CO_2 \leftrightharpoons CaCO_3 + SiO_2 + H_2O$	−25

predicting the temperature development in a bottom ash landfill under different modes of emplacement.

2. Experimental

2.1. Field observations

Three vertical sensorfields (SF1, SF2, SF3) were embedded in two bottom ash landfills in the south of Germany. Temperatures were recorded using Pt-100 temperature sensors (R + S Components, Moerfelden, Germany, measurement range from −200 to +300 °C).

The bottom ash in SF1 was deposited in irregular time intervals (see Table 2) depending on the amount bottom ash to be disposed, over an 8-month period to a maximum thickness of ten meters [1]. SF2 was emplaced within 3 weeks to its final height of 10 m. The bottom ash for SF1 and SF2 was stored for 3–6 weeks before being deposited at the landfill. In SF3, bottom ash was emplaced in layers with a thickness of 1 m every 2 months up to a final height of 5 m. The bottom ash in this sensorfield was stored for a maximum duration of 3 days prior to deposition.

2.2. Numerical simulation

The landfill is represented in a computer model as a one-dimensional column, consisting of a geological barrier (GB) underneath the landfill, a liner system (LS), the main bottom ash (BA) body, and (optionally) a surface sealing (SS) (Fig. 1). The individual layers of this linear model used in this work are represented by discrete volume elements with a thickness

Table 2
Bottom ash deposition parameters during the installation of the test field

Location within the landfill	Date of depositing, corresponding ambient temperature and bottom ash amount		
	SF1	SF2	SF3
At the FML	13 June 1997 (24 °C)	18 May 1999 (21 °C)	6 December 2000 (4 °C)
In the drain	27 June 1997 (22 °C)	18 May 1999 (21 °C)	6 December 2000 (4 °C)
0.5 m above drain	27 June 1997 (22 °C, 600 m^3)	18 May 1999 (21 °C, 300 m^3)	6 December 2000 (4 °C, 1280 m^3)
1.5 m above drain	17 July 1997 (26 °C, 800 m^3)	18 May 1999 (21 °C, 410 m^3)	7 February 2001 (−3 °C, 1500 m3)
3.0 m above drain	17 July 1997 (26 °C, 750 m^3)	18 May 1999 (21 °C, 580 m^3)	11 April 2001 (7 °C, 1620 m3)
4.5 m above drain	27 August 1997 (27 °C, 650 m^3)	18 May 1999 (21 °C, 750 m^3)	3 August 2001 (26 °C, 1800 m3)
6.0 m above drain	24 October 1997 (7 °C, 810 m^3)	18 May 1999 (21 °C, 620 m^3)	
7.5 m above drain	1 November 1997 (15 °C, 720 m^3)	6 June 1999 (23 °C, 580 m^3)	
9.0 m above drain	3 February 1998 (−1 °C, 760 m^3)	6 June 1999 (23 °C, 610 m^3)	

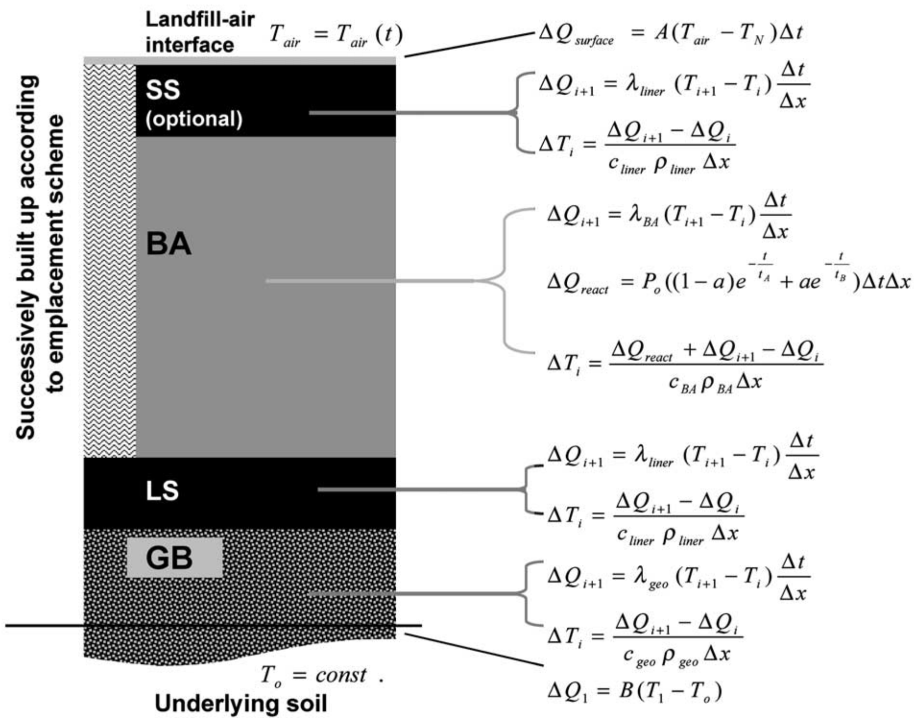

Fig. 1. Schematic structure of the linear column consisting of a geological barrier underneath the landfill (GB), a liner system (LS), the main bottom ash (BA) body as well as (optionally) a surface sealing (SS). The equations on the right side show how the heat balance of the individual layers used in the simulation model. The index 0 indicates the underlying soil, the index n corresponds to the air (i.e. the topmost layer).

