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Comparison between lab- and full-scale applications of in situ aeration of an old landfill and assessment of long-term emission development after completion

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ABSTRACT

Sustainable landfilling has become a fundamental objective in many modern waste management concepts. In this context, the in situ aeration of landfills has been recognised for its potential to convert conventional anaerobic landfills into biological stabilised state, whereby both current and potential (long-term) emissions of the landfilled waste are mitigated. In recent years, different in situ aeration concepts have been successfully applied in Europe, North America and Asia, all pursuing different objectives and strategies.

In Austria, the first full-scale application of in situ landfill aeration by means of low pressure air injection and simultaneous off-gas collection and treatment was implemented on an old, small municipal solid waste (MSW) landfill (2.6 ha) in autumn 2007. Complementary laboratory investigations were conducted with waste samples taken from the landfill site in order to provide more information on the transferability of the results from lab- to full-scale aeration measures. In addition, long-term emission development of the stabilised waste after aeration completion was assessed in an ongoing laboratory experiment. Although the initial waste material was described as mostly stable in terms of the biological parameters gas generation potential over 21 days (GP_{21}) and respiration activity over 4 days (RA_4), the lab-scale experiments indicated that aeration, which led to a significant improvement of leachate quality, was accompanied by further measurable changes in the solid waste material under optimised conditions. Even 75 weeks after aeration completion the leachate, as well as gaseous emissions from the stabilised waste material, remained low and stayed below the authorised Austrian discharge limits. However, the application of in situ aeration at the investigated landfill is a factor 10 behind the lab-based predictions after 3 years of operation, mainly due to technical limitations in the full-scale operation (e.g. high air flow resistivity due to high water content of waste and temporarily high water levels within the landfill; limited efficiency of the aeration wells). In addition, material preparation (e.g. sieving, sorting and homogenisation) prior to the emplacement in Landfill Simulation Reactors (LSRs) must be considered when transferring results from lab- to full-scale application.

1. Introduction

The establishment of sustainable landfills is a key strategy in modern waste management concepts. Since conventional municipal solid waste (MSW) landfills are regarded as a potential source of significant organic and inorganic emissions over long-time periods (Williams, 2005), measures have to be taken to sustainably mitigate both the current and (potential) long-term emissions of the waste materials in terms of landfill gas and leachate. By converting anaerobic landfills into biologically stabilised state through accelerating organic matter degradation under mainly aerobic conditions, the time and effort necessary for post-closure management can be shortened (Cossu et al., 2003; Heyer et al., 2005; Ritzkowski et al., 2006). Several different in situ aeration concepts and methodologies have already been successfully utilised in Europe, North America and Asia including high pressure (e.g. Bio-Puster® concept; Kaltenbrunner, 1999) and low pressure aeration (Cossu et al., 2003, 2007; Heyer et al., 2005; Berge et al., 2007b) as well as semi aerobic (Hanashima, 1999; Matsufuji and Sinha, 1990; Chong et al., 2005; Matsufuji and Tachifuji, 2007; Aziz et al., 2010) and aerobic bioreactor concepts (Berge et al., 2007a,b), all pursuing specific objectives and strategies. While high pressure aeration is usually intended to minimise explosion danger and odour annoyance during landfill excavation or landfill mining projects, low pressure aeration as well as the semi aerobic method has been recognised for its potential towards landfill remediation aimed at accelerated biological waste stabilisation (Ritzkowski and Stegmann 2012; Matsufuji and Tachifuji 2007). In contrast, the aerobic bioreactor concept is generally implemented to

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increase the operating lifetime of landfills by more quickly recovering capacity and reducing leachate treatment costs (Bilgili et al., 2006).

In general, in situ aerobic stabilisation processes have a significant potential for improving the quality of leachate with respect to organic pollutants (chemical (COD) and biochemical oxygen demand (BOD)) and inorganic nitrogen (NH_4), reducing greenhouse gas (GHG) emissions and accelerating waste mass subsidence (Heyer et al., 2005; Prantl et al., 2006; Ritzkowski et al., 2006). In Europe, the majority of aeration projects follow the concept of low pressure aeration combining a system of gas wells for air injection and parallel off-gas extraction and treatment (Ritzkowski and Stegmann, 2012).

In Austria, the first full-scale application of in situ landfill aeration by means of low pressure air injection and simultaneous off-gas collection and treatment was implemented on an old MSW-landfill in autumn 2007. A large-scale field experiment (pilot project) had been conducted on the same landfill from May 2003 until October 2005, aerating 20,000 m^3 of waste via six air injection wells (Prantl, 2007; Prantl et al., 2007). A reduction in actual emissions in both the liquid and gas phase as well as the acceleration in the biodegradation of the solid waste matter could be clearly demonstrated.

In the present study, complementary laboratory investigations in Landfill Simulation Reactors (LSRs) (90 l vessels) were conducted on waste samples taken from the landfill site prior to the full scale aeration in order to determine the potential emission reduction of the landfilled waste and its long-term emission behaviour after aeration completion.

In the past, a comparison between lab- and full-scale applications provided estimates of the time required to achieve an adequate or targeted stability level of the solid waste materials to conclude the active aeration process in the corresponding landfill (Prantl et al., 2007; Ritzkowski and Stegmann, 2007). According to Ritzkowski and Stegmann (2012) the question still remains whether lab-scale investigations accurately represent the conditions occurring in old landfills during full-scale aeration.

Thus, the purpose of this paper is to outline and discuss the influence of aeration measures on the emission behaviour of waste material comparing both laboratory and field scale investigations derived from an Austrian case study on an old, small landfill site. Particularly examined is whether, and how far, the results of lab-scale investigations can pertain to field conditions in order to predict the development of emissions and the stabilisation effect of the waste mass under full scale landfill conditions. Results induced by in situ aeration are presented concerning changes both in the gas and liquid phase as well as in the solid waste mass and more information on the transferability of results from lab- to full-scale is provided for a broader discussion among experts. In addition, the lasting effect of waste stabilisation after aeration completion as well as the aerobic degradation potential of previously, anaerobically operated waste material was assessed in laboratory experiments over 75 weeks.

2. Materials and methods

2.1. Site description

The old MSW landfill site is located south-east of Vienna at 47°58′ Latitude, 16°36′ Longitude in the region of Lower Austria, 245 m above sea level. In this area, the mean annual precipitation is 440 mm and the mean annual temperature is 10.5 °C (Prantl et al., 2006). The total landfill site has an area of 2.6 ha, where 200,000 Mg (fresh matter) of untreated municipal and commercial waste were deposited in two different sections (VA01 and VA02) between 1976 and 1995. The first part of the old landfill (VA01), closed in 1985 after 9 years of operation, was installed on a natural clay-liner without an artificial impermeable bottom seal and leachate collection system. The second landfill section (VA02), which was built with a base seal as well as a base drainage system, started operation in 1986. The depth of disposed solid waste was between 3 and 18 m. Both parts were covered with a thin layer of soil material and a compost/soil mixture respectively.

The in situ aeration plant was installed in autumn 2007 and consists of 37 gas wells for aeration and collection of exhausts as well as a biofilter for off-gas purification. Fig. 1 depicts the installation arrangements of the aeration plant as well as the two landfill sections. Each of the gas wells is connected via pipes to a distribution system either for low pressure aeration or gas extraction. The air injection and extraction system comprises six distribution networks (for aeration: RE2, 3, 5; for extraction: RE1, 4, 6), which are connected to the operating unit by three main aeration and extraction pipes. These pipes are in turn connected to one main line each. The gas wells (outer diameter 13 cm) are fully perforated over their entire length except for 1 m blank casing below the surface. The operating unit, installed in a mobile container, comprises side channel blowers for either low pressure aeration (approx. 20 mbar) or, by administering negative pressure, exhaust air extraction as well as a condensate separator.

The distribution stations are installed in such a way that three sections (areas of influences) can be differentiated (see Fig. 1). All pipes were installed without thermal insulation about 1 m above ground with a slope to the operating unit. The initial aeration and extraction capacity of the plant was 600 m^3/h, which was increased to 1000 m^3/h in autumn 2010 by installing a second aeration and extraction aggregate.

