Waste Management 55 (2016) 99–107

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

# Aeration of the teuftal landfill: Field scale concept and lab scale simulation

Marco Ritzkowski [a,*], Beat Walker [b], Kerstin Kuchta [a], Roberto Raga [c], Rainer Stegmann [a]

[a] Institute of Environmental Technology and Energy Economics, Hamburg University of Technology, Harburger Schlossstr. 36, 21079 Hamburg, Germany[1]
[b] Deponie Teuftal AG, Bindenhausstrasse 42d, 3098 Köniz, Switzerland
[c] DII, Department of Industrial Engineering, University of Padua, via Marzolo, 9, 35131 Padova, Italy

A R T I C L E I N F O

*Article history:*
Received 18 March 2016
Revised 23 May 2016
Accepted 2 June 2016
Available online 11 June 2016

*Keywords:*
Landfill aeration
Moisturization
Post-closure care
Bio-stabilization
Leachate pollution

A B S T R A C T

Long lasting post-closure care (PCC) is often the major financial burden for operators of municipal solid waste (MSW) landfills. Beside costs for the installation and maintenance of technical equipment and barriers, in particular long term treatment of leachate and landfill gas has to be paid from capital surplus. Estimations based on laboratory experiments project time periods of many decades until leachate quality allows for direct discharge (i.e. no need for further purification). Projections based on leachate samples derived from the last 37 years for 35 German landfills confirm these assumption. Moreover, the data illustrate that in particular ammonium nitrogen concentrations are likely to fall below limit values only after a period of 300 years.

In order to avoid long lasting PCC the operator of Teuftal landfill, located in the Swiss canton Bern, decided to biologically stabilize the landfill by means of a combined in situ aeration and moisturization approach. In December 2014 the aeration started at a landfill section containing approximately 30% of the total landfill volume. From summer 2016 onwards the remaining part of the landfill will be aerated. Landfill aeration through horizontal gas and leachate drains is carried out for the first time in field scale in Europe. The technical concept is described in the paper.

Parallel to field scale aeration, investigations for the carbon and nitrogen turnover are carried out by means of both simulated aerated landfills and simulated anaerobic landfills. The results presented in this paper demonstrate that aeration is capable to enhance, both carbon mobilization and discharge via the gas phase. This effect comes along with a significant increase in bio-stabilization of the waste organic fraction, which positively affects the landfill emission behavior in the long run. In terms of leachate pollution reduction it could be demonstrated that the organic load decrease fast and widely independent of the adjusted aeration rates whereby ammonium nitrogen load efficiently decrease later and only under higher aeration rates.



## 1. Introduction

The Teuftal landfill, located in the Swiss canton Bern, is the largest sanitary landfill in Switzerland. For more than 40 years both, municipal solid waste (MSW), construction and demolition waste, bottom ashes, flue gas cleaning residues as well as industrial waste are disposed of at different landfill sections. Untreated MSW has been landfilled between 1973 and 2000 on an area of approximately 12 ha. This section of the landfill which contains approx. 3.2 million tons of waste (approx. 2.1 million tons dry matter) is hereafter referred to as bioreactor. Based on the available records regarding the landfilled waste materials it can be assumed that the amount of organic carbon in the fresh MSW was in a range of 18–20% based on dry mass. Since 1 January 2000, landfilling of organic waste is prohibited in Switzerland (Schweizerischer Bundesrat, 1990). Consequently, the bioreactor has been covered with biologically non-reactive waste (slightly contaminated soil) during the past 16 years.

Between 1982, when landfill gas (LFG) collection started for the first time, and 2013 a total of approx. 256 million $m^3$ LFG at an average methane concentration of 45% (average $CO_2$ concentration: 32%) has been collected from the bioreactor and used for combined electrical and thermal energy production. Since 1996 the collected amounts of LFG declined significantly down to hourly mean values well below 100 $m^3/h$ in 2013. At the same time, analysis results for leachate samples taken directly out of the most

* Corresponding author.
*E-mail address:* m.ritzkowski@tu-harburg.de (M. Ritzkowski).
[1] www.tu-harburg.de/iue/.

http://dx.doi.org/10.1016/j.wasman.2016.06.004
0956-053X/

reactive zone of the bioreactor still exhibited significant concentrations particularly for ammonium-nitrogen ($NH_4$-N, up to 1500 mg/l) and dissolved organic carbon (DOC, up to 600 mg/l).

In order to diminish long lasting PCC associated with severe costs and monitoring efforts (Heyer et al., 2005; Laner et al., 2012), the landfill operator in cooperation with the Hamburg University of Technology decided to biologically stabilize the bioreactor by means of a combined in situ aeration and moisturization approach. According to Heyer et al. (2005) the net costs for investment and operation of aerated landfills range from € 1.1 to € 3.0 per $m^3$ of aerated waste material. However, the investment made during and for the aeration will pay out through reduced expenditures for long term leachate and LFG treatment as well as monitoring. It is expected, that total cost reductions of at least 10–25% are possible as regards closure and aftercare measures. In December 2014 the aeration started at a section of the bioreactor containing approx. 30% of its total waste volume. There, landfill aeration using horizontal gas and leachate drains for air injection and off-gas extraction is carried out for the first time in full scale. The applied technology differs significantly from other approaches previously reported for landfills in Switzerland (Bachofner et al., 2010). Section 2 provides an overview on the technical concept applied for biological stabilization of the bioreactor. The stabilization processes is currently ongoing. First intermediate results from this field scale study are provided whilst final results will be presented at a later date. Sections 3 and 4 present the set-up and major findings from lab scale simulation tests which have been conducted in parallel to the field scale study.

## 2. Stabilization concept (field scale)

### 2.1. In situ aeration

Under consideration of site specific conditions it was decided to implement a large scale in situ aeration trial on Section 3 of the bioreactor. This section covers an area of approx. 4.8 ha and contains approx. 557,000 $m^3$ of MSW. Based on an estimated wet waste density of 1.2 ton per $m^3$ and a measured average moisture content of 35.5% (wt), the total amount of dry waste in bioreactor Section 3 is calculated to approx. 431,100 tons.