of $d = 5$ cm. Heat conduction was computed according to Fourier's law:

$$q_{\text{eff}} = -\lambda_{\text{eff}} \frac{\partial \vartheta}{\partial z} \tag{1}$$

(q_{eff}: effective heat stream, λ_{eff}: effective heat conductivity, $\partial\vartheta/\partial z$: temperature gradient) with a discrete time step of $\Delta t = 30$ min. The heat capacities and thermal conductivities of the different layers in the landfill are given in Table 3. The bottom of the geological barrier was implemented as a fixed head boundary (i.e. a fixed-temperature element with a temperature of 8 °C and an infinite heat capacity; experimentally, the natural groundwater temperature was found to vary only in a temperature range between 6 and 10 °C). By choosing a sufficiently thick GB layer, influences of the boundary on the model area were kept to a minimum. Heat transfer between bottom ash and either surface sealing or atmospheric air (air temperatures were recorded at the dump location) was approximated by a linear heat transmission. Precipitation, wind and sunshine were known from field measurements to have minor impact on landfill temperature [1]. Vapour and fluid phase convection processes which also appear to have minor influence [1] are not explicitly considered in the model.

Table 3
Initial and boundary conditions for the model of the generation and transport of heat in a bottom ash monofill

Initial and boundary conditions	
Initial heating rate, $P_{(0)}$	Variable
Rate constant of the first exponential, t_A (h^{-1})	0.0006
Rate constant of the second exponential, t_B (h^{-1})	0.00005
Heat transition to the air A	Variable
Heat transition to the soil B	Variable
Fraction of the slow heat generation process, a	0.07
Model height	
Geological barrier	Variable
Liner system	Variable
Bottom ash	Variable
Surface sealing	Variable
Heat conductivity ($W\,m^{-1}\,K^{-1}$)	
Bottom ash, λ_{BA}	0.7
Liner material (clay), λ_{liner}	1.3
Geological barrier, λ_{geo}	0.6
Specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)	
Bottom ash, c_{BA}	0.8
Liner system, c_{liner}	1.85
Geological barrier, c_{geo}	0.88
Temperature	
Bottom ash	Variable
Geological barrier	Variable

For the calculations done in the model I, a biexponential decaying heating rate was used. The use of this biexponential decaying heating rate is a somewhat crude approximation for a much more complicated superposition of many endothermic and exothermic reactions with both concentration and transport limitations going on in the bottom ash. For each layer of the bottom ash body, the heat production due to exothermic reactions in the bottom ash is computed with an overall heating rate $P(t)$ given as

$$P(t) = P_{(0)}((1-a)e^{-t/t_A} + ae^{-t/t_B}) \quad (2)$$

with $P_{(0)}$ representing the initial heating rate of bottom ash, t_A and t_B being the rate constants of the fast and slow reaction processes, respectively, and a being the fraction of the slowly-decaying reaction of the overall heating rate.

The parameters of the biexponential heating rate curve were adjusted by repeatedly running the model with different parameter sets, comparing the model results with the experimental data and choosing new sets of parameters in order to achieve both good correspondence with the experimental data and consistence with the mineralogical observations. As our results show, the parameter set obtained in this process allows a good simulation of the experimentally observed temperature profiles. A possible explanation for two different time scales for the reaction can be the accessibility of reactive material in the bottom ash, which is straightforward on the outside of the bottom ash grains but strongly transport-limited in their cores.

Most parameters of the model were taken from [13–17]. The parameters of the heating rate function were calibrated with field data from SF1.

For all the calculated simulations, the time profile of the air temperature (daily averages) was used as recorded at the landfill site from June 1997 to June 2001. Circadian temperature fluctuations must not necessarily be taken into account for the experimental data since such short-time temperature changes reach only less than 1 m into the landfill body [18,19].

3. Results

3.1. Sensitivity analysis

In order to highlight the significance of chemical, physical and installation parameters controlling heat generation and transport in a bottom ash monofill, a sensitivity analysis was performed. The focus of the analysis was on the parameters that directly affect temperature development in the landfill and in its liner system. Several simulations were performed to assess the model's sensitivity to its chemical, physical and technical parameters. These parameters include the rate of heat release as a result of the exothermic chemical reactions in the bottom ash material, heat transition processes to the bottom and the air, the heat conductivity and the specific heat capacity of the bottom ash and the liner system. To assess the effects of these parameters, one parameter at a time was varied while keeping the others at their basic values. Table 4 summarises the selected sensitivity analysis simulations with the corresponding rationale behind the value chosen for the parameters at each simulation. The simulations performed for this purpose (Fig. 2) lead to the following conclusions:

- The heating rate is the most important factor influencing the temperature increase in the bottom ash landfill, both at the centre as well as at the landfill liner system.
- Heat conductivity of the bottom ash comes next in order of importance.
- At the liner system, heat conductivity of the liner system has a minor influence on temperature development.
- The remaining parameters do not affect the maximum temperature reached in the bottom ash landfill.