2.2. Field-scale monitoring

In order to observe and verify the aeration effect in the deposited waste mass of the landfill, 28 monitoring wells were installed at different depths along the entire area of the landfill (1–5 m depths). Inside the wells, the concentration of methane (CH_4), carbon dioxide (CO_2) and oxygen (O_2) as well as the temperature, water level and pressure difference are monitored every second month. The gas composition and the pressure difference are measured using a mobile gas analyser equipped with a differential pressure sensor. Temperature probes (PT100) and electric contact gauges used for measuring the water level have been inserted manually into the monitoring wells. In this paper, only the results of the temperature measurements are provided.

Surface CH_4 concentrations were screened twice a year using a portable Flame Ionisation Detector (data not shown). Furthermore, 41 on-site gauges for geodetic levelling (in a grid of 25 m × 25 m) are used to measure settlement of the landfill once a year (see Fig. 1).

Leachate samples from an old existing leachate well were taken every second month (n = 19) and a set of chemical parameters (see Section 2.4) were analysed.

Solid waste samples were taken (by means of drilling) prior to aeration start to characterise the initial waste reactivity and properties, and again after 2.5 years (see Section 3.3). Final waste sampling will be conducted after about 5 years of operation in 2013. Prior to aeration start 42 solid waste samples were taken during gas well drilling. 41 samples originating from the interim sampling after 2.5 years were taken more or less evenly distributed over the entire landfill area at different depths.

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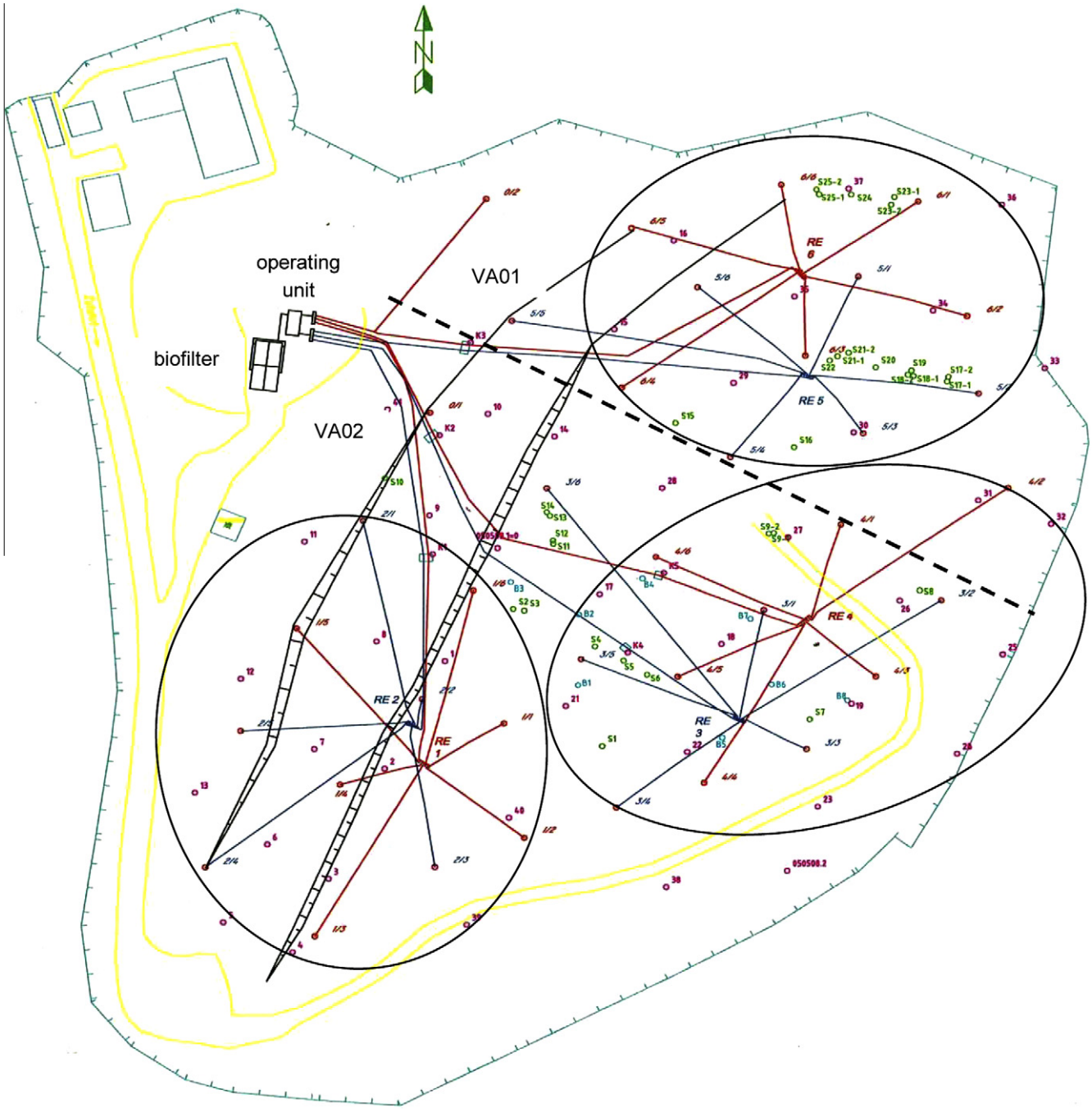

Fig. 1. Installation arrangements for in situ aeration of the old landfill (the circle represents the three areas of influences; the two sections VA01 and VA02 are separated by the dashed line; the distribution network for aeration are labelled as RE 2, 3 and 5, whereas the distribution network for extraction are labelled as RE 1, 4 and 6).

2.3. Lab-scale investigations

Prior to the aerobic system's start-up waste samples taken from the landfill site were placed into six 90 l LSRs (diameter 40 cm, height 70 cm) made of stainless-steel, which were operated both under aerobic (LSR 1, 5 and 6) and anaerobic conditions (LSR 2, 3 and 4). The temperature was controlled constantly at 40 °C to simulate the field temperature of an aerated landfill. The waste material was sieved to a particle size <20 mm, thoroughly homogenised and filled into the LSRs (about 120 kg wet waste material). During the emplacement process, the material was slightly compacted every 10 cm with a hand tamper leading to a density of approx. 1.6 kg/l. The experimental setup of the LSR under anaerobic conditions is given in Fig. 2. LSRs 1, 5 and 6 were aerated with a continuous air flow of 3 l air/h (1 l/kg DM d). The air flow rate was regulated by means of float-type flow controller and measured by a digital flow measuring device. The volumetric concentrations (CH_4, CO_2 and O_2) of the exhaust air as well as the landfill gas (LFG) quantities of the anaerobic assays produced were periodically measured using a mobile gas analyser (see Section 2.2) and drum gas meters, respectively. The LSRs were irrigated weekly with 1.2 l of deionised water to accelerate the degradation processes and to obtain specific liquid/solid (L/S) ratios. 48 h after irrigation samples were taken for leachate characterisation. During the first 40 weeks of operation, the leachate was routinely removed on a weekly basis and the pH and conductivity (EC) were measured

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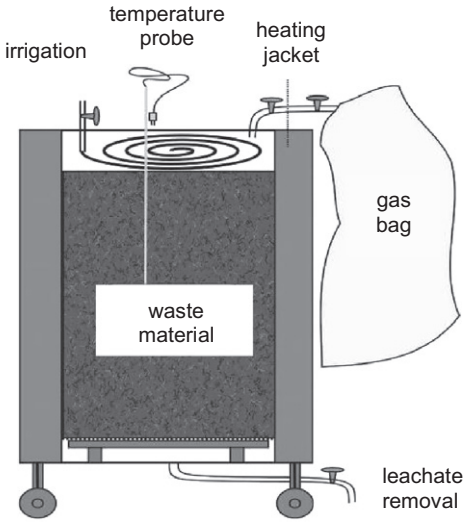

Fig. 2. Experimental setup of the anaerobic landfill simulations reactors.

immediately. For each LSR, leachate samples were taken periodically every second, fourth or eighth week, and samples were hermetically sealed and stored at −20 °C until analysis.

LSRs 2, 3 and 4 were operated for 740 days as the anaerobic reference, whereas the operation period of the aerated LSRs 1, 5 and 6 was divided into an anaerobic (81 days) and aerobic phase (659 days). The solid waste matter was tested prior to being placed in the LSR, during the test run (interim sampling in test week 39) and after the experiment (approx. 745 days test run or in week 107). In order to investigate the long-term emission behaviour of the aerobically "stabilised" waste material as well as the aerobic degradation potential of the previously anaerobically operated waste, LSRs 1 and 2 were switched after 94 weeks (659 days) of aeration, meaning that the aeration of LSR 1 was stopped and LSR2 began to be aerated. Emission data will be presented for a "switched" test run of 75 weeks (522 days).