The aeration is realized using the existing horizontal gas and leachate drainage networks. Between 1987 and the year 2000, a total of 6 drainage networks have been installed at a vertical spacing of approx. 7 m. The highest situated drainage network (N6) is located directly at the interface between bio-reactive and non-reactive wastes and functions as a protection against water infiltration into the bioreactor. In contrary, network N1 is located closest to the valley bottom. The waste layer at the landfill base is considered low in bio-degradability, due to its age and composition (in particular higher amounts of excavated soil). Through the N1 network leachate originating from the bioreactor can be effectively drained out of the landfill. Each drainage network consists of a main drainage pipe and a number of smaller inlet lines. The latter branches off at an angle of 45° and a horizontal distance of 18–20 m. The minimum slope towards the main collection pipes is 5%. Fig. 1 shows a cross section of the bioreactor (Section 3) and provides an overview on the location of the drainage networks.

The aeration of bioreactor Section 3 was initiated in December 2014. During the initial stabilization period ambient air is injected into a total of 3 horizontal drainage networks (N1, N3 and N5) whereas the other 3 networks are used for parallel off-gas extraction. In order to diminish any diffuse gaseous emissions, the upmost drainage network is subject to off-gas extraction only whilst for moderate aeration of the underlying older waste mass the lowest network is permanently aerated. The remaining 4 intermediate drainage networks will be altered in their specific operation mode (either air injection or off-gas extraction) in order to ensure a widely aerobization of the deposited wastes and to avoid the potential formation of preferential flow paths.

At present, the devices for aeration and off-gas extraction are operated at an intermittent mode. Following a 100-min operation phase the blowers are turned off for a down time of approx. 20 min. During down time the drainage networks are depressurized which allows for the drain-off of leachate. The injected amount of oxygen is widely consumed during down times and the pressure variations during start up and close down positively contribute towards the intended complete distribution of air in the landfill section. Moreover, the operation mode ensures moderate energy consumption by the total bio-stabilization system which is further aided by the special type of blowers chosen for aeration and off-gas extraction. The installed screw type compressors are capable to operate at pressures up to 300 mbar whilst consuming approx. 30% less energy in comparison to rotary piston compressors which are often used for landfill aeration.

In comparison with other projects for low pressure aeration the required positive pressure differences for air injection at the Teuftal landfill are significantly higher. The usually reported pressure differences are in a range of 20–80 mbar and may, according to definition, not exceed 0.3 bars in maximum (Ritzkowski and Stegmann, 2012). For air injection into Section 3 of the bioreactor up to 250 mbar is required in order to realize an air volume of approx. 990 $m^3$/h. These higher pressures are due to the significant load caused by the MSW and the overlaying non-reactive waste layer, in combination with the specific installations used for air injection (i.e. horizontal drainage networks). In the extreme case at the lowest drainage system N1, a load of up to 54 Mg/$m^2$ can be expected.

The off-gas extracted from Section 3 is directly transferred into the upper drainage networks of the adjacent Sections 1 and 2 of the bioreactor. This strategy has been chosen in order to enable a pre-aeration of the remaining landfill sections associated with a reduction in the required aeration period. Along with the slight aeration caused by the residual oxygen content in the off-gas, a further aspect of the off-gas transfer comes with the biological oxidation of residual methane. The latter is expected to take place mainly during the perfusion of the gas through the overlaying non-reactive waste material.

Based on the results of the online monitoring system a specific carbon mobilization rate of 1.76 Mg/d (SD = 0.37) has been realized during the first 13 months of in situ aeration. The carbon load is calculated for the average volume of extracted off-gas (i.e. 1009 $m^3$/h from December 2014 until December 2015) and continuously analyzed concentrations of carbon dioxide (mean value: 9% v/v) and methane (mean value: 4.4% v/v). The specific carbon load in the off-gas was in the range of 65–84 g per $m^3$ (mean: 72 g/$m^3$; SD: 0.01).

### 2.2. In situ moisturization

Although the average moisture content of the waste in Section 3 (35.5% by mass, based on wet waste, see Table 1) can be considered sufficient for aerobic bio-decomposition, some zones exhibit significantly lower moisture contents of down to 18.4%. At these low moisture levels bio-degradation processes are limited and may even be inhibit completely (Liang et al., 2003). Moreover, through the extraction of water saturated off-gases from the landfill in combination with increased transpiration rates under elevated waste temperatures, the aeration process may contribute towards decreasing moisture content of the landfilled waste in the bioreactor (Ritzkowski, 2013).

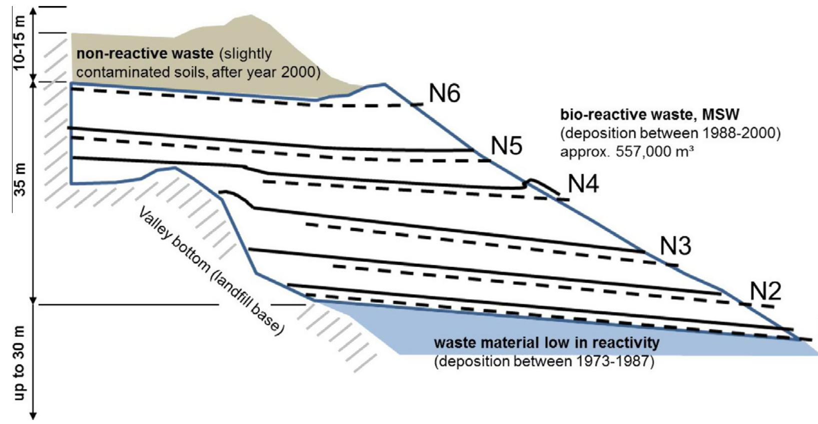


**Fig. 1.** Cross section of bioreactor Section 3 at the Teuftal landfill. Indicated are the 6 combined leachate and gas drainage networks (N1 to N6) located in the central part of the landfill.

