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Landfill aeration for emission control before and during landfill mining

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ABSTRACT

The landfill of Modena, in northern Italy, is now crossed by the new high velocity railway line connecting Milan and Bologna. Waste was completely removed from a part of the landfill and a trench for the train line was built. With the aim of facilitating excavation and further disposal of the material extracted, suitable measures were defined. In order to prevent undesired emissions into the excavation area, the aerobic in situ stabilisation by means of the Airflow technology took place before and during the Landfill Mining. Specific project features involved the pneumatic leachate extraction from the aeration wells (to keep the leachate table low inside the landfill and increase the volume of waste available for air migration) and the controlled moisture addition into a limited zone, for a preliminary evaluation of the effects on process enhancement. Waste and leachate were periodically sampled in the landfill during the aeration before the excavation, for quality assessment over time; the evolution of biogas composition in the landfill body and in the extraction system for different plant set-ups during the project was monitored, with specific focus on uncontrolled migration into the excavation area.

Waste biological stability significantly increased during the aeration (waste respiration index dropped to 33% of the initial value after six months). Leachate head decreased from 4 to 1.5 m; leachate recirculation tests proved the beneficial effects of moisture addition on temperature control, without hampering waste aerobization. Proper management of the aeration plant enabled the minimization of uncontrolled biogas emissions into the excavation area.

1. Introduction

Landfill conditioning by means of in situ aeration can be necessary for waste pre-treatment prior to landfill mining (LFM), in order to reduce the effects connected to biogas uncontrolled emissions from the waste mass during the excavation (Cossu et al., 2003a).

Among the first examples of LFM in Europe, the case of Burghof landfill in Germany (Rettenberger, 1995) involved the application of an odor stabilization technique, consisting in air injection and gas extraction for 2 weeks before starting the excavation, carried out by means of 3.5 m probes pressed into the waste, at a distance of 5–6 m from each other. With a very similar plant design, the Smell Well System was used before mining Sharjah's landfill in the United Arab Emirates, the main difference being that in this case the aerobic conditions were maintained for a longer period of time (6 weeks) before the excavation (Goeschl and Rudland, 2007).

Compared to landfill aeration within the scope of post-closure care and its completion (Ritzkowski and Stegmann, 2013), in the case of landfill conditioning before LFM the aeration time can be shorter as the goal is not the abatement of the emission potential but the control biogas formation and migration in the excavation area (Ritzkowski and Stegmann, 2012). However, a prolonged aeration can result in increased biological stability of the organic fraction also, which would prove beneficial in case the final disposal in new landfill sectors is foreseen for (a fraction of) the excavated waste. As a matter of fact, despite the current development of innovative concepts such as the Enhanced Landfill Mining (Jones et al., 2013) where the integrated valorisation of landfilled waste streams both as materials and energy by means of innovative transformation technologies is envisaged, a very common purpose of LFM is still to relocate the waste from unlined landfill sectors to new lined ones (Jain et al., 2013), with the additional gain of new landfill volume.

In the many cases where the material below the waste acts as a (natural or constructed) barrier to leachate migration and leachate extraction systems are either missing or not effective, relevant leachate tables are expected to be present and to hamper proper waste excavation. In such cases, each aeration well can be

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equipped with pneumatic ejectors (or other kinds of pumps) in order to enable leachate extraction, as developed with the Airflow patented technology by the University of Padova together with its spinoff company, Spinoff srl. The Airflow technology was used for landfill conditioning in the framework of a reclamation project proposed for an old site in northern Italy, involving landfill mining with material and energy recovery and the construction of new landfill sectors for the non-recoverable fraction of the excavated waste and for the future waste disposal needs of the region. In this case, an in situ aeration period of 6 months was considered adequate to reach a significant biological stabilization of the deposited waste before excavation, also in view of the further landfill disposal (Raga and Cossu, 2014).

Active aeration is among the recommended measures to prevent odorous emissions before the excavation of temporary biodegradable waste storage facilities also, where anaerobic conditions have developed due both to waste quality and storage conditions (Wagner and Bilitewski, 2009).

Conversely, in the case of very well stabilized old waste deposits the use of the in situ aeration before LFM can be unnecessary, as recently documented by Jain et al. (2013), who report that uncontrolled gas emissions and odor were not an issue during landfill excavation and the processing of the excavated material.

This paper presents results from a very unusual project where in situ aeration by means of the Airflow technology was applied in the central part of an old landfill, for waste conditioning before and during LFM carried out to enable the construction of a 19 m deep trench for a railway line, that was supposed to cross the landfill laying on the natural soil at its bottom. The very specific challenges posed by this project were related to the expected leachate and biogas emissions into the excavation area from the adjacent and still active landfill sectors. Among the many measures foreseen to guarantee safe work conditions during the LFM, the application of in situ aeration was prescribed by the local authorities. Following a number of preliminary tests a tailor-made aeration plant was designed, installed and run in different conditions in order to adjust the settings to the specific case.

The project enabled the evaluation of the effectiveness of the Airflow technology for landfill aerobization before and during the LFM, to prevent undesired emissions into the excavation area. Moreover, useful information on the evolution of waste and leachate quality during the aeration were obtained, together with insight on best practices for the enhancement of the involved processes.

The case study will be presented, the technical choices discussed and the results analyzed in the following chapters.

2. Description of the in situ aeration project

The landfill site, built in a former clay pit, is located in an industrial area a few kilometres from the town of Modena, in northern Italy. The site is approximately 40 ha wide and comprises 4 main landfills (RSU1, RSU2, RSU3 and RSU4 in Fig. 1). MSW disposal was started in the early 1950s in RSU1, to continue in the following decades until the years 2000, when RSU4 was still in operation. Most of the landfill sectors in the site were built before a standard practice for planning and siting of waste management plants and landfills was available (Raga et al., 2010; Pivato et al., 2013) and the first national legislations on waste management were issued; they are a typical example of uncontrolled waste disposal site, very common in Europe until the 1980s (Marella and Raga, 2014).