2.4. Analysis of solid waste material and leachate samples

In general, solid waste samples from the field-scale and pilot-scale investigations were characterised for (1) chemical parameters, including pH-value, electric conductivity (EC), ammonium (NH_4-N), nitrate (NO_3-N), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), organic content (loss on ignition = LOI), total organic carbon (TOC), and total nitrogen content (TN); and (2) biological parameters, such as respiration activity over 4 days (RA_4) and gas generation potential over 21 days (GP_{21}). pH-value and EC were determined in a 1:10 eluate with deionised water. NH_4-N, NO_3-N, COD and BOD_5 were analysed according to standardised methods (OENORM M 6265; EN ISO 11732; EN ISO 13395; DIN EN 1899-2:1998). Total carbon (TC) and total inorganic carbon (TIC) from which TOC was calculated, as well as TN were determined by combustion in a Variomax CNS analyser. The loss on ignition was determined by combustion at 550 °C in a muffle furnace. The respiration activity (RA_4) was quantified in a Sapromat (Sapromat E, Voith Sulzer, Germany) according to OENORM S2027-1 (2004). The gas generation potential (GP_{21}) was analysed using an Incubation test (Binner, 1996) over a period of 21 days. Data of the basic characterisation of the waste material used for the LSR investigations compared to the results of the status analysis of the landfill site are presented in Table 1.

Various parameters were determined in the leachate samples including pH-value, EC, NH_4-N, NO_3-N, COD, BOD_5 and heavy metals, such as chrome (Cr), copper (Cu) and zinc (Zn) (OENORM EN ISO 11885).

3. Results and discussion

It should be noted that the initial reactivity potential of the waste material at the investigated landfill site was quite low at the beginning of the aeration measure since anaerobic biological degradation processes decreasing the organic content had already occurred for a time period of 21–31 years (Table 1). In particular, the biological parameters (GP_{21}: median value 0.5 Nl/kg dry matter (DM) and RA_4: median value 1.7 mg O_2/g DM) indicated that under anaerobic conditions no further significant degradation of the organic substance could be expected. These biological parameters are also clearly below the limit values for the final disposal of mechanically–biologically pre-treated waste in Austrian landfills (RA_4 = 7 mg O_2/g DM; GP_{21} = 20 Nl/kg DM; Austrian Landfill Ordinance). In addition, the application of FT-IR (Fourier Transformation Infrared Spectroscopy), which has been proven to be an

Table 1
Data of the basic characterisation of the waste material used for the LSR investigations compared to the results of the status analysis of the landfill site; WC = water content; LOI = loss on ignition at 550 °C (organic content); TOC = total organic carbon; TN = total nitrogen content; RA_4 = respiration activity within 4 days; GP_{21} = gas generation potential within 21 days; EC = electric conductivity; COD = chemical oxygen demand; BOD_5 = biochemical oxygen demand within 5 days; LSR = Landfill Simulation Reactor; DM = dry matter; WM = wet matter; and n.a. = not analysed.

	WC (% WM)	LOI (% DM)	TOC (% DM)	TN (% DM)	RA_4 (mg O_2/g DM)	GP_{21} (Nl/kg DM)
LSR-1	29.5	11.8	6.3	0.3	1.9	0.6
LSR-2	30.0	11.8	6.3	0.3	1.8	n.a
LSR-3	29.3	11.6	6.1	0.3	1.9	0.7
LSR-4	28.2	11.7	6.5	0.3	1.6	n.a
LSR-5	27.2	11.4	6.2	0.3	1.6	0.6
LSR-6	29.3	12.0	6.0	0.3	2.2	n.a
Median LSR	29.3	11.8	6.2	0.3	1.9	0.6
Median total landfill	27.9	12.5	6.4	0.3	1.7	0.5
	pH (–)	EC (μS/cm)	NH_4-N (mg/kg DM)	NO_3-N (mg/kg DM)	COD (mg O_2/kg DM)	BOD_5 (mg O_2/kg DM)
LSR-1	7.5	1390	460	9	610	100
LSR-2	7.6	1610	620	7	680	40
LSR-3	7.6	1360	500	6	700	50
LSR-4	7.6	1440	570	6	710	50
LSR-5	7.5	1370	340	6	610	50
LSR-6	7.6	1460	470	9	530	30
Median LSR	7.6	1415	485	7	645	50
Median total landfill	8.1	1110	580	2	2210	420

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appropriate tool for assessing the stability of old waste materials according to their spectral characteristics (Smidt et al., 2011), confirmed that the waste investigated was quite stable prior to aeration start. However, the landfill site has been identified as a posing risk to the groundwater due to the lack of a complete base sealing system.

The former field and laboratory experiment (pilot project), conducted between 2003 and 2005 formed the basis of the full-scale aeration in terms of the achievable stability levels of the solid waste material, an appropriate aeration rate (0.7–0.8 l air/kg DM d) as well as an estimate of the required operation period (approx. 4–5 years) (Prantl, 2007; Prantl et al., 2006, 2007). A theoretical maximum carbon discharge of approx. 20 g C/kg DM could be calculated using Lineweaver–Burk-Linearisation (Prantl et al., 2007), which correspond to 30% of the total organic carbon. On the basis of these investigations, a target value of 15 g C/kg DM (75% of the maximum carbon discharge) was set by the local authorities for the full-scale aeration plant. This approach corresponds to the recommendations by Ritzkowski and Stegmann (2007), who suggested introducing a certain factor (80–90%) of the total carbon discharge via the gas phase determined by LSR tests in order to specify the target value for the aerated landfill. The defined target values for the biological parameters (GP_{21} and RA_4) as well as for the chemical ones (BOD_5, COD, NH_4-N) are displayed in Fig. 5.

3.1. Effects on the gas phase and carbon discharge

Fig. 3a represents the total carbon discharge and the oxygen utilisation rate obtained under laboratory and field conditions. In order to show the entire range of the carbon discharge as well as the aeration rate, the secondary *y*-axis was plotted with a logarithmic scale. The total amount of air injected in relation to the total mass of solid waste (A/S ratio) and, therefore, also the carbon discharge differ by a factor of 10 between the LSRs and full-scale measures. This factor corresponds to the status quo of the full scale application after 3 years of aeration (02/2008–12/2010). The aeration rate (approx. 1.0 l/kg DM d) for the LSR investigation was based on the pre-investigations by Prantl et al. (2007). In addition, an acceleration of the degradation processes in the LSR-simulation was required in order to investigate the maximal reduction potential of the waste mass as well as to ascertain whether the required target values determined by the local authorities could be reached