**Table 1**
Operational parameter for six simulated landfills, used for long term investigations of the emission behavior of solid waste samples derived from the Teuftal landfill.

| LSR | LSR-volume ($m^3$) | Operation time Total (non-aerated/aerated) (d) | Operation mode | Leachate re-circulation rates (l/kg TS d) | Leachate effluent ($l/m^2$ a) | Waste density ($Mg/m^3$) | Dry matter (kg) | Aeration rate (average) (l/kg TS h) |
|---|---|---|---|---|---|---|---|---|
| SAL-1 | 0.08 | 482 (160/322) | AN[a] → A[b] | 0.11 | 212 | 0.61 | 37.4 | 0.025 |
| SAnL-1 | 0.08 | 325 (325/0) | AN | 0.12 | 212 | 0.58 | 34.0 | – |
| SAL-2 | 0.08 | 482 (160/322) | AN → A | 0.09 | 212 | 0.72 | 45.8 | 0.025 |
| SAnL-2 | 0.08 | 325 (325/0) | AN | 0.09 | 212 | 0.67 | 45.3 | – |
| SAL-3 | 0.08 | 482 (160/322) | AN → A | 0.11 | 212 | 0.61 | 37.5 | 0.0125 |
| SAL-4 | 0.08 | 482 (160/322) | AN → A | 0.09 | 212 | 0.63 | 43.0 | 0.0125 |

[a] AN = anaerobic.
[b] A = aerobic.

In order to compensate for, both any potential moisture losses and partly insufficient moisture contents, the strategy of combined aeration and moisture addition has been developed for the Teuftal landfill. Moisture addition is realized by two different means: Firstly, through infiltration of leachate into the upmost drainage system of the bioreactor Section 3. Through a total of 10 inlets, connected to the branches of the drainage system, approx. 2 $m^3$ leachate per hour is infiltrated into the waste mass. In this connection, the very coarse gravel-filled grain trenches around the mains of network N6 are used for moisture supply thus leaving the mains open for continuous off-gas extraction. Under an estimated horizontal expansion of 3–1 it can be assumed that the waste at Section 3 will be widely affected by the moisturization, even below the drainage network N5. Secondly, the ambient air used for the aeration is moisturized prior to its injection into the waste mass. Moisturization is realized by means of nozzles, injecting de-mineralized water into the air stream (Fig. 2). The use of deionized water is necessary in order to avoid clogging of the injection nuzzles.

## 3. Material and methods

### 3.1. Solid waste samples

The landfill section undergoing the accelerated bio-stabilization (Section 3 of the bioreactor) has been filled since 1986. Of particular interest for the combined aeration and moisturization approach, however, is the central zone where waste has been deposited until the year 2000. This zone exhibited a height of approx. 35 m and contains approx. 557,000 $m^3$ MSW which has been subject to intensive bio-degradation processes under the prevailing anaerobic conditions for the last 16–28 years.

In April 2014, a total of 11 boreholes have been drilled for the installation of temperature sensors over the entire vertical profile of sector 3. In this connection a total of 43 individual solid waste samples have been taken from 9 locations at 4 or 5 different depths per borehole (vertical spacing approx. 5 m in the bio-reactive waste zone). Fig. 3 shows the sampling locations at Section 3.

The samples have been air-tight sealed and transported to the Institute of Environmental Technology and Energy Economics at TUHH for detailed characterization. An individual analysis has been done in 23 cases (representing a total of 5 sampling locations) whilst for the other 4 sampling locations consolidated samples over the entire depths have been prepared and analyzed. Results of both chemical-physical as well as biological tests are summarized in Section 4.1.

### 3.2. Simulated aerated and anaerobic landfill

The investigations for simulated aerated and anaerobic landfills follow different objectives. Firstly, by means of simulated anaerobic landfills, a verification of the observed LFG generation rates from the full scale bioreactor should be achieved. This is important since LFG generation rates may have declined due to specific ancillary conditions in the landfill (e.g. limited moisture content and/or water movement), thus could eventually be enhanced again by improving these conditions. Secondly, the anaerobic experiments should serve as references for the simulated aerated landfills and allowing for direct estimation of the improvement in both the landfill emission behavior and landfill emission potential. For the

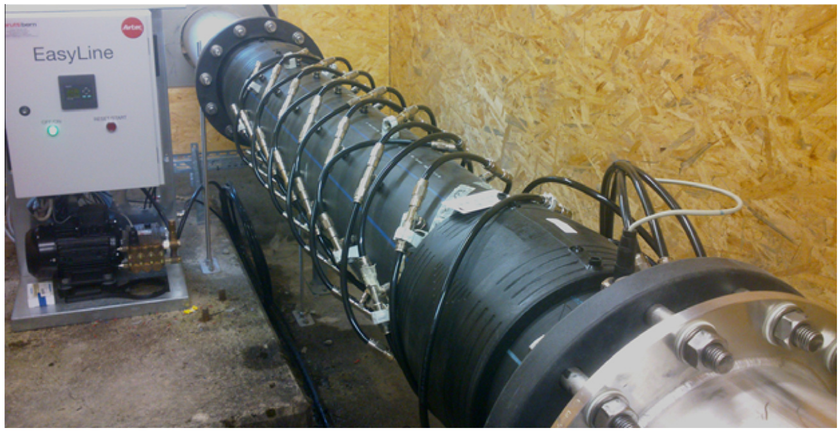


**Fig. 2.** Installation for the moisturization of air by means of injection nozzles, applied at the in situ aerated Teuftal landfill.