As sketched in Fig. 1, the high velocity railway line currently connecting Milan to Bologna in Italy, was designed to cross landfills RSU2 and RSU3, involving the excavation of a trench 400 m long and 80 m wide in the upper part, to reach the natural soil at the bottom after the removal of approximately 200,000 tons of waste.

The case study reported in this paper is related to the conditioning and excavation works in the area of RSU2 that were carried out to serve as a pilot for the full scale application to the bigger RSU3 area.

RSU2 was used for MSW disposal in the period 1985–1988 and contained approximately 630,000 tons of waste, over a surface of 5 ha and with an average depth of 19 m. Based on the design of the railway track, the aeration of RSU2 involved approximately one third of the landfill (Fig. 1).

A preliminary risk assessment of RSU2 was carried out (Cossu et al., 2003b), based on the evaluation procedure developed in the framework of the EU Life project "Evaluation and Preliminary Assessment of old Deposits – EVAPASSOLD" (Allgaier and Stegmann, 2005). After the evaluation the site was classified among the "*potentially emitting old deposits* (*with a low permeable surface cover*, *and a still high emission potentials*, *but currently low substance emissions*)". The landfill characterization was carried out preliminary to the aeration, focusing on waste fractional composition (in view of possible material or energy recovery), waste, biogas and leachate quality, leachate piezometric levels, landfill permeability, radius of influence of the aeration wells. The results, reported in chapter 3, enabled the proper design of the aeration plant.

2.1. The Airflow system

Based on the thorough overview reported in Ritzkowski and Stegmann (2012), the Airflow can be classified among the low pressure aeration systems, with simultaneous active aeration and off-gas extraction. Compared to other low pressure aeration systems, a specific feature of the Airflow system is the pneumatic leachate extraction from aeration wells, carried out in order to keep the leachate table low inside the landfill and thus increase the volume of unsaturated waste available for air migration. Further details and a more comprehensive description of the Airflow system are available elsewhere (Raga and Cossu, 2014).

Due to the fact that the central part only was destined for landfill mining, the aeration was purposely designed in order to prevent biogas emissions into the excavation area from the side slopes and the adjacent non-aerated landfill sectors. For this reason, the aeration wells were installed in an area larger than where the excavation was supposed to occur (Fig. 2), in such a way that the following 2 goals could be attained:

- enhance the biological stability not only of the waste to be mined, but also of those contiguous to the excavation area;
- maintain a depression on the trench slope during LFM by means of proper adjustment of flow rates in the aeration wells adjacent to the excavation area.

In order to be able to keep the aeration plant running during the excavation of the trench, the installation was designed with two independent aeration units (Unit 1 and Unit 2 in Fig. 2); two automatic systems enabled the continuous monitoring and control of flow rates as well as of extracted gas composition. Two independent leachate extraction systems and two commercial biofilters for off-gas treatment were also installed. The volume of each biofilter was approx. 25 m^3, the biofiltration media being a mixture of compost and wood chips.

The aeration plant in operation before the excavation comprised 12 air injection wells, 15 gas extraction wells and 13 monitoring wells (screened at 7, 12 and 17 m depth from landfill surface) as shown in Fig. 2. As better described in the next paragraph, before the beginning of the LFM, the aeration and monitoring wells

Fig. 1. Layout of the railway track through the landfill site. The black square highlights the area where the aeration took place, in RSU2 landfill.

in the excavation area were shut and dismissed; as a consequence, 7 gas extraction, 6 air injection and 4 monitoring wells only were available and used to prevent gas migration into the trench during LFM (Fig. 2).

Each aeration unit was designed with maximum air injection as well as gas extraction capacity of 800 m^3/h; average air injection and gas extraction flow rates in steady state conditions before starting the excavation were 610 and 660 m^3/h, respectively.

2.2. Project outline

In Fig. 3 representative cross sectional views of the aeration plant during the project phases are reported.

In situ aeration in an area contiguous and connected to non-aerated landfill sectors brought about the challenge of avoiding continuous extraction of biogas from the non-aerated zones during steady state running of the aeration plant, as this would result in potentially explosive mixtures of air and methane reaching the blowers. For this reason, as visible in Fig. 3a depicting the situation at start of landfill conditioning, the wells at the boundary of the plant were used as air injection wells (lateral injection (L_{in}) wells), in such a way that mainly process gas from aerobic degradation with very limited methane content reached the lateral extraction (L_{ex}) wells.

Before the beginning of the excavation the central injection (C_{in}) wells as well as the central extraction (C_{ex}) wells (Fig. 3b), in both cases placed within the excavation area, were shut and disconnected from the network. At the beginning of the excavation L_{in} and L_{ex} wells were maintained in operation at the average flow rate of 280 and 350 m^3/h respectively, to both control the gas composition at the boundaries of the plant and to go on with leachate extraction. Indeed, L_{ex} wells were meant to create a depression and to draw air from the excavation area; on the contrary, as in the previous phase, L_{in} wells were meant to create a sort of a barrier and avoid biogas migration toward L_{ex} wells from the rest of the landfill. As better discussed in the next chapter, this choice proved unfavourable and therefore, a few days after the beginning of the excavation works, L_{in} wells were shut as shown in Fig. 3c; L_{ex} wells only were kept in operation at a higher average gas extraction rate (up to 420 m^3/h) and the results in terms of minimization of biogas migration into the excavation area were more satisfactory.