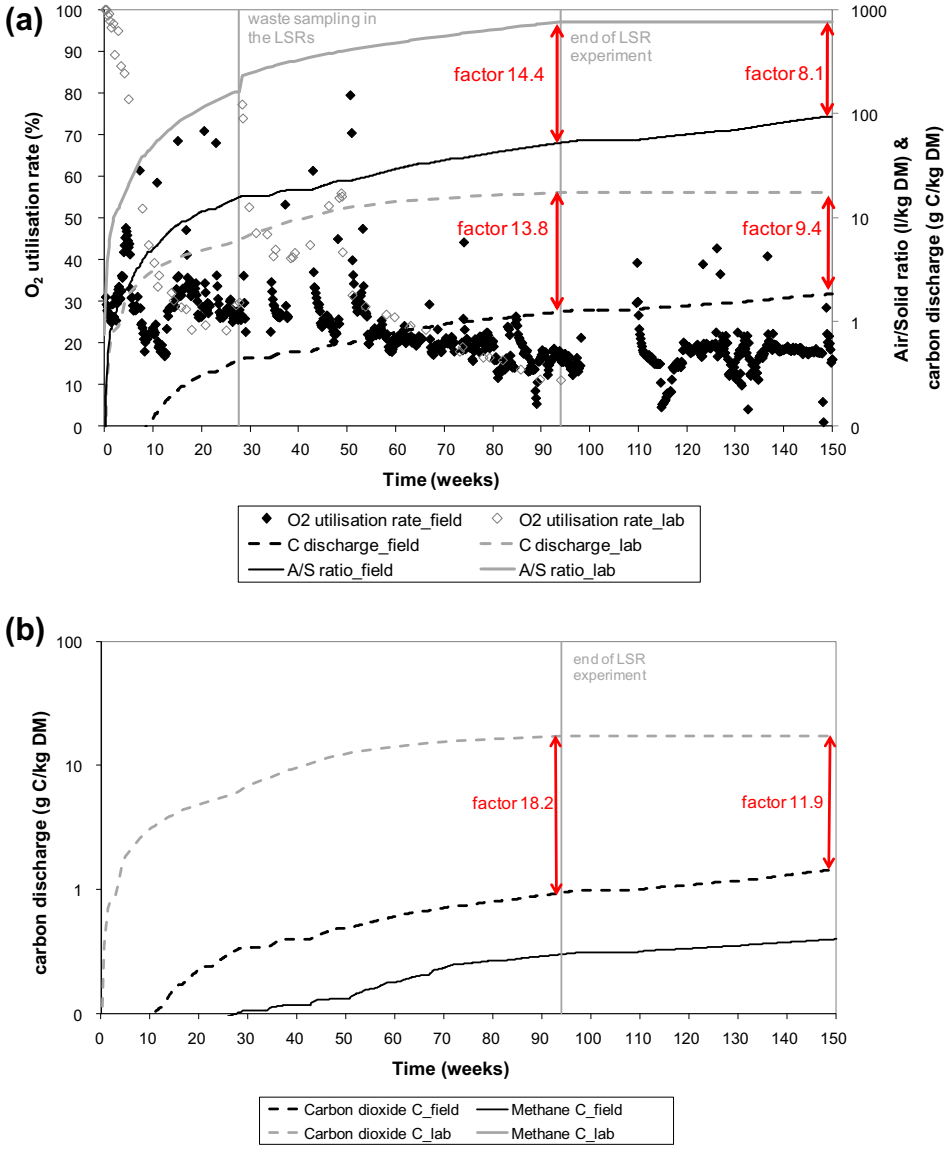

Fig. 3. Cumulative carbon discharge via the gas phase, the oxygen utilisation rate and the air/solid ratio (A/S) (a) as well as the carbon discharge (CO_2 and CH_4) (b) under laboratory and field conditions.

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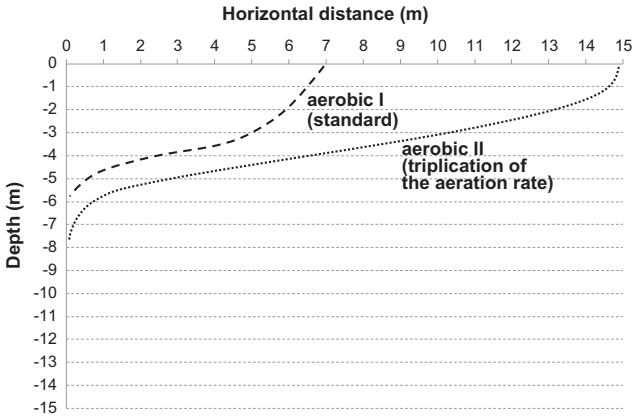

Fig. 4. Schematic picture of the vertical and horizontal aeration radius (detection limit 5 vol.% O_2) during two different aeration states: aerobic I (standard) and aerobic II (triplication of the aeration rate by concentrating the full aeration capacity to the northern part via the distribution network RE5) (adapted from Bogolte in Gamperling et al., 2011).

within the calculated project time-period of 3 years. It was not possible to apply the recommended aeration rate in the field due to technical limitations (high air flow resistivity due to high water content of waste and temporarily high water levels within the landfill). Thus the initial rate was 0.06 l/kg DM d, which could be increased to 0.09 l/kg DM d by the operation of a second aggregate. In comparison Ritzkowski et al. (2006) applied aeration rates ranging from 0.2 to 0.6 l/kg DM d in laboratory experiments and 0.3 l/kg DM d in the full-scale application. From March to May 2009 specific aeration tests were carried out at the northern section (VA01) of the site in cooperation with the project partner "TERRA Umwelttechnik GmbH" in order to assess the efficiency of the aerations wells installed, in terms of the vertical and horizontal aeration radius (Gamperling et al., 2011). Additional monitoring wells were installed to measure the gas composition continuously (CH_4, CO_2 and O_2) at different depths ranging from 1 m to 10 m. A detection limit of 5 vol.% O_2 was chosen in order to define the aeration radius. By tripling the aeration rate (the full capacity of the air blower was only applied to the northern section via the distribution network RE5) the efficiency of the aeration wells, in particular

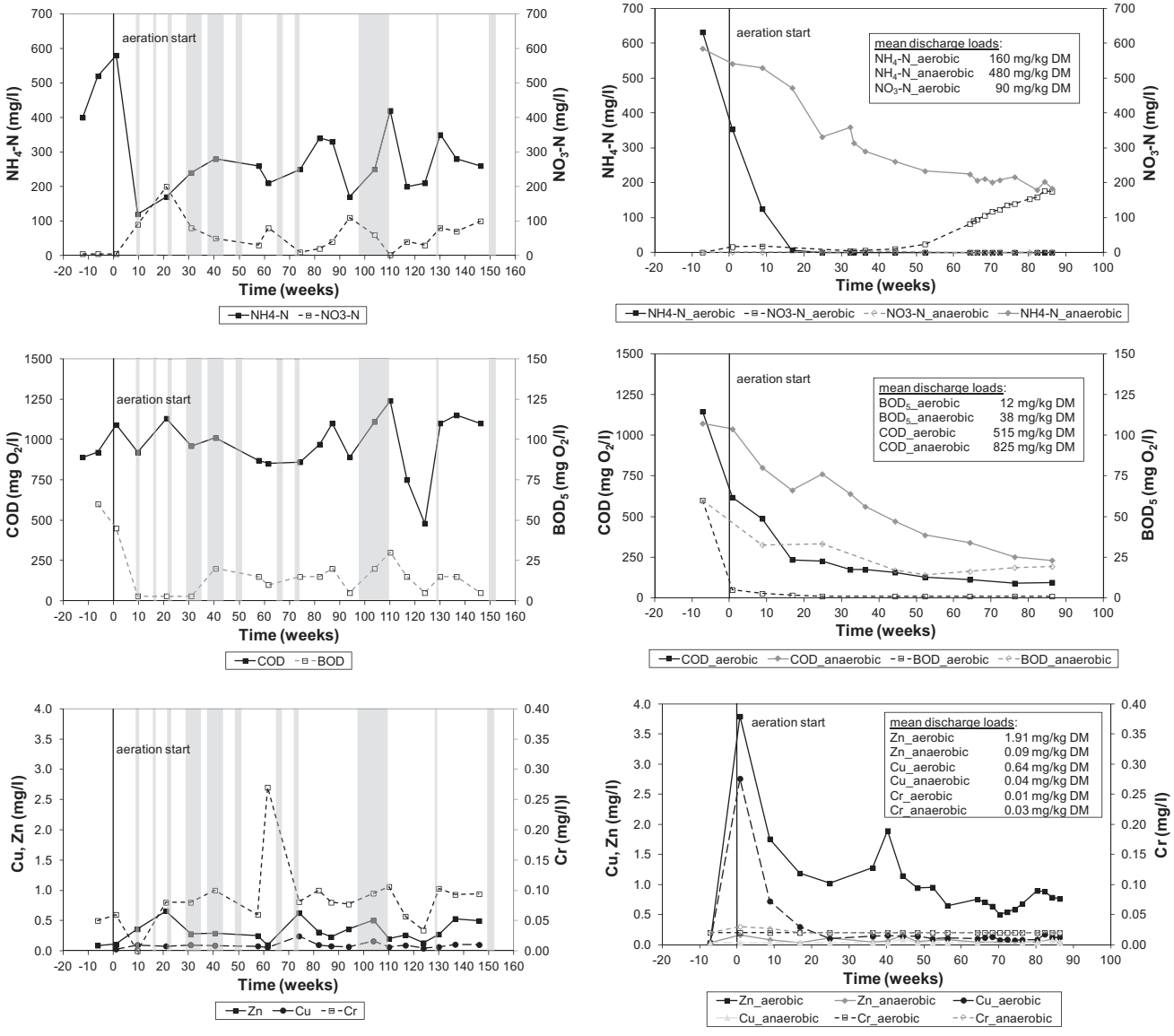

Fig. 5. Trend of organic and inorganic leachate compounds in the field- (a) and lab-scale (b) experiments; (grey bars indicate a stop of aeration).