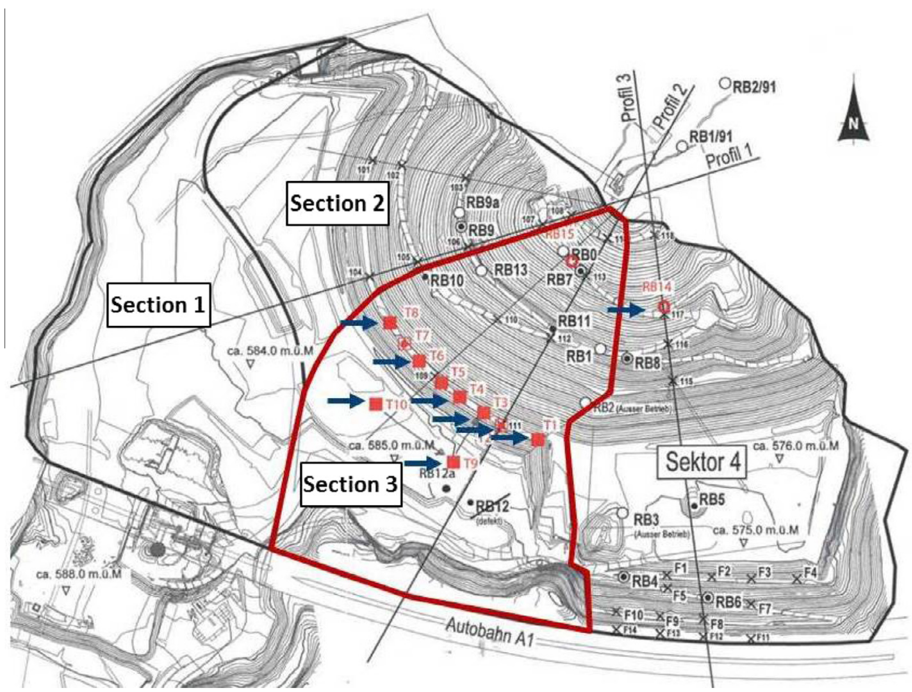


**Fig. 3.** Sampling locations (indicated by blue arrows) and boreholes (red dots) at Section 3 of the bioreactor landfill. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

latter it is of particular interest to determine any potential changes in the leachate pollution. An enhancement in leachate quality shall be connected to the applied operation mode and may provide indications on how to design and operate the full scale application in the most efficient way.

### 3.2.1. Set-up and operation of reactors

A total of six reactors, filled with solid waste material from the Teuftal landfill, are operated in parallel at constant room temperature of 37 °C. In two cases the reactors are operated under strict anaerobic conditions with leachate re-circulation (hereafter referred to as Simulated Anaerobic Landfill - SAnL) whilst the remaining four reactors are aerated with leachate re-circulation (hereafter referred to as Simulated Aerobic Landfill - SAL). For aeration, two different flow rates are applied: moderate aeration (approx. 0.0125 l/kgTS h) and intensified aeration (approx. 0.025 l/kgTS h).

In two cases, the same waste samples were placed into two parallel reactors (SAL-1 and SAnL-1; SAL-2 and SAnL-2). In this regard, SAnL-1 and -2 serve as control by simulating the landfill behavior under conditions as they would normally prevail in the Teuftal landfill.

Long term processes and related emissions from landfills can be simulated during short periods (decades vs. months) by application of reactor experiments. In accordance with the adjusted operation mode (anaerobic or aerated) the acceleration effect is caused either by the enhanced leachate generation rates or by the enhanced amount of injected air. The leachate is drained from the waste, collected in an air tight container, and recirculated twice a day, associated with an enhanced leaching of the waste material. Produced landfill gas (LFG) quantities as well as off-gas volumes (aerated LSR) are measured by means of drum gas-meters. Leachate was sampled and analyzed bi-weekly (exchange of 1.0 l leachate with 1.0 l of tap water) and gas samples were taken and analyzed twice per week. Fig. 4 shows the experimental set up of

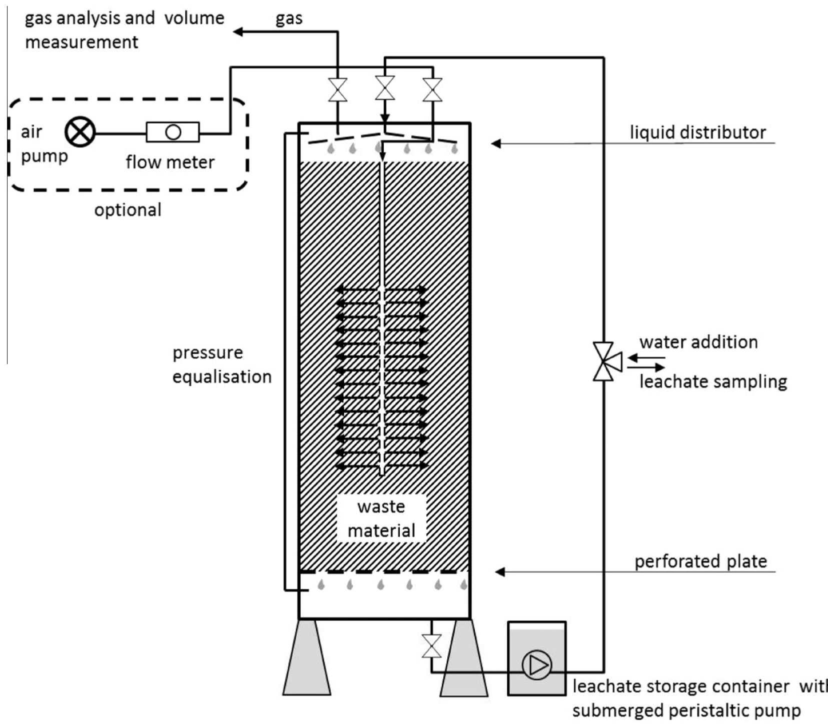


**Fig. 4.** Experimental set-up of the landfill simulation reactors for long term investigation of the emission behavior under anaerobic and aerobic conditions.

the LSR for long term investigations under both anaerobic and aerobic conditions.