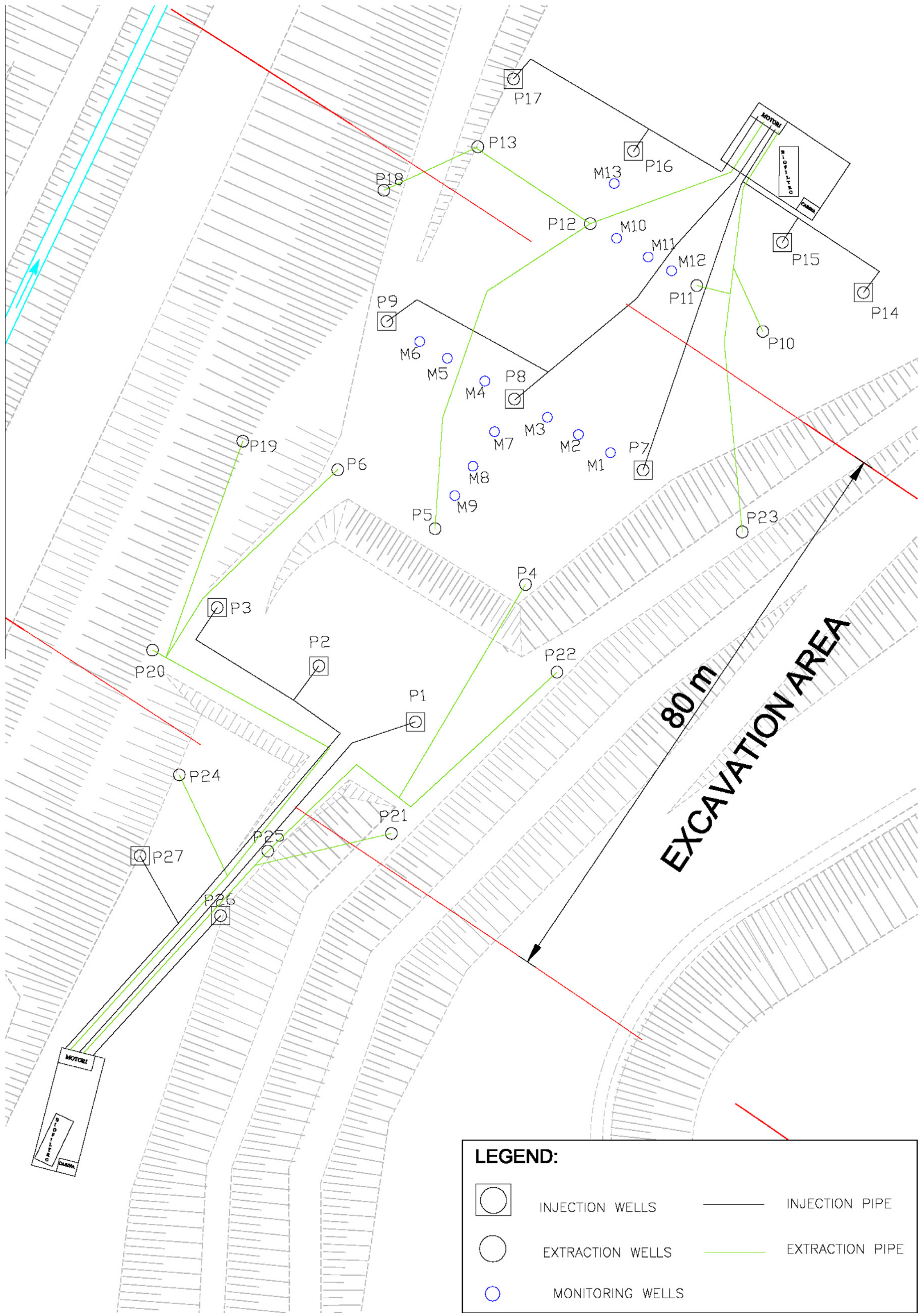

Fig. 2. In situ aerobic stabilization of the landfill of Modena. Lay-out of air injection and biogas extraction wells. Unit 1 and 2 are independent in order to enable continuous operation of the plant during the excavation in the central part of the landfill.