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the vertical influence, could be only slightly improved (approx. 1 m) as can be seen in Fig. 4. In contrast, the horizontal influence could be increased by 7–8 m compared to the standard aerobic state. It can be deduced that depending on the design and spacing of the aeration lances, an increase of the aeration rate does not necessarily improve the spatial aeration efficiency of the plant and, thus, the success of waste stabilisation.

During an operation period of 3 years a total aeration volume of approx. 13.1 Mio m^3 was injected leading to a discharge of 260 Mg carbon (1.8 g C/kg DM) in the extracted off-gas (13.2 Mio m^3). Under optimised laboratory conditions, an average of 17.2 g C/kg DM was discharged in the aerated LSRs after 94 weeks of aeration. In comparison with the performance of the anaerobic LSRs, about 97% more carbon could be discharged in the aerated ones. These results indicate that a switch to aerobic milieu conditions influences the degradation of anaerobically hardly degradable organic compounds in a positive way. During this study the target value of 15 g C/kg DM was achieved within 500 days under laboratory conditions, while only 7% could be reached on full-scale within the same time period and approx. 12% after 3 years of aeration (status quo).

In the starting phase of the aeration measures under laboratory conditions, the aerobic LSRs showed high oxygen utilisation rates (>90%) indicating a rapid and complete consumption of the injected air by the microorganisms (Fig. 3a). After some weeks the O_2 utilisation rate decreased considerably to 20%, indicating that a large portion of the biodegradable organic compounds had already been mineralised. Withdrawal of solid waste samples after 28 weeks gave rise to more biological activity and therefore, the O_2 utilisation rate increased again followed by a considerable drop. At the end of the laboratory investigations the O_2 utilisation rate levelled off at 12%.

The initial O_2 utilisation rate under field conditions was rather low (approx. 30%), when compared with the optimised conditions in the laboratory (optimal operation conditions and material preparation). Similar observations have been made by Prantl et al. (2007) with the pilot-scale project on the same landfill site. Ritzkowski et al. (2006) showed an initially high utilisation rate of approx. 30–50% on the old Kuhstedt landfill. However, the initial waste reactivity was also comparatively higher as indicated by the biological parameters (RA_4 = 6.2 mg O_2/g DM, GP_{21} = 23.4 l/kg DM).

During the first 2 years of in situ aeration the O_2 utilisation rate diminished (down to 15%) under field conditions, whereas in the third year of operation it remained rather stable at 17% although the aeration rate was increased from 600 m^3/h to 1000 m^3/h in autumn 2010 (week 131). High rates of O_2 utilisation could be particularly observed directly after the restarts following plant shut-downs.

A comparison between the carbon discharges (illustrated as the discharge of CH_4 and CO_2) between lab-scale and full-scale is given in Fig. 3b. About 56 Mg of CH_4, corresponding to 22% of the total carbon, was discharged in the extracted off-gas prior to treatment on the investigated landfill site. Almost no methane was released in the aerobic LSRs indicating a more homogenous aeration of the waste material. The difference in the percentage of the methane emitted via the gas phase is an initial indication of the difficulties of aeration on a full-scale application due to the fact that anaerobic zones are still located within the landfill body (Prantl, 2007; Ritzkowski et al., 2006). In general, the heterogeneous nature of the waste itself, well design and spacing, areas with water saturation as well as interruptions or shut downs of the aeration measure contribute to the existence and extent of such anaerobic niches (Hrad et al., 2012; Ritzkowski and Stegmann, 2012). During the operation period of 3 years, 11 out of 28 monitoring wells showed a water level >0.5 m, whereby six monitoring wells had a permanent high water level. Ritzkowski (2010) measured carbon loads in the form of CH_4 ranging from 54.6 Mg/a to 102.4 Mg/a in the extracted off-gas of an aerated landfill during a 2001–2006 aeration project carried out in Germany.

It should be noted that, besides optimal operating conditions (e.g. constant temperature, more homogenous aeration, and higher aeration rate), material preparation prior to the emplacement in the LSRs (e.g. sieving and homogenisation) may contribute to a higher carbon discharge per kg DM waste in the LSRs compared to the field application. Since the waste material was sieved to a particle size <20 mm, approx. 50% of the initial material (>20 mm) mainly consisting of coarse mineral components, plastic parts, foils, etc. was discarded. In addition, homogenisation led to a larger surface area of the waste material which is more favourable for microbial activity. Hence, the carbon discharge achieved under laboratory conditions can be considered as the maximum degradation potential which may be not attainable within a reasonable economic aeration period under real field conditions.

3.2. Effects on leachate quality

Fig. 5 illustrates the development of some relevant organic and inorganic compounds in the leachate both under laboratory and field conditions. As previously mentioned, only one section of the investigated landfill (VA02) was built with a base drainage system and, accordingly, the leachate samples may not be representative for the entire landfill site (5–7% collected leachate amount from VA02 compared to annual precipitation). However, the section VA02 represents the younger and, therefore more reactive part of the landfill site. In addition, a direct comparison between laboratory and field conditions is limited since the liquid/solid ratios (L/S) of both studies differ by a factor of >10. While the L/S in the LSRs reached a value of 1.66, the L/S ratio was approx. 0.13 assuming that 30% of the precipitation from 2008 to 2010 percolated through the landfill body (Gerzabek and Reichenauer, 2006).

During this study, leachate from both laboratory (pH 7.8–8.5) and full-scale (pH 7.5–8.2) remained alkaline during the aeration measures, while the pH values in leachate from the anaerobic LSRs were predominantly in the range of 6.9–7.3. It is important to note that sampling intervals differed between lab-based and full-scale operation. Since leachate samples were taken every second month from the investigated landfill, natural variations of the leachate quality may not be fully represented in the field application.

As illustrated in Fig. 5, the leachate compounds NH_4–N, COD and BOD_5 were noticeably reduced under optimised aerobic conditions in the laboratory indicating a rapid conversion of readily available organic matter and nitrogen pools. The BOD_5 (initial value approx. 60 mg O_2/l) in the leachate, representing easily-degradable organic matter, showed the greatest decrease since it was no longer detectable after 15 weeks. Ammonium nitrogen (initial value approx. 600 mg/l), which represents a key issue in determining the long-term leachate quality and therefore the aftercare period (Burton and Watson-Craik, 1998), were significantly reduced within the first 17 weeks of aeration and remained at very low levels (<1 mg/l). Within 17 weeks of aeration the COD fell rapidly to 23% of the initial value and thereafter the decreased slightly, reaching a concentration of 10% of the initial value. However, the anaerobic LSRs (reference) also showed a decreasing tendency of these values most probably due to leaching effects (L/S 1.44). The leached NO_3-N could not compensate for the reduction of NH_4-N during the laboratory experiment. Nitrate-nitrogen (NO_3-N), as an end product of nitrification, was measured in the leachate of the aerated LSRs after a lag-phase of 50 weeks and reached values up to 200 mg NO_3-N/l at the end of the experiment. At no stage nitrite could be detected in the leachate. Nitrification accounted for 55% of ammonium-nitrogen removal throughout the lab-scale

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investigation. The lag-phase suggests that simultaneous nitrification and denitrification processes occurred readily within the waste mass (Berge et al., 2006; Hao et al., 2010; Price et al., 2003). However, further pathways for nitrogen are possible, especially in the first aeration phase, including its incorporation into microbial biomass (Kylefors, 2008) or humic substances (Fellner and Laner, 2011) as well as ammonia stripping via the gas phase (Ritzkowski and Stegmann, 2003) promoted by a rise of temperature (see also Section 3.4) and pH (Lei et al., 2007).

Higher nitrogen (N_2) concentrations (as a difference between 100 vol.% and the sum of CH_4, CO_2 and O_2) were observed during the lag phase, most probably due to the existence of micro-anoxic niches within the waste in the first months, allowing the onset of denitrification and the formation of elementary nitrogen (Berge et al., 2007a). However, nitrogen discharge in the form of nitrous oxide (N_2O), as an intermediate product during incomplete denitrification or nitrification under unsuitable conditions, might be also an issue during in situ aeration (Berge et al., 2007a; Huber et al., 2009; Zeng et al., 2012). The discharge loads of the measured leachate compounds under laboratory conditions are displayed in Fig. 5b. The NH_4-N (480 mg/kg DM) as well as the BOD_5 load (38 mg/kg DM) of the anaerobic waste was about three times higher compared to the values obtained under aerobic conditions during the same investigation period. In contrast, the COD load (825 mg/kg DM) was only one and a half of that emitted in the aerated waste.