The waste material sampled in April 2014 was adjusted to field capacity after placement into the reactors. Additional water was added to obtain excess liquid to be used in the operation of the leachate recirculation system. For the first seven weeks all simulated landfills were operated under anaerobic conditions. Afterwards, during a period of 25 weeks, intermittent aeration was applied to the 4 SAL (i.e. hybrid operation mode). Since week 35 these 4 SAL are continuously aerated. In Table 1 the main operational parameters for the simulated anaerobic and aerated landfills are summarized. Fig. 5 presents a graphical overview on the operation modes of SAL including indications on specific aeration rates applied during the hybrid phase.

### *3.2.2. Analytical methods applied to SAL and SAnL*

The gas composition ($H_2$, $N_2$, $N_2O$, $O_2$, $CO_2$, $CH_4$) was determined weekly by means of gas chromatography (HP 5890, Agilent).

Solid waste samples were characterized before the start of the simulation experiments. For chemical investigations, unaltered waste material was used. Total solids (TS) and volatile solids (VS) were measured according to DIN 38 414 - S 2 and DIN 38 409 - H 1–3, respectively. TOC was calculated from the difference between TC and TIC. TC and TIC have been measured for dried material in accordance with DIN EN 15936 by means of a Multi EA 4000 analyzer (Analytik Jena AG). TKN has been measured in accordance with the procedure described in VDLUFA A.2.2.1. The gross calorific value has been measured according to DIN EN 51900 by means of IKA C 5000 (IKA-Werke GMBH&CO.KG). The respiration index ($RI_4$) has been determined by means of a respirometer (Sapromat D12, VOIT GmbH, Heidenheim) and the gas formation potential ($GP_{21}$) has been analyzed according to DIN 38414-8.

Leachate samples were taken from the storage containers every second week. The pH and EC values were measured immediately after collection of the samples. For $NH_4$-N, COD and Cl the samples were stored at $-18$ °C until analysis. Ammonium nitrogen has been measured in accordance with DIN 38406-E5-2 through distillation, COD has been measured by means of cell test (Hach) and chloride has been measured in accordance with DIN 38405 - D1-2.

## 4. Results and discussion

### *4.1. Characterization of solid waste samples*

Solid waste samples derived from Section 3 of the bioreactor have been analyzed in view of their specific state of bio-stabilization. Table 2 summarizes the results of both chemical-physical as well as biological investigations of the solid waste samples taken at the Teuftal landfill.

Analytical results presented in Table 2 clearly demonstrate the significant heterogeneity of the landfilled solid waste material. Particularly high standard deviations of more than 50% of the mean value have been found for the gross calorific value (H0) and the gas formation potential (GP21). For the latter, the highest individual value exceeds the mean by approx. 19 times whilst the second highest value falls below the average.

The observed range of the analytical results underlines the general difficulty to achieve a high significance by means of individual waste samples. Outliers tamper the mean values significantly if they are not eliminated. On the other hand, elimination of outliers may be justified for statistical reasons, but reduce the significance of the overall results. In order to overcome these problems waste samples can be characterized by means of landfill simulation experiments in lysimeters. Both waste mass and volume used for these tests are significantly larger (factor ≈1250) in comparison to the chemical-physical or biological analysis. This leads to an increased representativeness of the investigated samples and enhances the significance of the results.

However, based on the analyzed mean and median values of both chemical-physical and biological analysis, the waste inventory of the bioreactor can be characterized as widely biologically

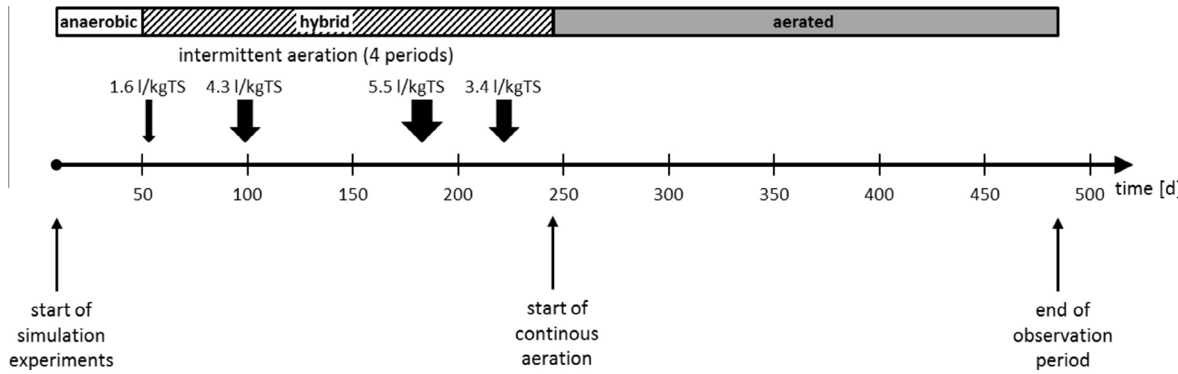


**Fig. 5.** Operation modes of SAL and indications on specific aeration rates applied during the hybrid phase.

**Table 2**
Results of chemical-physical and biological analysis of waste samples taken from the Teuftal landfill.

| Parameter | Unit | Sampling 04/2014 | | | |
|---|---|---|---|---|---|
| | | Mean | Median | Stand. dev. | Range |
| Total solids (TS) | % (wt.) | 64.5 | 64.2 | 8.5 | 46.7–81.6 |
| Volatile solids (VS) | % (TS) | 24.1 | 24.3 | 8.1 | 10.9–40.6 |
| Total organic carbon ($TOC_{solid}$) | % (TS) | 9.9 | 8.9 | 4.0 | 3.8–19.6 |
| Total Kjeldahl nitrogen (TKN) | ‰ (TS) | 4.5 | 4.4 | 1.4 | 2.1–6.9 |
| Upper heating value | kJ/kg | 4.439 | 4.003 | 2040 | 1581–9372 |
| Respiration index ($RI_4$) | $mgO_2$/kgTS | 1.5 | 0.8 | 1.1 | 0.4–5.5 |
| Gas formation potential ($GP_{21}$) | $l_N$/kgTS | 3.2 | 1.1 | 11.8 | 0.3–62.0 |

n = 27.