Table 4
Summary of the sensitivity analysis simulations

Variable	Basic values	Sensitivity values (basic value multiplied by the number in parentheses)
Heat conductivity of the bottom ash, λ_{BA} ($W\,m^{-1}\,K^{-1}$)	0.7	(0.05, 0.1, 0.2, 0.5)
Heat conductivity of the liner material, λ_{liner} ($W\,m^{-1}\,K^{-1}$)	1.3	(0.05, 0.1, 0.2, 0.5)
Specific heat capacity of the bottom ash, c_{BA} ($kJ\,kg^{-1}\,K^{-1}$)	0.8	(0.05, 0.1, 0.2, 0.5)
Specific heat capacity of the liner system, c_{liner} ($kJ\,kg^{-1}\,K^{-1}$)	1.85	(0.05, 0.1, 0.2, 0.5)
Initial heating rate of the bottom ash, $P_{(0)}$ ($W\,m^{-3}$)	25	(0.05, 0.1, 0.2, 0.5)
Heat transition to the air A ($W\,m^{-2}\,K^{-1}$)	1	(0.05, 0.1, 0.2, 0.5)
Heat transition to the soil B ($W\,m^{-2}\,K^{-1}$)	20	(0.05, 0.1, 0.2, 0.5)

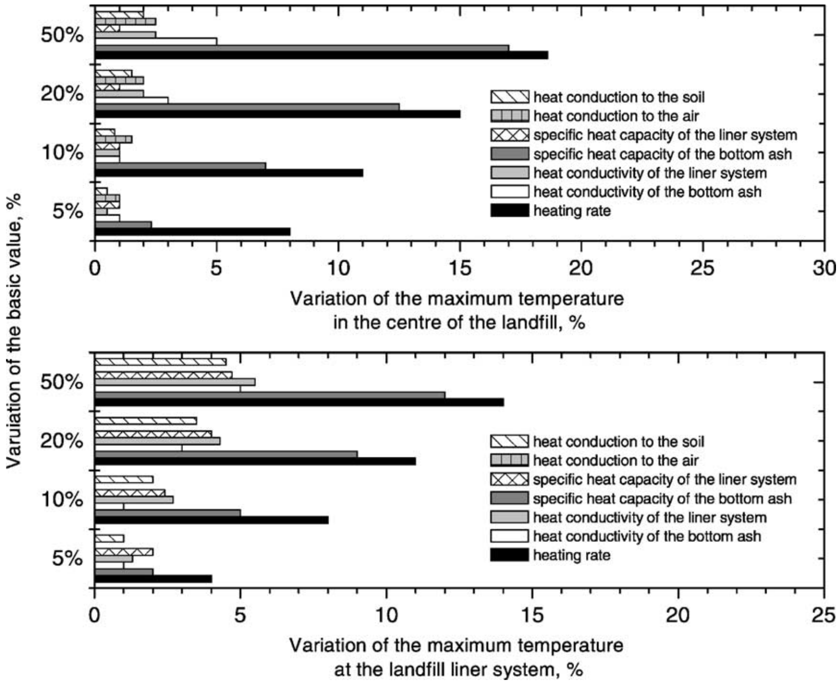

Fig. 2. Effect of variation of basic values on the maximum temperature in the centre of the landfill and at the landfill liner system.

- Heat exchange with the air seems to have no major influence on the temperature development at the landfill liner system.

3.2. Temperature development

Temperature development in selected landfill levels of SF1, SF2 and SF3 is shown in Fig. 3. There was an observed temperature increase immediately after the deposition of a bottom ash layer in each sensorfield. After reaching its maximum 90–160 days after bottom ash deposition, temperature decreased again in all observed landfill layers.

In the following we will present the simulation results for the installed sensorfields and a range of typical emplacement schemes which are summarised in Table 5.

3.3. Calibration and prediction

During model calibration, we have worked out the heating rate of the 3–6-week stored bottom ash material as used in SF1. In order to determine the heating rate of bottom ash when subjected to a previous storage period, the registered temperature development of SF1 was simulated by means of the model. A heating rate upon emplacement of approximately 25 $W\,m^{-3}$ for the bottom ash material could be determined using the simulation. With