The full-scale aeration plant likewise showed a strong decreasing tendency of NH_4-N, BOD_5 and COD together with an increase of NO_3-N, especially in the first aeration phase. In general, a cessation of aeration, as indicated by grey bars, caused a slight increase in NH_4-N, COD and BOD_5 concentrations, while NO_3-N decreased considerably. During the aeration period of 3 years ammonium-nitrogen reduced from approx. 580 mg/l to 100–350 mg/l, whereas nitrate-nitrogen reached values up to 100–200 mg/l. Similar to the lab-scale investigations, the BOD_5 (initial value 60 mg O_2/l) under field conditions depreciated significantly to very low values (<3 mg O_2/l) within 10 weeks of aeration. However, after a plant shut-down at the end of 2008 the BOD_5 concentration grew slightly and remained at between 5 and 30 mg O_2/l. In contrast, COD concentration remained rather stable between 800 and 1200 mg O_2/l with the exception of week 124, where values <500 mg O_2/l could be detected.

Under both laboratory and field conditions the mobilisation of heavy metals was observed. Different investigations have indicated that the transition from anaerobic into aerobic conditions might affect heavy metal mobilisation in landfills (Martensson et al., 1999; Ritzkowski and Stegmann, 2001). Several factors could influence the metal mobility in landfill leachate under aerobic conditions including the pH value, the oxidation–reduction potential (Ritzkowski and Stegmann, 2001; Kjeldsen et al., 2002), the cation exchange capacity of the waste as well as the interaction of metals with dissolved organic compounds (Flyhammar and Hakansson, 1999; Martensson et al., 1999). Martensson et al. (1999) found two-times greater concentrations of Zn, Cd and Cr leachate from 20-year-old waste under aerobic conditions compared to anaerobic conditions. In contrast, Hantsch et al. (2003) could not observe an aeration effect on the heavy metal content in the leachate from old landfill waste materials under laboratory conditions. However, average metal concentrations were generally at a low total level in all studies.

In the present study, the existence of Zn and Cu in the leachate differed significantly between aerobic and anaerobic conditions in the LSRs, whereas Cr remained stable at the detection limit (0.02 mg/l) under both conditions. The highest concentration of Zn (up to 4 mg/l) and Cu (up to 2.8 mg/l) under laboratory conditions could be observed in the beginning of the aeration with a considerable decrease over time (see Fig. 5b). The heavy metals discharge loads are shown in Fig. 5b. Results from the field study revealed a different phenomenon concerning the Cu values in comparison with the laboratory investigations, i.e. concentrations of Cu (0.03–0.24 mg/l) in the leachate did not change, in contrast to Zn and Cr. While the Zn (0.09 and 0.63 mg/l) and Cr (0–0.27 mg/l) level changed slightly during the aeration measures, Cu remained at lower levels in contrast to the laboratory investigations. Nonetheless, the total level of heavy metals remained rather low in both laboratory and field studies meeting the limit values of the Austrian drinking water regulation (Cr = 0.05 mg/l; Cu = 2.0 mg/l; TWV-BGBl. II Nr. 121/2007).

3.3. Effects on solid waste materials

The results of the solid waste characterisation prior to aeration start and during aeration measures as well as both under laboratory and field conditions are compared using box-and-whisker plots. It is important to note that this chart type was chosen in order to provide a better visualisation of the contrasting results of the investigations. Box-and-whisker plots are not usually used with a small sample number such as those from the LSRs tests.

Fig. 6 illustrates some relevant chemical (TOC, COD, BOD_5, NH_4, NO_3) and biological parameters (GP_{21}, RA_4) of the waste material of both laboratory and field investigations. Results from field investigations are divided into the initial waste sampling in 2007 and after 2.5 years of operation. The graph is also separated between samples from sections 1 and 2 (VA01 and VA02) and the entire landfill. Under laboratory conditions both the solid waste matter and the eluate were analysed prior to the emplacement in the LSR, during the test run (interim sampling in test week 39 including anaerobic phase, 28 weeks after aeration start) and after the experiment (about 94 weeks of aeration). In each case the grey line indicates the target value given by the local authority. Table 2 gives a short overview of the different conditions between lab-scale and field-scale concerning the time of aeration (expressed in weeks) the air/solid ratio as well as the liquid/solid ratio.

As already stated, the initial reactivity potential of the old waste material was already low prior to aeration start. As illustrated in Fig. 6, all parameters measured, except for ammonium-nitrogen, were below the target values defined by the local authorities (grey line) at the beginning of the lab-based experiment. However, the lab-scale investigations indicated that further aerobic treatment led to increased biological stabilisation of the solid waste material by reducing the decomposable organic compounds. The respiration activity (RA_4) as well as the gas generation sum (GP_{21}) could be considerably reduced by 90% and 83% of the initial values respectively. Under anaerobic conditions, leaching effects might have caused a reduction in the reactivity, but to a smaller extent (reduction of the initial value: RA_4: 17%, GP_{21}: 71%). In addition, a TOC reduction of 25–30% was achieved under optimised conditions. In a pilot project on the same abandoned landfill, Prantl et al. (2007) calculated this amount as the maximum theoretically degradable part of the total organic carbon using Lineweaver–Burk-Linearisation. In comparison, the anaerobic LSRs showed a mean TOC reduction rate of 9%. The organic parameters BOD_5 and COD in the eluate were significantly reduced in comparison to the anaerobically operated LSRs. The easily degradable organic matter (BOD_5) as well as the COD in the eluate were reduced by approx. 50% under aerobic conditions, whereas these parameters were not reduced during the anaerobic phase. In addition, the ammonium-nitrogen concentrations in the eluate decreased by 99% in the aerobic LSRs while nitrate-nitrogen, as an indication of nitrification processes, increased by a factor of seven. Due to leaching effects a reduction of 61% of the NH_4-N concentration in the eluate was also detected in the anaerobic LSRs.

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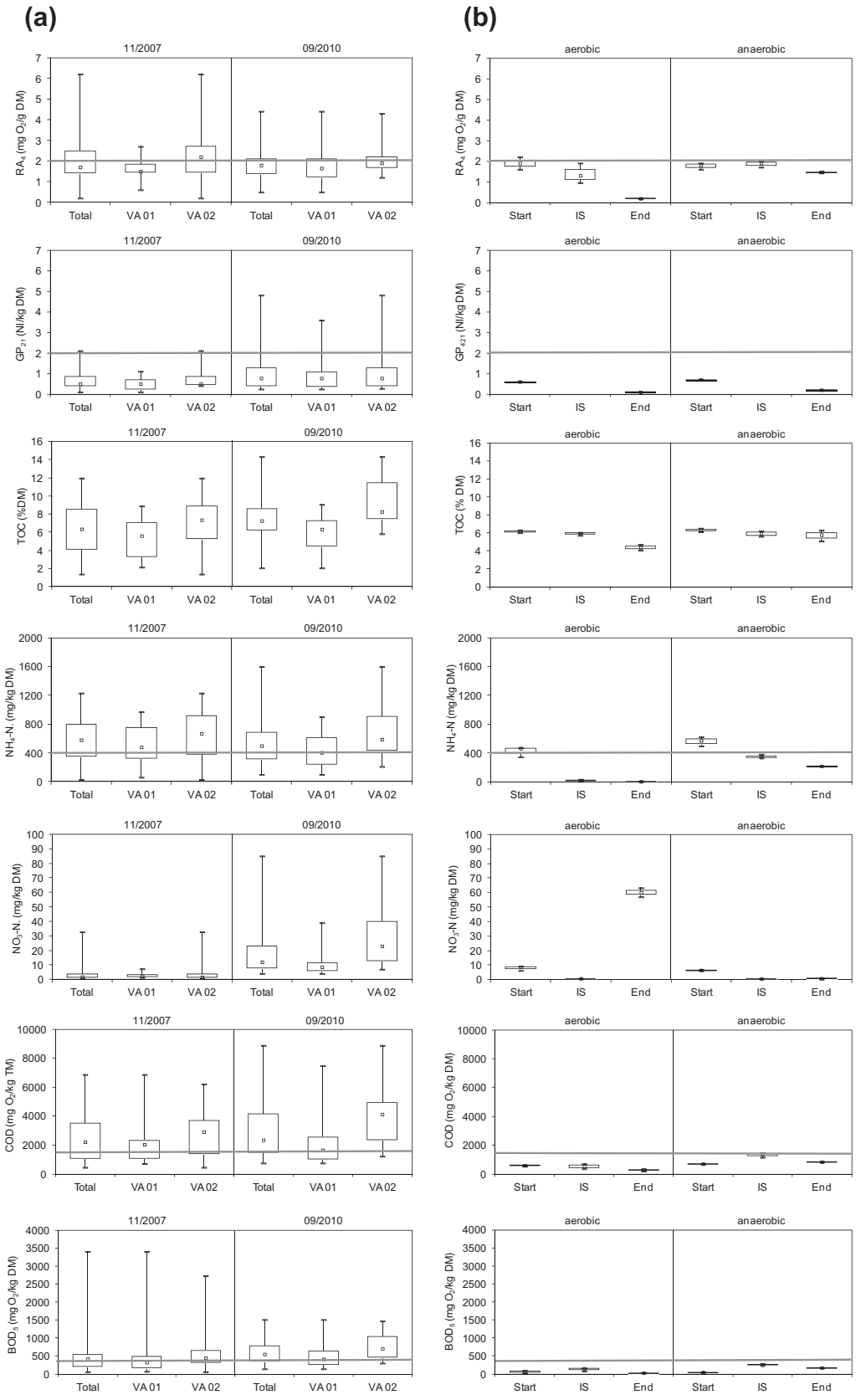