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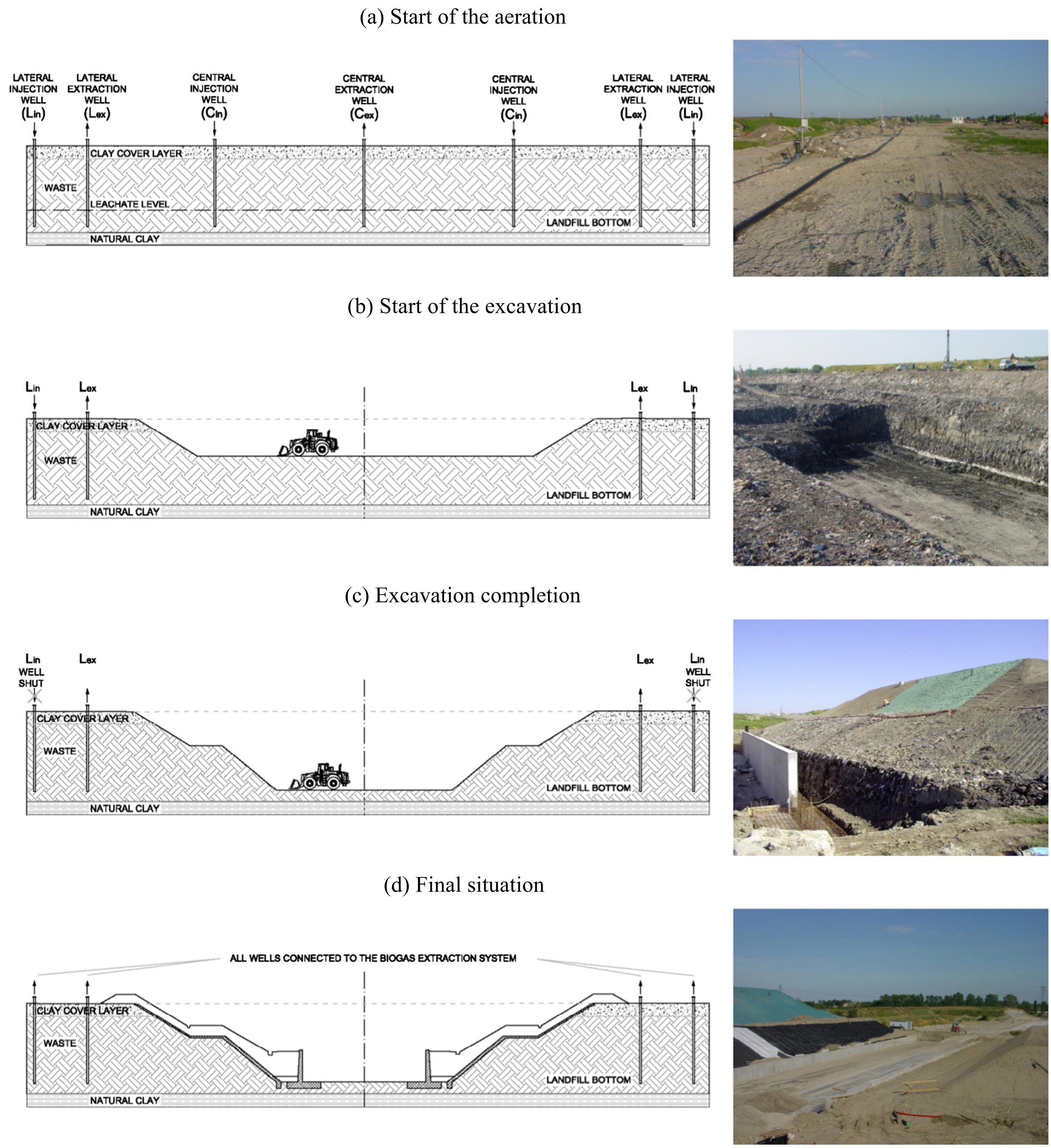

Fig. 3. Scheme illustrating the different phases during excavation works.

The overall situation at the end of the excavation works is represented in Fig. 3d.

2.3. Management and monitoring plan

During the operations a monitoring plan was carried out with analyses of waste samples (every three months at three depths), leachate and gas samples, taken from different points in the landfill at different stages of the process. The plan also provided for the monitoring of temperature, pressure and leachate level in the landfill body. The monitoring of gas composition was carried out in the extraction as well as in the monitoring wells; the monitoring of temperatures was performed in all of the above and in the air injection wells. Samples of leachate were periodically extracted and analyzed. Waste samples were drilled and analyzed for the determination of the main stability parameters (respiration index, BOD_5/COD ratio in leaching test eluate) and the results were compared with those obtained for waste samples collected before the start of the aeration process.

Moisture addition tests by means of leachate recirculation were carried out in a limited area of the installation for a preliminary evaluation of:

– the influence of aerobic condition on the variation of leachate characteristics;
– the effects of increased moisture content on air migration in the waste body;
– the influence of moisture addition on waste temperature.

Approximately 10 m^3 of leachate extracted from aeration well P8 were injected over a period of one month in monitoring wells M3 and M4, close to P8, at a depth of 7 m from landfill surface.

The uncontrolled biogas emissions through the landfill surface at start and during the excavation were monitored by means of a static flux chamber consisting of a steel cylinder of 50 cm in diameter and 45 cm in height provided with temperature and pressure probes, according to the procedure described in Muntoni and Cossu (1997) and in Pratt et al. (2013). Five measurement campaigns were conducted right before start and during the excavation; the first one with the Airflow plant off, the second one with both air injection and gas extraction active, the following three with gas extraction only. Each measurement campaign lasted one day and involved six placements of the flux chamber on landfill surface.

Table 2
Some relevant data from landfill characterization before the start of the aeration. n.d. = not detectable.

Parameter	Range or average value
Waste hydraulic conductivity	$9 \cdot 10^{-6}$–$5 \cdot 10^{-5}$ m/s
Landfill surface	1.5 ha
Landfill depth	19 m
Leachate head from landfill bottom	4 m
Biogas quality	
CH_4	60%
CO_2	40%
Leachate quality	
pH	7.6
BOD_5	360 mg/L
COD	2810 mg/L
N-NH_4^+	1740 mg/L
N-NO_3^-	n.d.
Cl^-	2920 mg/L
Waste biological stability	
RI_4	1.64 mgO_2/gDM

3. Results and discussion

3.1. Preliminary landfill characterization

In Table 1 the results of the fractional composition analyses of waste samples taken at two different depths in the landfill (4.5–6.0 and 6.0–10.0 from landfill surface) are reported. The first 4 m were not considered as actually consisting of clay cover material only. As expected and typical in landfill of that period, where huge amounts of daily cover materials were used, a significant presence of fines (0–20 mm) was ascertained. The fraction 20–50 mm was not sorted due to difficulties in identifying the nature of different materials.

In Table 2 some relevant data from landfill characterization before the start of the aeration are reported. Due to the nature of the local available material (clay) used as daily cover, low values were expected for waste hydraulic conductivity; indeed, values in the range $9 \cdot 10^{-6}$–$5 \cdot 10^{-5}$ m/s resulted from the pumping tests, higher than those measured in a similar case study (Raga and Cossu, 2014). The average leachate head was at 4 m above the natural clay layer at the bottom of the landfill and the leachate extraction system was continuously operated since the Airflow installation in order to reduce it to the greatest extent possible.