stabilized with a small to moderate residual emission potential. In particular the results of the biological tests (both aerobic and anaerobic with 1.5 $mgO_2$/gDM and 3.2 $l_N$/kgDM, respectively) confirm the advanced level of previous bio-stabilization which took place under the prevailing anaerobic conditions in the landfill during the past 22 years. Other landfill aeration projects reported results in a similar dimension. For waste samples taken from the landfill of Modena in northern Italy the average value of RI4 was 1.6 $mgO_2$/gDM (Raga et al., 2015); Hrad et al. (2013) reported a median RI4 value of 1.7 $mgO_2$/gDM for waste samples derived from an old landfill near Vienna, Austria; and Brandstätter et al. (2015) found an average RI4 value of 1.7 $mgO_2$/gDM for 40 year old waste from a former MSW landfill in Austria.

### 4.2. Results from SAL and SAnL operation

#### 4.2.1. Verification of LFG generation rates

The SAnL were operated under strict anaerobic conditions for simulation of the situation at the bioreactor, without accelerated bio-stabilization. After 12 months of operation it became obvious that the observed bio-degradation processes in these tests fall significantly behind the ones observed in the aerated tests. Under optimized conditions (i.e. temperature: 37 °C; leachate re-circulation, waste moisture content at field capacity: 42 wt.%) both SAnL have reached the stable methanogenic phase after a period of six and eleven weeks, respectively. During the stable methanogenic phase, an average LFG generation rate of 0.6 l/MgTS h (range: 0.2–1.0 l/MgTS h) has been observed with slightly decreasing trend towards the end of the 12 months operation period.

Since the bioreactor Section 3 holds approx. 431,100 Mg of waste (dry matter), the theoretical LFG generation rate from the full scale landfill is calculated to an average of 250 $m^3$/h with a range from 86 to 431 $m^3$/h. In contrast, in 2012 approx. 100 $m^3$ LFG per hour has been extracted from the bioreactor under sub-optimal conditions (i.e. partly insufficient moisture content, no leachate re-circulation, no final top cover in place). This value at the lower end of the theoretical LFG generation rates demonstrate that - eventually - through application of optimization measures (e.g. moisture addition, leachate re-circulation) at the bioreactor an increase of the collectable amounts of LFG may be possible. However, since the amount of mobilized (i.e. bio-degradable) organic carbon under anaerobic conditions is very limited (2.25% of the residual TOC during a period of 12 months, based on the results of the SAnL), the total amount of LFG to be theoretically formed in the bioreactor accounts to a maximum of 1.8 million $m^3$ during reasonable time frames. This amount is less than 2% of the total amount of LFG which has been collected from the bioreactor Section 3 during the past 28 years. Moreover, in consideration of the fact that the major share of this amount will be produced at specific LFG production rates smaller than required for efficient energy recovery, the decision for an accelerated stabilization of the bioreactor can be considered economically worthwhile.

#### 4.2.2. Decomposition of organic carbon and mobilization via LFG or off-gas

Under simulated aerated landfill conditions the microbial metabolism rates are significantly enhanced in comparison to anaerobic metabolism (Bilgili et al., 2007). This is partly due to the faster growth rates of the microbial biomass, but also attributed to different substrates to be degraded under altered redox conditions. In particular lignin containing biomass (woody material) can be decomposed in aerated landfills whereas no metabolism pathway for these substrates exists under anaerobic conditions (Brandstätter et al., 2015). Consequently, the carbon conversion rates of SAL are enhanced and the overall stabilization process of the organic fraction is significantly increased.

During the first year of operation the accumulated carbon load, discharged as $CO_2$ and $CH_4$ from the SAL, exceeded the carbon load from SAnL by more than factor 3. In relation to the initial amount of organic carbon in the solid waste material the reduction is approx. 3.7 times higher from the simulated aerated landfill compared to the anaerobic one (Fig. 6).

Although the overall increase in carbon conversion (in consequence of the aeration) is considered moderate, it is worth mentioning that the intermittent aeration strategy during the first 8 months of the simulation experiments led to an instantaneous

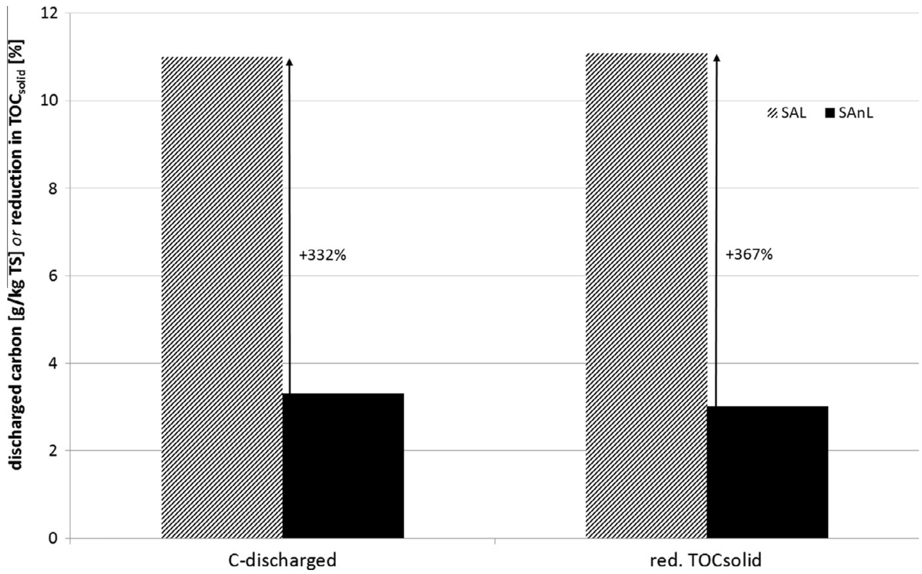


**Fig. 6.** Discharged carbon and reduction of total organic carbon in the solid waste material from both aerated (SAL) and anaerobic simulated landfill (SAnL).

increase in the specific carbon loads released via the off-gas. Thereafter, during the initial two months of continuous aeration (after months 8 of the simulation experiment) the carbon discharge reached a specific value of 0.06 g C/l air$_{injected}$ on average.