Fig. 6. Comparison of chemical (NH_4-N, NO_3-N, COD, BOD_5, TOC) and biological parameters (GP21, RA4) between field (a) and laboratory (b) conditions (VA01: older landfill section, VA02: newer landfill section); (horizontal lines indicate the target values given by local authorities).

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Table 2
Overview of the different conditions between lab- and field-scale aeration.

	Field-scale		Lab-scale		
	Aeration start	Sampling	Aeration start	Sampling	End
Time (weeks)	0	137	0	28	94
Air/solid ratio (l/kg DM)	0	79	0	226	760
Liquid/solid ratios (l/kg DM)	0	~0.13[a]	0	0.76	1.67
Aeration rate (l/kg DM d)			0.06–0.09	1.0	1

[a] The L/S ratio is based on the assumption that 30% of the precipitation from 2007 to 2010 percolated through the landfill.

In comparison with the performance of the LSR tests, measurable changes in the solid waste material under field conditions were less significant, most probably due to the high heterogeneity of the landfill body. Only ammonium-nitrogen and nitrate-nitrogen in the eluate showed a noticeable influence by the aeration measures. Ammonium-nitrogen was reduced by approx. 100 mg/kg DM in both sections (VA01 and VA02), while nitrate-nitrogen was increased by a factor of six. In general, the high variability of individual parameters is a first indication of the difficulties of solid waste sampling. A representative sampling in a heterogeneous waste body is very challenging and often requires a large, comprehensive pool of samples in order to fulfil statistical aspects.

A further indication of the accelerated waste mass degradation in the field is the extent of the landfill settlements. At the investigated landfill, settlements were measured in the range of 10–50 mm per year in the older section VA01, while in the younger section up to 100–170 mm per year could be detected. In comparison Heyer et al. (2005) measured settlements between 150 and 700 mm at the old Kuhstedt landfill after an aeration period of <2 years.

3.4. Effects on the temperature development

In general, landfill aeration leads to temperatures in a range of 35–50 °C due to intensive aerobic conversion processes (Heyer et al., 2005). In addition, the temperature appears to be a crucial factor controlling nitrogen dynamics within a MSW landfill. Increasing temperatures (>40 C) reduces the activity of ammonia and nitrite oxidisers (Grunditz and Dalhammar, 2001) and at the same time promotes the development of free ammonia (Lei et al., 2007). In addition, certain ammonia concentration levels could further inhibit nitrification (Onay and Pohland, 1998; Hao et al., 2010). Until now, most of the lab-scale experiments were conducted in a mesophilic temperature range (20–35 °C) (Ritzkowski et al., 2006; Ritzkowski and Stegmann, 2012; Prantl et al., 2007) and, therefore, may have not provided representative estimates of the nitrogen development of an aerated landfill. During this study, the LSRs were operated at a constant 40 °C, which has been observed in the majority of aerated landfills so far (Heyer et al., 2005). The mean temperature development at different depths within in the landfill body is shown in Fig. 7. The highest temperatures (up to 41–48 °C in summer 2009) were observed in the younger section of the landfill (VA02) in the surrounding of the distribution network for aeration RE 3 (in a depth of 2–4 m) indicating the greatest activity of aerobic biodegradation. Temperatures remained above 30 °C even during winter months. Not surprisingly, temperatures at a depth of 1–2 m were highly influenced by the ambient temperature. The coldest temperature (down to 4 °C in winter 2008/2009) was recorded in a monitoring well where high water levels were observed. In contrast, at a depth of 4–5 m temperatures remained in the range of 30 °C throughout the investigation period. Compared to the constant temperature conditions in the LSR (40 °C), under field conditions a decrease of microbiological activity is conceivable at decreased temperatures, e.g. lower than

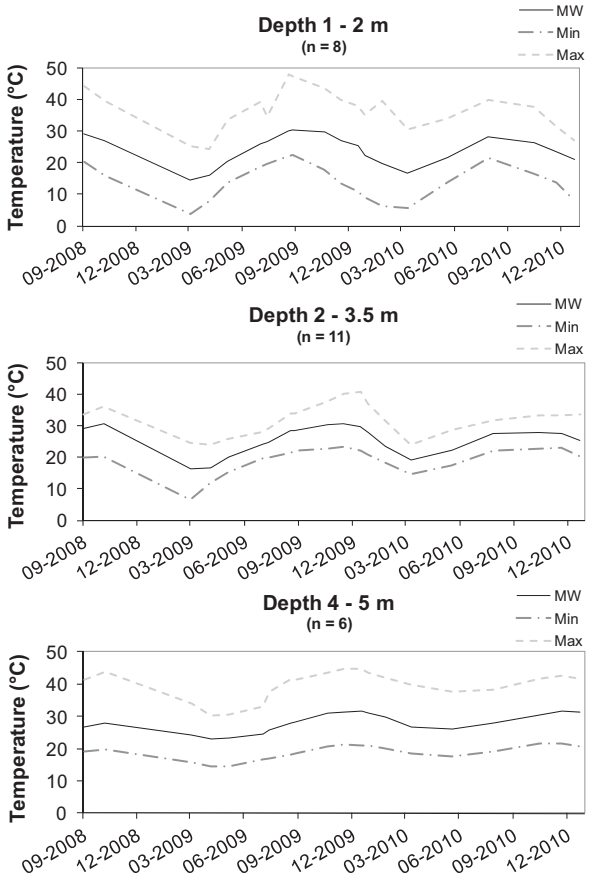

Fig. 7. Mean temperature development within the landfill body at different depths (MW: mean value; max: maximum value; min: minimum value).

20 °C or even lower during winter. According to van't Hoff's law, the velocity of biochemical reactions and microbial processes increases twofold or more for each rise of 10 °C in temperature. This is generally true when temperatures approximate those at which the reaction and processes normally occur. These circumstances might have additionally contributed to the difference between lab- based experiments and the full-scale operation.