The average value of RI_4 was 1.64 mgO_2/gDM, with peak value of 3.1 mgO_2/gDM, in 30 samples analyzed, collected at different depths and in different points in the landfill during the installation of the Airflow plant. These values are typical of well stabilized waste; however, leachate quality suggests a still high emission potential, with ammonia nitrogen and chloride present in concentrations up to 1.8 and 3.3 g/L respectively. Due to the very good insulation of the deposited waste both at the bottom and at the top and to the lack of leachate drainage and extraction systems, the leachate present was probably mainly produced when the landfill was in operation; the high concentrations of ammonia nitrogen and chloride in such old landfills are typical of a limited liquid to solid ratio.

The biogas composition was typical of landfills in the methane phase, with average values for concentration of CH_4 and CO_2 equal to approximately 60% and 40% respectively.

In situ aeration tests provided an indicative value of 20 m for the wells' radius of influence, defined as the maximum distance where an increase of pressure of at least 1 hPa can be measured with an air injection rate of 50 m^3/h. The maximum distance between wells was then set at 30 m.

3.2. Development and outcomes of the aeration

3.2.1. Effects on the gas phase

At the beginning of operations the air injection and gas extraction rates were automatically adjusted by means of the patented safety features of the Airflow system, in order to avoid the extraction of potentially explosive gas mixtures that can be present in the aerated landfill in the initial phase, when air slowly replaces the biogas present in the landfill body and methane concentrations drop to values in the range 5–15%.

In Fig. 4 the evolution of gas composition in four of the lateral extraction (L_{ex}) wells (P10, P11, P12, P13) is reported. Similarly, Fig. 5 shows the gas composition in the monitoring points M10, M11, M12, M13 (at 7 m depth in the landfill body), which were in place both before and during the excavation. The values reported for CO_2 and CH_4 concentrations at the beginning of the test are lower than the typical values previously mentioned (40%

Table 1
Results of composition analyses of waste samples taken at two different depths (4.5–6.0 m and 6.0–10.0 m from landfill surface).

	Oversieve, sample 4.5–6.0 m							Oversieve, sample 6.0–10.0 m						
Screen (mm)	200	100	75	60	50	Total		200	100	75	60	50	Total	
Unit	kg	kg	kg	kg	kg	kg	%	kg	kg	kg	kg	kg	kg	%
Paper and wood	1.6	1.2	0.9	0.8	0.7	5.2	3.2	0.6	1.4	0.8	0.7	1	4.5	2.7
Plastics and textiles	1.1	1.3	1.3	0.8	0.9	5.4	3.3	7.7	2.8	1.3	1.6	1.1	14.5	8.6
Metals	0	1.6	0.5	0.2	0.1	2.4	1.5	1.8	4.3	0.2	0.6	1	7.9	4.7
Glass and stones	11	17.8	10.4	6	7.4	52.6	31.9	0.0	4.6	3.7	5	5	18.3	10.9
	Fraction 20–50 mm					31.2	18.9		Fraction 20–50 mm				31.8	18.9
	Fines (0–20 mm)					68.2	41.3		Fines (0–20 mm)				91.4	54.3
	Total					165.0	100.0		Total				168.4	100.0

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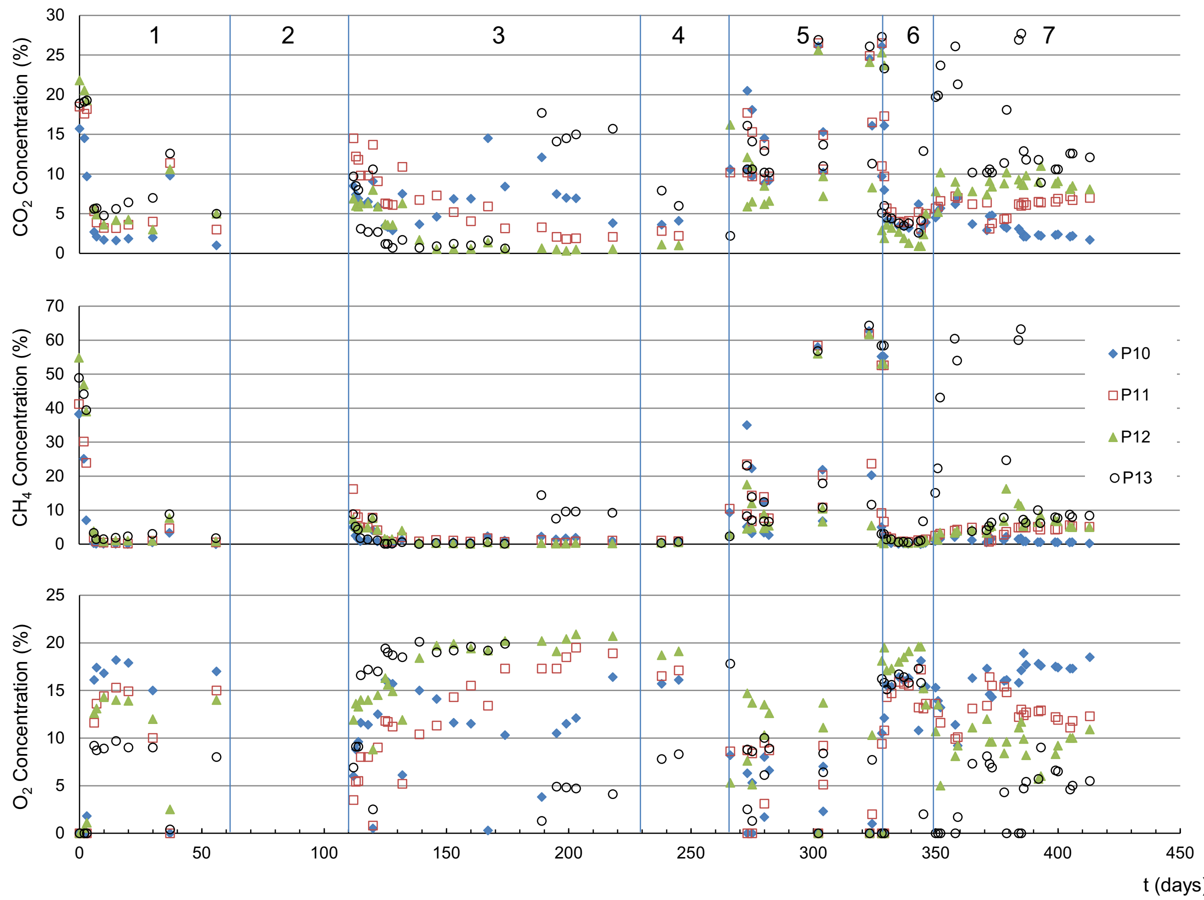