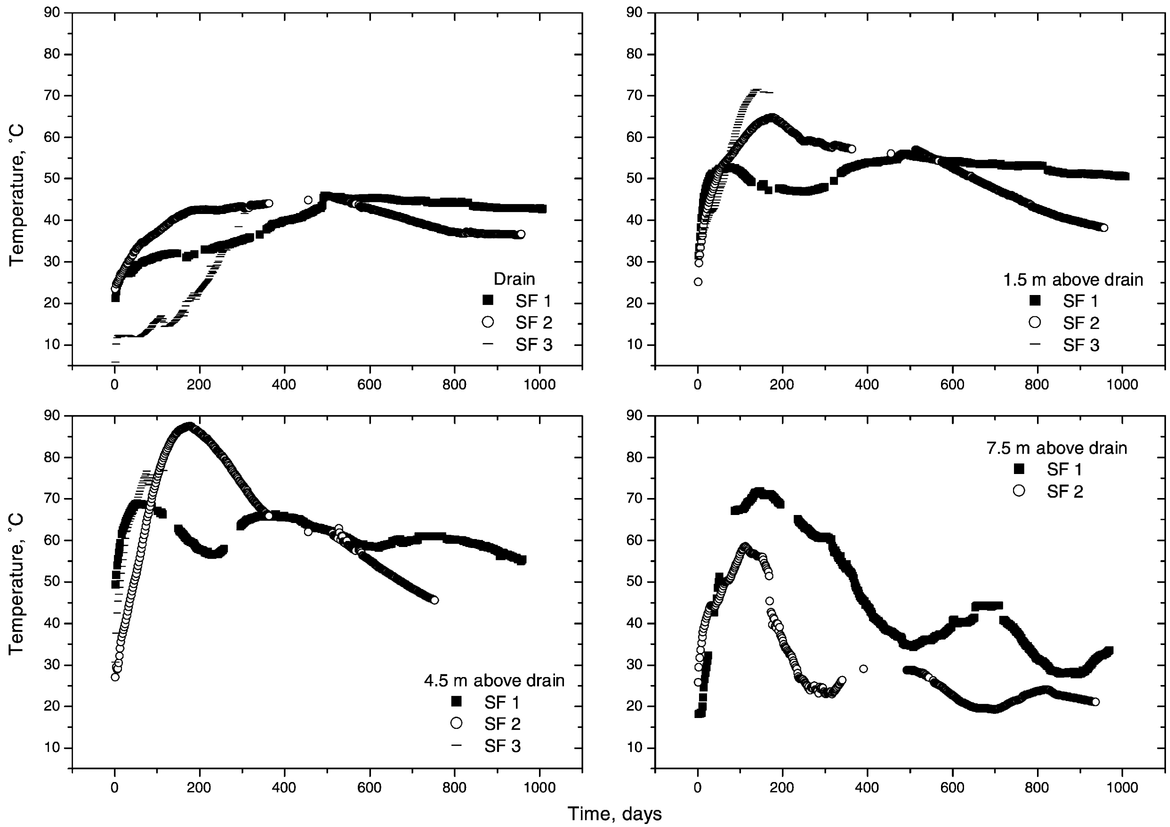

Fig. 3. Measured temperature development in the three sensorfields (SF1–SF3).

Table 5
Deposition procedure for the calculated temperature development in the several model runs of heat generation in a bottom ash landfill

Simulation no.	Emplacement mode	Bottom ash storage time	Heating rate upon emplacement ($W\,m^{-3}$)
A	Deposition in discrete intervals of 1 m every 2 months	3–6 weeks	25
B	Deposition within 2 weeks to its final height, surface sealing directly after the deposition of bottom ash	3–6 weeks	25
C	Deposition according to SF1, surface sealing after 3 years	3 months	15

the biexponential decrease of the initial heating rate described above, the experimentally observed temperature maximum of 87 °C in the centre of the landfill at SF1 after 4–5 months after deposition could be reproduced in the simulation. The maximum temperature at the landfill base was reached with 46 °C 18 months after the deposition of the first bottom ash layer. Fig. 4 shows the deviations of the calculated temperatures from the real data measured on the landfill site during the first 1000 days. As can be seen from the figure, the model closely describes temperature development in the lower (liner system) and central (4.5 m above liner system) landfill areas. In the upper landfill areas, there is slight deviation from the measured temperatures in the first winter minimum. This affect is possibly due to a variation in the bottom ash quality which is not accounted for in the simulation. There is an overall good correlation between the calculated and measured data ($R^2 = 0.834$, $N = 8443$).

With the initial heating rate of 25 $W\,m^{-3}$ and the biexponential decay, we have calculated a released energy of 250 $MJ\,m^{-3}$ for the first 2 years of storage in the landfill. This amount corresponds with the data observed by Speiser [8].

3.4. Validation and prediction (SF2)

After this calibration, the model was validated using the measured temperature data of SF2 (900 days measurements). With the heating rate value upon emplacement of 25 $W\,m^{-3}$ determined above, there was good agreement between simulated and observed data. Fig. 5 shows the deviations of the calculated temperatures from the real data measured on the landfill site during the first 850 days. With these data, a good correlation between the calculated and measured data ($R^2 = 0.867$, $N = 7521$) was found.

3.5. Validation and prediction (SF3)

In the second validation phase, the initial heating rate of the fresh quenched bottom ash material, as used in SF3 was measured. In order to determine the initial heating rate of the bottom ash, the measured temperature development during the first 6 months of storage in SF3 with its new emplacement mode was simulated by means of the model. An initial heating rate of approximately 45 $W\,m^{-3}$ for the bottom ash material in the absence of a preliminary storage period could be determined. With the biexponential decrease of the