*4.2.3. Changes in leachate pollution*

In order to allow for a better and direct comparison between the individual simulated landfills, the concentrations of investigated leachate compounds (i.e. $NH_4$-N and COD) have been set in relation to the accordant chloride concentrations. This approach is based on the assumption that chloride is not undergoing bio-chemical reactions in the course of the simulation experiments, thus concentrations are connected solely to leaching processes. If the calculated ratios between the concentrations of the parameters of concern and the chloride concentrations are behaving with similar trend, it can be assumed that the parameter of concern is undergoing no bio-chemical reactions. If the ratio is declining, decomposition is likely to occur whereas for increasing ratios mobilization processes are assumed.

In contrast to the observed instantaneous increase in carbon discharge via the gas phase, the leachate quality has not been affected by the intermittent aeration strategy during the first 8 months of simulation experiments. No significant changes in COD and $NH_4$-N concentrations have been observed during this period. For both parameters the ratio to the accordant chloride concentrations remained at a level equal to the one calculated for the SAnL.

After the initialization of continuous aeration (following month 8 of SAL operation) the COD/Cl ratio decreased immediately and significantly for the simulated aerated landfill whereas the value for the SAnL remained unchanged (Fig. 7). Furthermore, the different aeration rates applied (‘moderate’ at 0.0125 l/kgTS h or ‘intensive’ at 0.025 l/kgTS h) had no significant impact on the evolution of the COD/Cl ratio.

For the ammonium nitrogen ($NH_4$-N) to chloride ratio, continuous aeration initially showed no significant impact. After a transition period of three months, when COD concentrations in SAL had already been reduced to low values, the $NH_4$-N/Cl ratio decreased for the intensively aerated SAL. At the same time the reduction in $NH_4$-N/Cl ratio for the moderate aerated SAL was significantly smaller, but exceeded the behavior observed for the control SAnL (Fig. 8).

The observed ammonium oxidation which is the reason for the reduction in $NH_4$-N/Cl ratio is considered as the secondary oxygen consuming reaction in SAL after the turnover of organic carbon. The reason for the differences in the reduction is probably related to the amount of available oxygen in the waste mass. For the moderate aerated SAL, oxygen concentrations in the off-gas have been determined at 3.8% (v/v) in average whereby intensive aerated SAL showed average $O_2$ concentrations of 5.9% (v/v). These findings are in line with results from previous studies which concluded that nitrification processes in SAL are widely independent from the applied aeration rates (for tested aeration rates between 0.01 and 0.03 l/kgTS h) as long as the oxygen concentration inside the waste mass remains sufficient (Ritzkowski and Stegmann, 2005). At the lower end of these values a limitation in oxygen availability may occur, which negatively impact on the evolution of the ammonium concentrations in leachate from aerated landfills.

## 5. Conclusions

At the Teuftal landfill in the canton Bern, Switzerland, biodegradable waste (MSW) has been deposited between 1973 and 2000. Today, 16 years after the completion of MSW deposition, the average waste age at the bioreactor is approx. 29 years. In the course of microbial decomposition under the prevailing anaerobic conditions, a significant share of bio-available organic carbon contained in the landfilled wastes has already been converted. This is reflected by both a total of 242 million $m^3$ of extracted LFG as well as decreasing LFG production rates since the late nineties. Today, the residual LFG generation potential is calculated to 1.8 million $m^3$ in total. At the same time, leachate pollutants remain at elevated levels, significantly above the Swiss limit values for direct discharge into receiving waters. It can be estimated, that both ongoing slight LFG production and leachate pollutants will necessitate long lasting post closure care associated with severe financial burdens for the landfill operator.

Against this background, the landfill operator initiated measures for the accelerated and sustainable bio-stabilization of the bioreactor. Since December 2014 a large scale aeration trial at Section 3 of the bioreactor has been started and from summer 2016 onwards the total bioreactor will be in situ aerated. Landfill aeration is amended by leachate addition through infiltration and moisturization of the injected air.

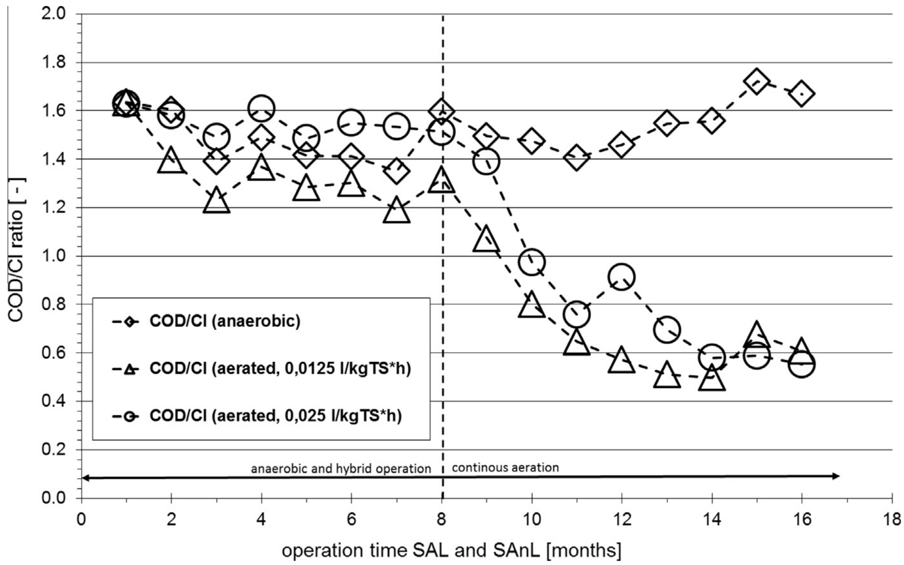


**Fig. 7.** Ratio between COD and chloride (monthly average) in leachate of simulated aerated (SAL) and anaerobic landfill (SAnL).