Fig. 4. Evolution of gas composition in extraction wells P10–P13. 1: Aeration, all plant running. 2: Technical stop. 3: Aeration, all plant running. 4: *C* wells shut. 5: Periodic technical stop and subsequent re-start of *L* wells. 6: Excavation start and Aeration (*L* wells on). 7: Excavation and gas extraction only (L_{ex} wells on).

and 60% respectively), as a consequence of previous aeration tests, carried out right before the start of the project and not presented in the paper.

The abovementioned two figures are divided in 7 zones related to different operation phases of the aeration plant. Zone 1 is related to the first two months of steady state aeration; the start-up phase lasted some days, until the methane concentrations in the main gas extraction pipe, where the gas streams from the different extraction wells merge, reached values below 5%. At the same time the oxygen content increased to an average concentration above 10% in the extracted gas. At day 63 an unexpected temperature increase was observed in monitoring well M3; the aeration plant was then switched off and the monitoring of temperature evolution and gas composition was carried on (zone 2 in Fig. 5). As visible in Fig. 6, the temperature continued to increase in the next days, up to 70 °C in the same monitoring point M3. The temperatures in monitoring point M3 were rather high since the beginning, mainly due to the high temperature of air injected into nearby well P8, caused by air compression in the blowers. Temperatures in gas extraction well P12, quite distant from air injection wells maintained slightly above the values recorded before the start of the aeration. In Fig. 7 the gas composition in M3 during the first months of operation is reported. After the temporary stop of the plant on day 63, methane concentration increased, but values lower than the initial ones were measured in many of the monitoring points, even one month after the stop of the aeration. At day 110 the aeration was re-started and steady state conditions were reached after a few days (zone 3 in Figs. 4 and 5).

At day 230 all C wells were permanently shut, in order to put the plant in the situation expected at the beginning of the excavation phase. As visible in zone 4 of Fig. 4, gas composition in L_{ex} wells P10–P13 remained virtually the same as before, with negligible influence of the methane produced in the central part of the landfill.

At day 265 the plant was completely turned off. One week later progressive re-start tests (*L* wells only) were run, in order to assess the performance of the system and to minimize the duration of the start-up phase (zone 5 in Fig. 4). The results obtained proved that after a technical stop, steady state operation conditions with methane concentration lower than 5% in the extracted gas could be reached within 2 h.

At day 330 excavation started in the central part of the landfill. As visible in zone 6 of Figs. 4 and 5, gas composition in the extraction and monitoring wells was as expected, being methane detected in negligible concentrations. Actually, the average O_2 concentrations were higher and CO_2 concentrations were lower than in the previous stages, preliminary to excavation (i.e. zone 3 in Figs. 4 and 5). This was probably due to the removal of the clay cover layer in the first days of the excavation, which might have fostered the flow of atmospheric air through the waste, toward the gas extraction wells.

Results of the monitoring of uncontrolled biogas emissions through the landfill surface at start and during the excavation are reported in Table 3. The peak values for CH_4 and CO_2 emissions through the landfill surface with the Airflow plant completely shut were of 2.57 and 1.57 NL/m^2 h respectively (average values 1.55 and 1.11 NL/m^2 h, respectively). The measurements were repeated with the Airflow plant operating in steady state conditions (L lines on) and, unexpectedly, higher values than those observed without aeration were recorded for CH_4 and CO_2 emissions through the landfill surface (peak values equal