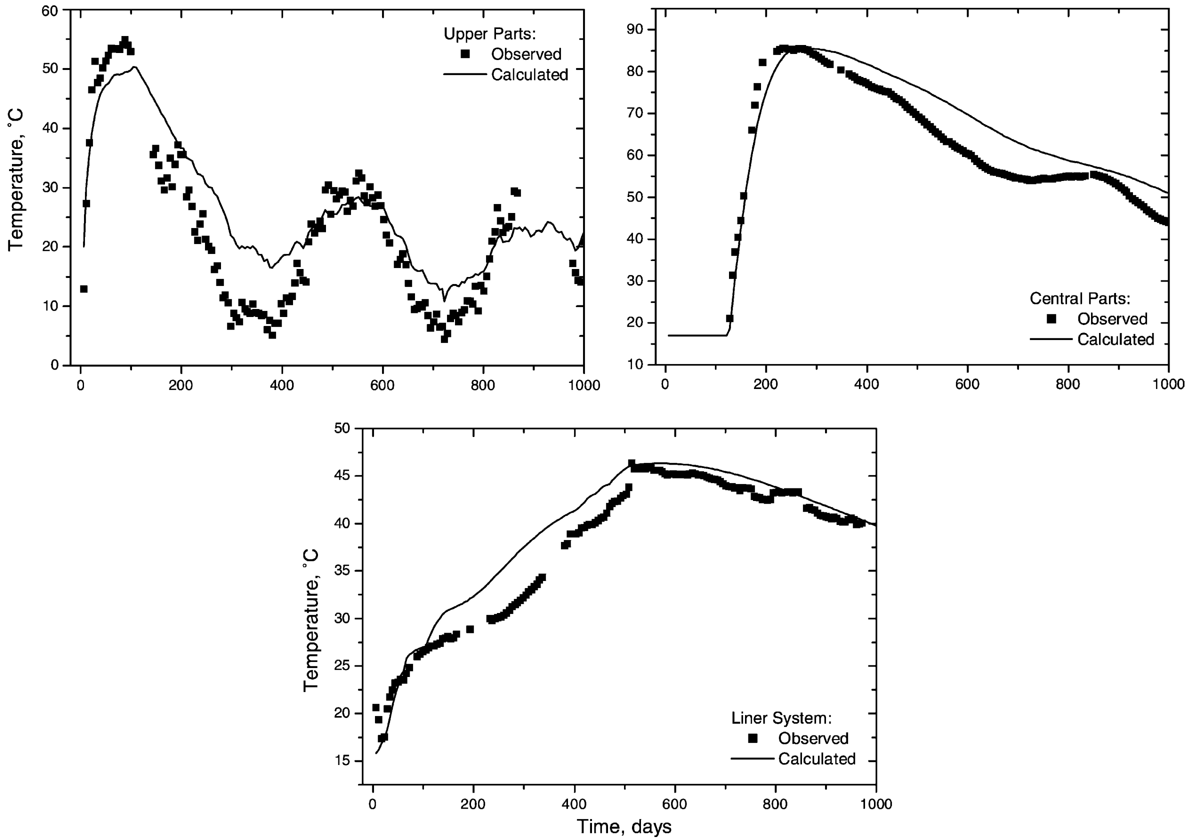

Fig. 4. Comparison of the numeric simulation and at the landfill measured temperatures in selected horizons of the landfill base (liner system), the central area (4.5 m above liner system) as well as the upper landfill area (1 m below surface) for the calibration of the model.

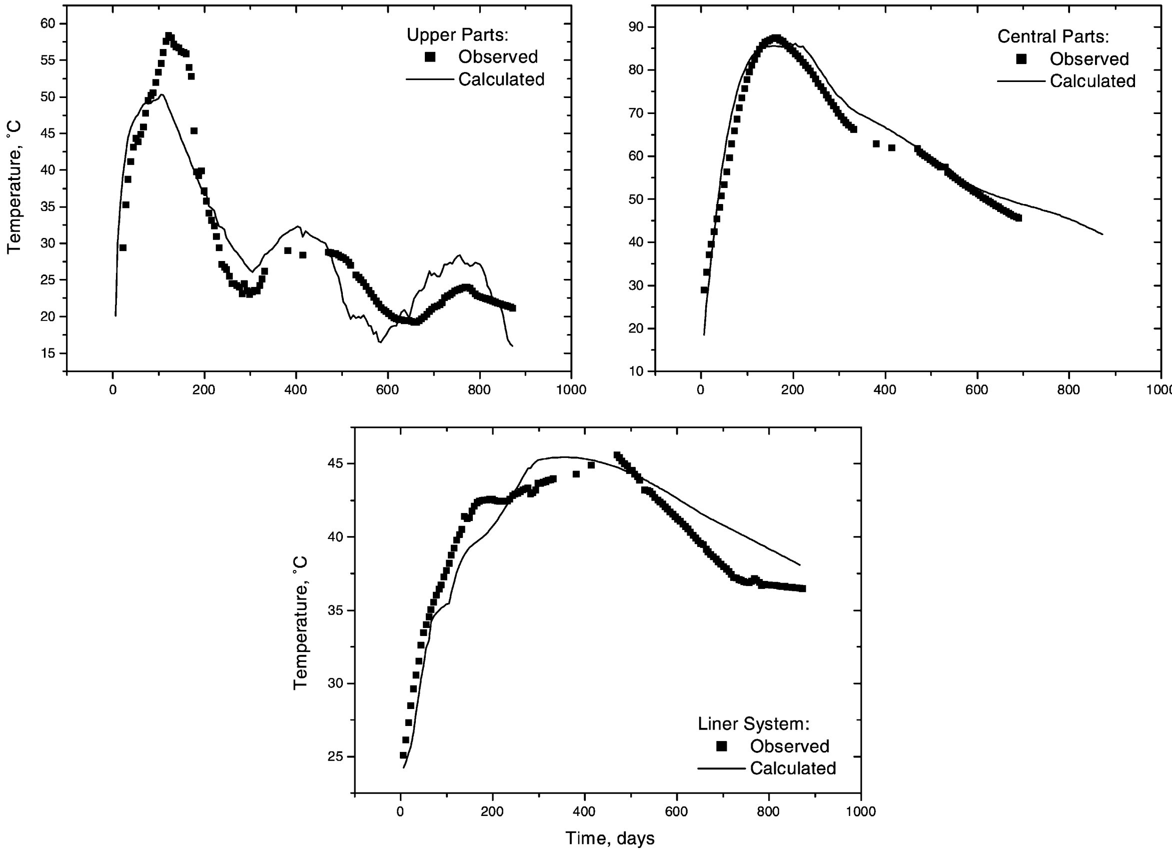

Fig. 5. Comparison of the numeric simulation and at the landfill measured temperatures in selected horizons of the landfill base (liner system), the central area (4.5 m above liner system) as well as the upper landfill area (1 m below surface) for the validation of the model (SF2).