3.5. Development of the emission behaviour after aeration completion

In order to determine the success of the aeration measure, the residual emission potential of the aerated waste material is currently being assessed in an ongoing laboratory experiment (LSR 1: switch from aerobic to anaerobic conditions). In addition, the aerobic degradation potential of the previously, anaerobically operated material is being determined (LSR 2: switch from anaerobic to aerobic conditions). The trend of inorganic and organic leachate compounds of the LSRs after the switch is depicted in

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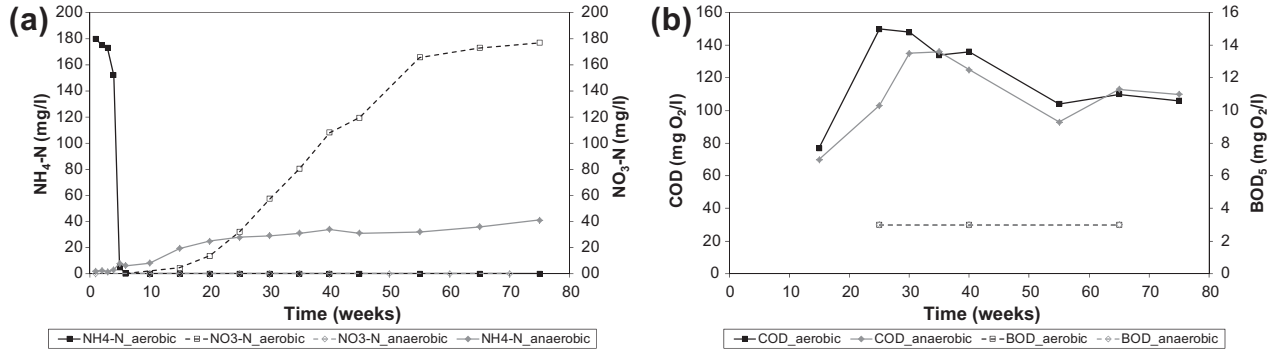

Fig. 8. Trend of inorganic (a) and organic (b) leachate compounds in the LSR 1 after aeration completion (not longer aerated = "anaerobic" condition) and LSR 2 (afterwards aerated = "aerobic" condition).

Fig. 8. After aeration stopped, LSR 1 showed only a slight increase in NH_4-N concentration and remained stable in the vicinity of 30 mg/l for 50 weeks (about 350 days). Similarly, Prantl et al. (2006) observed an increase of NH_4-N concentration from <1 NH_4-N mg/l to 40 mg NH_4-N/l in the leachate after 243 days of aeration completion. In the aerated LSR 2, NH_4-N concentration decreased to values lower than the detection limit within 6 weeks, while NO_3-N increased considerably to 180 mg/l. In contrast to the previous lab-scale experiment a lag-phase (no detectable NH_4 and NO_3 in the leachate) of only 15 weeks was observed. The development of the organic leachate compounds demonstrated the lasting effect on the stabilisation of waste. There was no significant difference between the COD concentration of the aerated and the anaerobic LSRs (70–150 mg O_2/l) indicating that COD reduction at low levels is caused by chemical–physical leaching processes (Prantl et al., 2006). During the investigation period of 75 weeks, the BOD_5 level remained below the detection limit of 3 mg O_2/l in both LSRs. After aeration completion in LSR 1, very low residual gas emissions (approx. 0.2 l/kg DM) were observed confirming the success of waste stabilisation. Methane was not detected in either the aerobic or the anaerobic LSR. The CO_2 content in the anaerobic LSR ranged between 2 and 11 vol.%. In the aerated LSR, a carbon discharge of 11 g C/kg DM was calculated during the 75 weeks aeration period, although the initial waste had already been degraded under optimal anaerobic conditions in the lab and leaching effects occurred due to the high L/S-ratio. The O_2 utilisation rate of LSR 2 showed a similar development compared to the previous laboratory experiment with initial high values (>90%) in the first 5 weeks followed by a considerable decrease to 13% during the remaining period until 75 weeks.

3.6. Estimation of the expected operation period

Several lab-scale investigations have been carried out in the past to glean knowledge about the achievable degree of emission reduction of in situ aerated landfills and, therefore, an estimate of the required operation period as well as the stability level of the waste material after aeration completion. Ritzkowski and Stegmann (2007) for example, suggest a dynamic approach using the $O_{2,utilised}$/solid-ratio to predict the total and residual operation period of an aeration measure. Applying their approach to the data of the current study gives an economically and practically unrealistic operation time period of about 17 years (based on a target value of 15 g C/kg DM and the respective $O_{2,utilised}$/solid-ratio of 30 m^3 O_2/Mg DM). The calculation is based on an actual aeration rate ranging from 600 to 1000 m^3/h including plant-shutdowns during winter months. Sensitivity analysis showed that the assumed total aeration volume is the most crucial factor. Assuming a total air volume of 1000 m^3/h (full capacity of the plant) without any shutdowns, the overall operation period could be decreased to 10 years.

According to the pre-investigations of the pilot-plant and lab-based calculations by Prantl (2007) and Prantl et al. (2006, 2007) a required operation time of about 4–5 years were predicted for the investigated landfill. However (after 3 years of operation) the current aeration performance in the field is a factor of 10 times behind the LSR-based predictions derived in this study, mainly due to technical limitations in the full-scale operation (e.g. high air flow resistivity due to high water content of waste and temporarily high water levels within the landfill; limited efficiency of the aeration wells) as well as degradation enhancing material preparation measures and optimal moister and temperature conditions in the lab-based experiment.

4. Conclusion

Although MSW material from the abandoned landfill investigated was characterised as being rather unreactive in terms of the biological parameters GP_{21} and RA_4, the LSR-studies under optimised lab-conditions showed that an accelerated degradation of the organic waste matter was still attainable, and a biological stabilised waste material could be achieved after about 2 years of aeration. Also the anaerobic references, which were operated under optimal anaerobic conditions and a high L/S factor over 740 days, showed a similar gaseous emission behaviour under aerobic conditions during the "switched" test run. These results reveal that waste, which seems to be mostly stable under anaerobic conditions, still possesses an aerobic degradation potential.

The "end material" of the aerated LSRs was characterised by a low RA_4 of 0.2 mg O_2/g DM, and a GP_{21} of 0.1 Nl/kg DM. At this stabilised state, the actual chemical leachate concentrations were rather negligible (e.g., NH_4-N = 0 mg/l; NO_3-N = 170 mg/l; BOD_5 < 1 mg O_2/l, COD = 95 mg O_2/l). Only the COD-value would not match the current requirements for direct leachate discharge into rivers in accordance with the Austrian Waste Water Emission Regulation AAEV (BGBl. Nr. 186/1996) so far, but no specific target value for COD was given by the local authority as end-point for the aeration project. Carbon discharge in the form of CO_2 (no methane was detectable) were about 0.01 g C/kg DM. Even 75 weeks after the shutdown of the aeration measure the leachate and gaseous emissions from this waste material remained low and stayed below the legally required Austrian discharge limits.

The reason that the legally required carbon discharge rate (target value defined by local authorities: 15 g C/kg DM) was achieved, even at the low initial reactivity of the waste material, is due to the optimised degradation conditions in the lab (constant optimal temperatures, homogeneous aeration, etc.). This fact is also

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impacted by the situation that the necessary preparation measures, the mechanical treatment and homogenisation of the waste prior to the filling of the LSR led to an optimally degradable waste material enriched in biogenic matter which fostered the microbial processes, and consequently the aeration measure. This issue must be thoroughly considered when transferring lab data to full-scale application and deducing field operation parameters.

Moreover, as occurred during this case study, the calculated and required aeration rate can often not be implemented directly in the field due to technical limitations and unforeseeable developments within the waste body, which may cause lag phases and time delays in operation. This "lag-factor" between lab and field performance depends mainly on the differences between the calculated (lab) rate and the real, implemented (field) aeration rate, the deviating aeration efficiency, the different L/S-ratios, differences in temperature and moisture development as well as the different "bioavailability" of the waste material due to preparation measures mentioned above.

As is indicated in this study, a simple increase in the aeration rate (input of air volume) does not lead inevitably to the designated effect on aeration performance in the field, since the spatial distribution of air in the landfill as well as inhomogeneous material seem to be limiting factors. Aeration tests carried out at the site show that the efficiency of the aeration wells, in particular the vertical influence, were only slightly improved by tripling the aeration rate. It can be concluded that, depending on the design and spacing of the aeration lances, an increase of the aeration rate does not necessarily improve the overall aeration efficiency of the plant and, thus, the success of waste stabilisation.

In the past, different lab-based experiments have been conducted to assess the predicted operation period of full-scale in situ aeration measures. In order to reliably predict field operation performance derived from lab-based tests, it is very important to observe and consider all the specific landfill-site properties, to adapt pre- or concomitant investigations, such as LSR tests continuously to varying and changing field conditions, and finally to find site-specific, tailor-made technical solutions for efficient full-scale aeration measures.

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