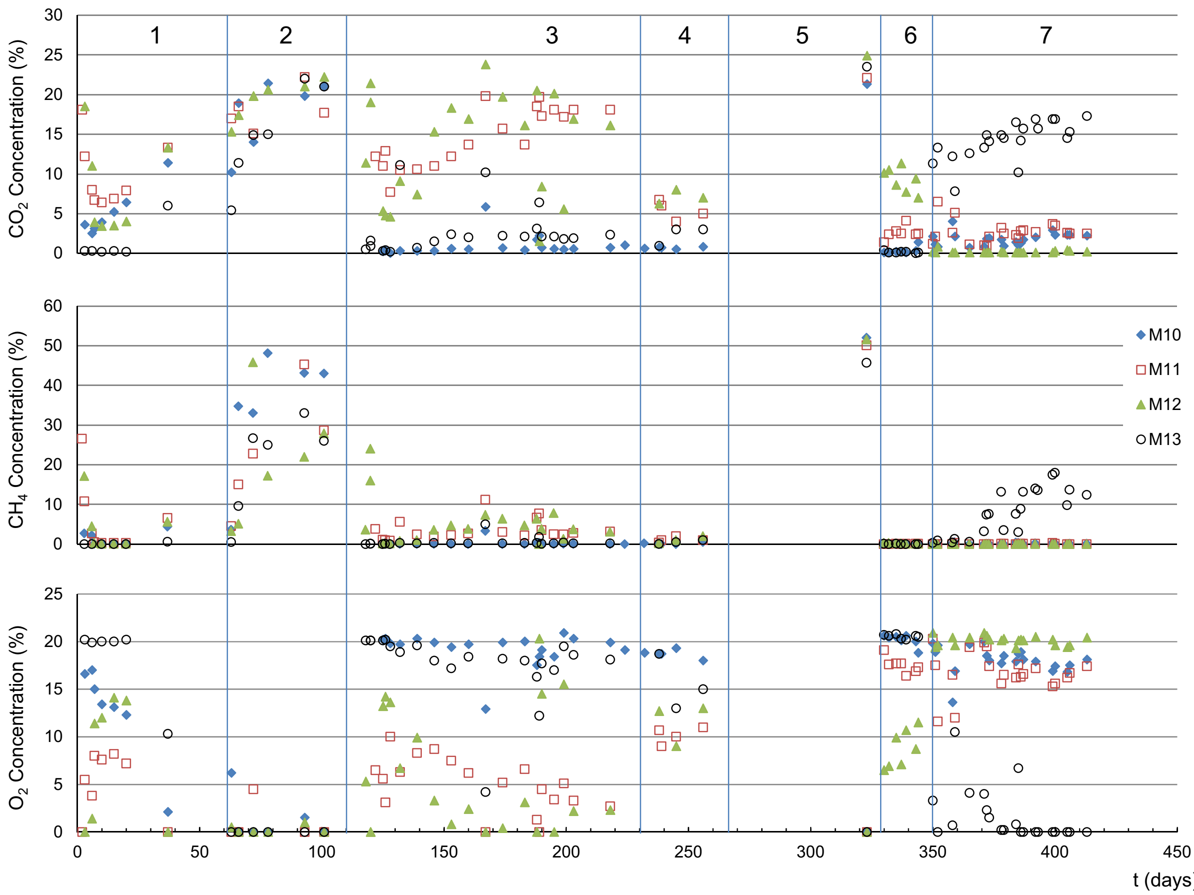

Fig. 5. Evolution of gas composition in monitoring wells M10–M13. 1: Aeration, all plant running. 2: Technical stop. 3: Aeration, all plant running. 4: *C* wells shut. 5: Periodic technical stop and subsequent re-start of *L* wells. 6: Excavation start and Aeration (*L* wells on). 7: Excavation and gas extraction only (L_{ex} wells on).

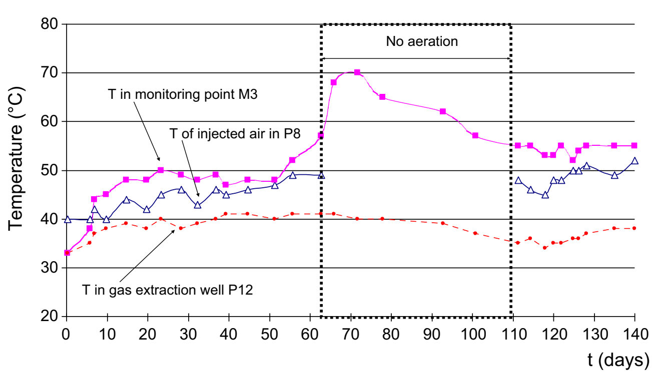

Fig. 6. Temperature *T* measured in air injection well P8, in the monitoring point M3 beside P8 and in the gas extraction well P12 during the first 5 months of operation.

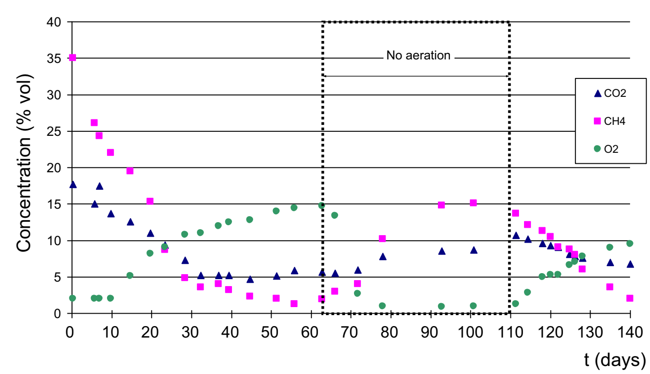

Fig. 7. Gas composition in monitoring point M3 during the first 5 months of operation.

to 3.31 and 2.81 NL/m^2 h, respectively; average values 2.82 and 2.09 NL/m^2 h, respectively). It was then assumed that this effect was caused by the pressure increase induced in the landfill body by the lateral injection wells, which might have fostered the migration of biogas toward the landfill surface, through preferential pathways. For this reason, from day 350 on L_{in} wells were shut and the plant was run with gas extraction (L_{ex}) wells only still active; this choice proved successful as a significant abatement of CH_4 and CO_2 emissions through the landfill surface was observed (Table 3). As expected however, the composition of the gas extracted from the landfill changed, as visible in zone 7 of Figs. 4 and 5: in such situation L_{ex} wells were extracting both the gas from the excavation area and the biogas from the rest of the landfill, not affected by the aeration. Among the gas extraction wells, P13 was affected the most. Eventually, with proper flux adjustment (increase of gas extraction rate from P13 among others), it was possible to control the increase of methane concentration both in the extraction wells and in the pipes toward the blowers and to keep it within the desired values. The gas composition in monitoring well M13, placed between L_{in} and L_{ex} wells (Fig. 2), was permanently affected by the shut of air injection, as visible in Fig. 5.

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Table 3
Peak and average values of biogas emissions through the landfill surface at start and during the excavation (5 campaigns), measured by means of a flux chamber (6 placements in each campaign).