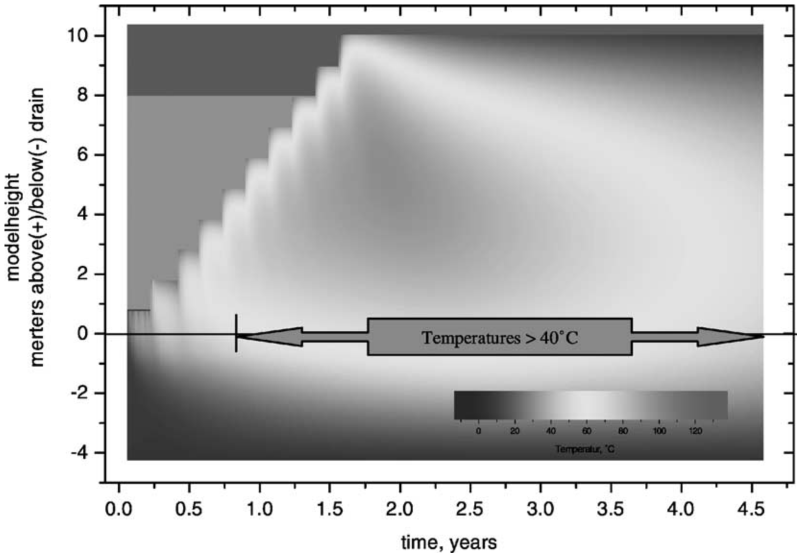

Fig. 6. Predicted temperature development in the second model validation (SF3). Initial heating rate for the fresh quenched bottom ash was set to 45 W m^{-3}, final bottom ash height to 10 m (deposited in discrete intervals of one meter every 2 months).

initial heating rate described above the observed temperature development during the first 6 months could be simulated by the model. The computer simulation results in a temperature maximum of 96 °C in the centre of the landfill (approximately 9 months after the deposition of this bottom ash layer) and 66 °C at its bottom. Fig. 6 shows the calculated temperature development in the landfill over a simulation time of 4.5 years. The high initial heating rate causes higher maximum temperatures in the bottom ash material that result also in higher temperatures in the landfill liner system, and thus may lead to thermal damage of the liner. Temperatures above 40 °C are calculated there from the sixth month after first deposition of bottom ash. Fig. 7 shows the deviations of the calculated temperatures from the real data measured on the landfill site. There is a good correlation between the calculated and measured data ($R^2 = 0.872$, $N = 4287$). With the calibrated and validated model several scenarios were calculated to generate an optimal handling scheme for municipal solid waste incineration (MSWI) bottom ash.

3.6. Simulation no. A: stepwise emplacement of previously stored ash

With the results achieved from the prior simulation, a step-wise emplacement strategy was simulated with bottom ash that was stored for 3–6 weeks before depositing at the landfill with a consequently reduced heating rate from initially 45 to 25 W m^{-3}. This reduced heating rate is also reflected in the temperature development in the landfill body. The maximum temperature reaches only 54 °C in centre and 38 °C at the basis of the landfill (Fig. 8). So there is no temperature above 40 °C at the liner system.

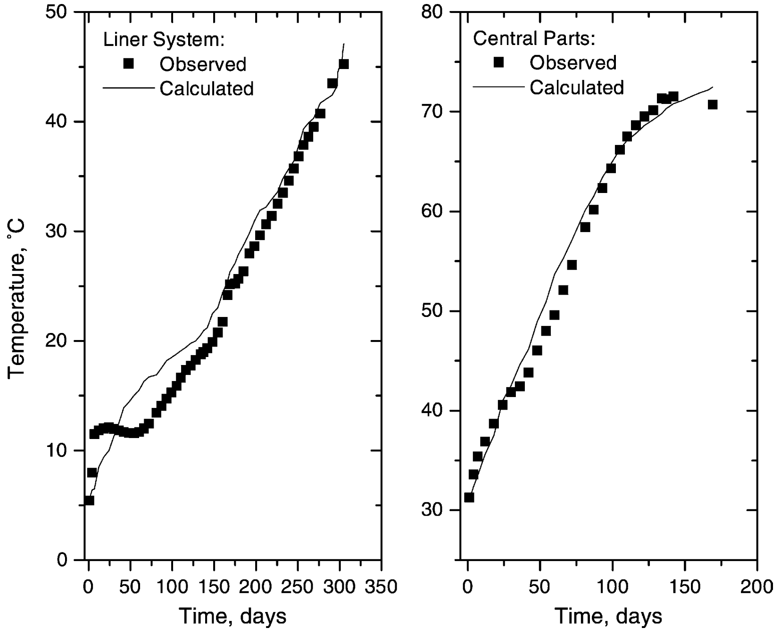

Fig. 7. Comparison of the numeric simulation and at the landfill measured temperatures in selected horizons of the landfill base (liner system) and the central area (3 m above liner system) for the validation of the model (SF3).