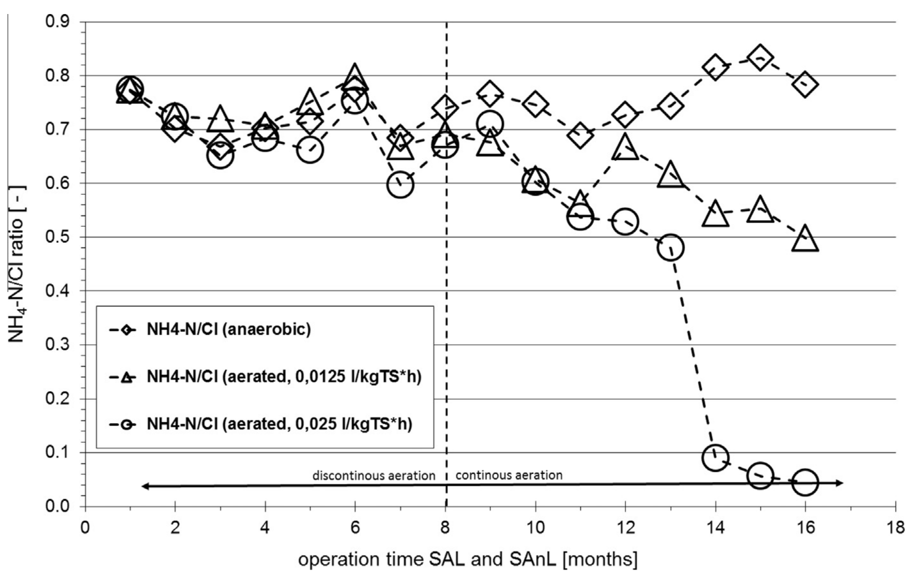


**Fig. 8.** Ratio between $NH_4$-N and chloride (monthly average) in leachate of simulated aerated (SAL) and anaerobic landfill (SAnL).

By means of parallel investigations of simulated aerated and anaerobic landfills the residual LFG generation potential could be assessed. Moreover, indications on the long term evolution of important leachate compounds could be gained from the conducted lab tests. Based on these test it can be expected that leachate pollution in terms of COD will be significantly reduced in the course of aeration. A significant reduction in the concentrations of ammonium-nitrogen, however, seems to be dependent on the amount of excess oxygen in the aerated waste mass. There are certain indications whereby the oxidation of ammonium will occur later (in comparison to the reduction in organic carbon compounds) and only if sufficient aeration rates are applied, connected to a comprehensive air supply of the entire waste mass.

## References


Bachofner, A., Meier, W., Düring, A., 2010. Aerobisation of landfills in Switzerland – discoveries from operation. In: Lorber, K.E., Adam, J., Aldrian, A., Arnberger, A., Bezama, A., Kreindl, G., Müller, P., Sager, D., Sarc, R., Wruss, K. (Eds.), DepoTech 2010, p. 887, ISBN: 978-3-200-02018-4.

Bilgili, M.S., Demir, A., Ozkaya, B., 2007. Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes. J. Hazard. Mater. 143 (1–2), 177–183.

Brandstätter, Chr., Laner, D., Fellner, J., 2015. Carbon pools and flows during lab-scale degradation of old landfilled waste under different oxygen and water regimes. Waste Manage. 40, 100–111.

Heyer, K.-U., Hupe, K., Ritzkowski, M., Stegmann, R., 2005. Pollutant release and pollutant reduction – impact of the aeration of landfills. Waste Manage. 25 (4), 353–359.

Hrad, M., Gamperling, O., Huber-Humer, M., 2013. Comparison between lab- and full-scale applications of in situ aeration of an old landfill and assessment of long-term emission development after completion. Waste Manage. 33, 2061–2073.

Laner, D., Crest, M., Scharff, H., Morris, J.W.F., Barlaz, M.A., 2012. A review of approaches for the long-term management of municipal solid waste landfills. Waste Manage. 32 (3), 498–512.

Liang, C., Das, K.C., McClendon, R.W., 2003. The influence of temperature and moisture contents regimes on the aerobic microbial activity of a biosolids composting blend. Bioresour. Technol. 86 (2003), 131–137.

Raga, R., Cossu, R., Heerenklage, J., Pivato, A., Ritzkowski, M., 2015. Landfill aeration for emission control before and during landfill mining. Waste Manage. 46, 420–429.

Ritzkowski, M., Stegmann, R., 2005. Mechanisms affecting the leachate quality in the course of landfill in situ aeration. In: Cossu, R., Stegmann, R. (Eds.), Proceedings of Sardinia 2005 – Tenth International Waste Management and Landfill Symposium. CISA Publisher, pp. 417–418, Session C15.

Ritzkowski, M., Stegmann, R., 2012. Landfill aeration worldwide: concepts, indications and findings. Waste Manage. 32 (7), 1411–1419.

Ritzkowski, M., 2013. Temperature development in aerated landfills. In: Cossu, He, Kjeldsen, Matsufuji, Reinhart, Stegmann (Eds.), Proceedings of Sardinia 2013 – Fourteenth International Waste Management and Landfill Symposium. CISA publisher, p. 123, Session B14.

Schweizerischer Bundesrat, 1990. Technische Verordnung über Abfälle (TVA) vom 10. Dezember 1990, modified 1 July 2011 PDF-File: <http://www.admin.ch/opc/de/classified-compilation/19900325/201107010000/814.600.pdf>.