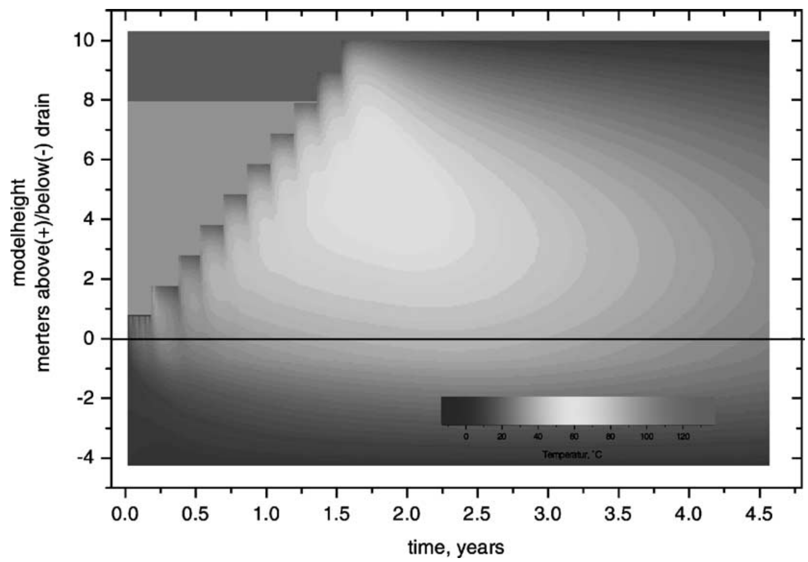

Fig. 8. Predicted temperature development in simulation no. A. Initial heating rate for the 3–6 weeks stored bottom ash was set to $25\,W\,m^{-3}$, final bottom ash height to 10 m (deposited in discrete intervals of 1 m every 2 months).

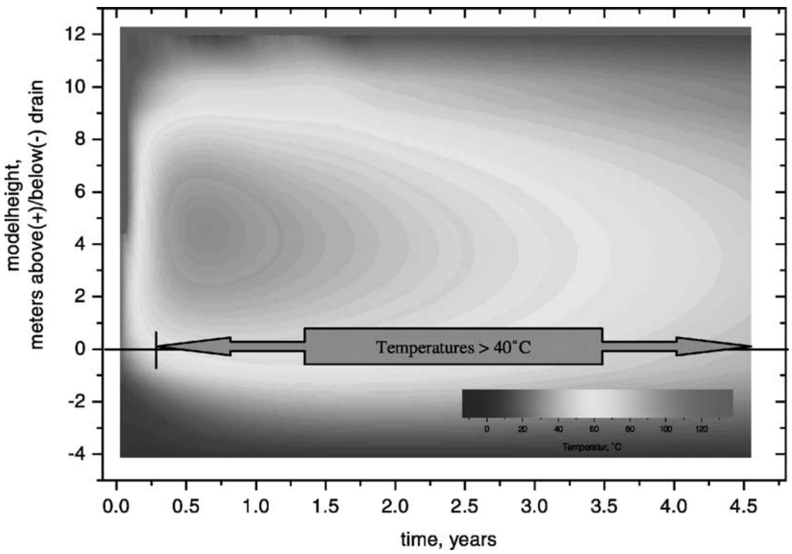

Fig. 9. Predicted temperature development in simulation no. B. Initial heating rate for the 3–6 weeks stored bottom ash was set to 25 W m^{-3}, final bottom ash height to 10 m (deposited in 3 weeks to its final height). Surface sealing was installed directly after the deposition of the bottom ash.

3.7. *Simulation no. B: surface sealing*

In the next simulation, the influence of a surface sealing on landfill temperature development was modelled. The simulated landfill has a bottom ash height of 10 m with a liner system (0.8 m) at its bottom and a geological barrier with a thickness of 3 m. In the model run, a surface sealing (2.5 m) was emplaced directly after the deposition of the 3–6 weeks stored bottom ash (initial heating rate: 25 W m^{-3}). With this sealing, the heat convection from the surface to the air is hampered. The result from this simulation shows that after a storage time of only 4 months, the temperature at the landfill centre rises to 97 °C (Fig. 9). Also at the liner system the maximum temperature (58 °C after a storage time of 7 months) is far beyond the critical temperature (40 °C) for the landfill liner durability. Here, temperatures above 40 °C are calculated from the third month after first deposition of bottom ash.

3.8. *Simulation no. C: storage time*

In the last simulation, the influence of the duration of preliminary bottom ash storage period on the landfill temperature was determined. The sensorfield was built-up according to SF1 and the surface sealing was installed after the final deposition of bottom ash. The initial heating rate was set to 15 W m^{-3}. This heating rate corresponds to a intermediate storage time of approximately 3 months. The calculated maximum temperature (56 °C in the centre of the bottom ash body) was obtained 300 days after the beginning of bottom ash

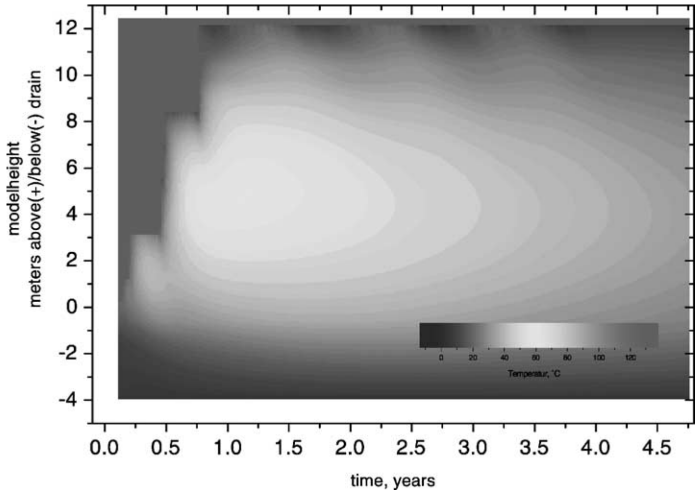

Fig. 10. Predicted temperature development in simulation no. C. Initial heating rate for the 3 months stored bottom ash was set to $15\,W\,m^{-3}$, final bottom ash height to 10 m (deposited in unequal intervals during a period of 8 months). Surface sealing was installed directly after the deposition of the bottom ash.

deposition (Fig. 10). At the liner system, a maximum temperature of 35 °C was calculated 1 year after the beginning of the bottom ash deposition.

4. Conclusions

In this paper, the temperature development under different modes of bottom ash emplacement was studied. According to the simulation of temperature development in MSWI bottom ash landfills, temperatures from 54 to 97 °C were calculated in the vertical centre of the bottom ash body depending on the emplacement strategy. At the liner system, temperatures reached 35–46 °C. It was shown, that the temperature increases are inversely correlated with the surface-to-volume ratio of the freshly applied ash layer (as realised in simulation B). Furthermore, a preliminary bottom ash storage period prior to disposal is necessary to prevent possible thermal damage at the landfill liner system. The simulation results show that the storage time is the key factor influencing the temperature development in the landfill. A storage time of 3–6 weeks reduces the initial heating rate from 45 to $25\,W\,m^{-3}$ (reduction of 46%) a 3 months storage time reduces the heating rate to $15\,W\,m^{-3}$ (reduction of 67%). The risk of a damage at the barrier systems is increased if preliminary storage of bottom ash is not utilised.

Comparatively, it was shown that a storage time of 3–6 weeks and a reduced surface-to-volume ratio lead to maximum temperature values (54 °C in the centre and 38 °C at the liner system) close to those calculated for a storage time of 3 months and a high surface-to-volume ratio (54 °C in the centre and 38 °C at the liner system).

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References

[1] R. Klein, T. Baumann, E. Kahapka, R. Niessner, Temperature development in a modern municipal solid waste incineration (MSWI) bottom ash landfill with regard to a sustainable waste management, J. Hazard. Mater. B83 (2001) 265–280.
[2] C. Albano, J. Trujillo, A. Caballero, O. Brito, Application of different kinetic models for determining thermal stability of PA 66/HDPE blends, Polym. Bull. 45 (2001) 531–538.
[3] P. Döll, Desiccation of mineral liners below landfills with heat generation, J. Geotech. Geoenviron. Eng. 123 (1997) 1001–1009.
[4] U. Holzlöhner, T. Meggyes, S. Seeger, Landfill technology in Germany, Land Contam. Reclam. 7 (1999).
[5] M. Jaros, H. Huber, Development of pH and alkalinity in bottom ash—simulation of the long-term behaviour, in: P. Lechner (Ed.), Waste Reports 08, Vienna, 1998.
[6] C. Speiser, T. Baumann, R. Niessner, Characterization of municipal solid waste incineration (MSWI) bottom ash by scanning electron microscopy and quantitative energy dispersive X-ray microanalysis (SEM/EDX), Fresenius J. Anal. Chem. 370 (2001) 752–759.
[7] A.E. Chandler, T.T. Hartlen, Municipal solid waste incinerator residues, Stud. Environ. Sci. 67 (1997).
[8] C. Speiser, Exothermer Stoffumsatz in MVA-Schlackedeponien: Mineralogische und geochemische Charakterisierung von Müllverbrennungschlacken, Stoff- und Wärmebilanz, Ph.D. Thesis, Technische Universität München, 2001.
[9] D.H. Komilis, R.K. Stegmann, The effect of municipal solid waste pretreatment on landfill behavior: a literature review, Waste Manage. Res. 17 (1999) 10–19.
[10] 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.
[11] O. Hjelmar, Disposal strategies for municipal solid waste incineration residues, J. Hazard. Mater. 47 (1996) 345–368.
[12] J. Pera, Use of incinerator bottom ash in concrete, Cem. Concr. Res. 27 (1997) 1–5.
[13] S.A. Bobrovnik, Determination the rate of some biexponential reactions, Biochem. Biophys. Methods 42 (2000) 49–63.
[14] S.L. Whittenburg, Bayesian analysis of biexponential time-decaying signals, Spectrochim. Acta A 54 (1998) 559–566.
[15] M. El-Fadel, A.N. Findikakis, J.O. Lecki, Numerical modelling of generation and transport of gas and heat in sanitary landfills. I. Model formulation, Waste Manage. Res. 14 (1996) 483–504.
[16] M. El-Fadel, A.N. Findikakis, J.O. Leckie, Numerical modelling of generation and transport of gas and heat in sanitary landfills. II. Model application, Waste Manage. Res. 14 (1996) 537–551.
[17] M. El-Fadel, A.N. Findikakis, J.O. Lecki, Numerical modelling of generation and transport of gas and heat in sanitary landfills. III. Sensitivity analysis, Waste Manage. Res. 15 (1997) 87–102.
[18] M.E. Sumner, Handbook of Soil Science, CRC Press, Boca Raton, FL, 1998.
[19] N.L. Brady, The Nature and Properties of Soils, Macmillan, New York, NY, 1990.