	Peak values		Average values	
	CO_2 (NL/m^2 h)	CH_4 (NL/m^2 h)	CO_2 (NL/m^2 h)	CH_4 (NL/m^2 h)
Airflow plant OFF	1.57	2.57	1.11	1.55
Air injection and gas extraction ON (day 340)	2.81	3.31	2.09	2.82
Only gas extraction ON (day 350)	0.38	0.13	0.22	0.08
Only gas extraction ON (day 360)	0.0	0.0	0.0	0.0
Only gas extraction ON (day 370)	0.71	0.39	0.29	0.15

3.2.2. Effects on waste and leachate

Waste biological stability was already good at the beginning of the project and it was increased by the aeration. The respiration index (RI_4) decreased from 1.64 mgO_2/gDM, measured at the beginning of the operations, to 0.55 mgO_2/gDM (33% of the initial value) after six months of operation of the aeration plant. This result was considered satisfactory in terms of abatement of residual biodegradability of the waste, in view of the excavation and of the further management of the excavated waste. Very similar initial conditions were reported for an Austrian case study where a median value of 1.7 mgO_2/gDM was calculated for the RI_4 (Hrad et al., 2013); however, no evidence of reduction was observed during the aeration project. Conversely, a higher reactivity for the deposited waste was reported for the Kuhstedt landfill case study, where the (average) initial RI_4 value of 6.2 mgO_2/gDM dropped to 2.2 mgO_2/gDM after 22 months of aeration (Ritzkowski et al., 2006).

The range of variability and average values of the RI_4 for waste sampled at different depths in the landfill before the beginning of in situ aeration and after 2, 4 and 6 months of operation are shown in Table 4. Contrary to what observed by Raga and Cossu (2014), no correlation between initial waste biological stability and landfill depth was ascertained; moreover, the effects of the aeration were clear at all depths. This latter result is probably due to the very effective leachate extraction carried out during the aeration, which enabled the significant decrease of the leachate table and the subsequent good air migration through the lower waste layers also. Actually, the average leachate head from landfill bottom dropped from 4 to 1.5 m during the six-month landfill conditioning prior to the beginning of the excavation.

As already stated in a similar case of a landfill only partially aerated (Raga and Cossu, 2014) proper assessment of the effects of the aeration on leachate quality was not possible due to the migration into the aerated landfill of leachate from the contiguous sectors where a higher leachate head was present, as aeration (with leachate extraction) was not taking place.

The evolution of leachate quality during the aeration is visible in Table 5, where the range of variability and the average values of the relevant parameters measured every two months in the leachate samples from the monitoring wells are reported. As already observed by other authors (Öncü et al., 2012; Raga and Cossu, 2014; Ritzkowski, 2011) an increase of the average concentration values of relevant parameters was recorded after the first months of aeration, probably due to the mobilization into the leachate phase of porous water (Ritzkowski and Stegmann, 2005) and to the enhanced waste degradation fostered by aerobic conditions. A slight decrease of BOD_5, COD and ammonia nitrogen concentrations together with the increase of concentration of oxidation products (i.e. nitrate, sulfate) was observed after 6 months of aeration; however, due to the limited efficiency of diffusion processes of the injected air into leachate saturated layers in the lower part of the landfill, beneficial effects of aeration on leachate quality were not expected in such a short time.

The leachate recirculation test showed that the periodic moisture addition through leachate injection into M3 and M4 did not

Table 4
Range of variability and average values of respiration index (RI_4, mgO_2/gDM) measured at different depths before the beginning of in situ aeration and after 2, 4 and 6 months of operation.

Month	Depth						
	5 m (10 samples)		10 m (10 samples)		15 m (10 samples)		
	RI_4 (range)	RI_4 (average)	RI_4 (range)	RI_4 (average)	RI_4 (range)	RI_4 (average)	Average (30 samples)
0	0.52–1.83	1.22	1.41–3.06	2.10	1.20–1.81	1.61	1.64
2	0.63–2.47	1.35	1.45–2.51	1.81	0.99–2.78	1.69	1.62
4	0.64–1.31	0.91	0.19–1.46	0.76	0.64–1.75	1.20	0.95
6	0.16–0.60	0.42	0.28–1.37	0.67	0.35–0.76	0.55	0.55

Table 5
Range of variability and average values of BOD_5, N-NH_4^+, N-NO_3^-, Cl^- and SO_4^{2-}, measured in samples of landfill leachate collected in 5 monitoring wells at the beginning of in situ aeration and after 2, 4 and 6 months of operation. n.d. = not detectable.

Month	pH	BOD_5 (range) gO_2/L	BOD_5 (average) gO_2/L	COD (range) gO_2/L	COD (average) gO_2/L	N-NH_4^+ (range) gN/L	N-NH_4^+ (average) gN/L	N-NO_3^- (range) mgN/L	N-NO_3^- (average) mgN/L	Cl^- (range) g/L	Cl^- (average) g/L	SO_4^{2-} (range) mg/L	SO_4^{2-} (average) mg/L
0	7.6	0.3–0.4	0.36	2.6–3.1	2.8	1.5–1.8	1.7	n.d.	n.d	2.5–3.3	2.9	n.d.	n.d
2	7.7	0.3–0.6	0.45	2.7–4.1	3.4	1.4–2.5	1.8	0.9–5.4	2.7	2.7–3.7	3.2	20–190	82
4	7.7	0.5–0.7	0.59	2.9–4.8	3.8	1.6–2.9	2.3	2.2–7.2	5.1	3.8–4.6	4.2	37–91	71
6	7.7	0.2–0.3	0.28	3.1–3.7	3.1	1.4–1.8	1.5	2.6–7.0	4.8	2.9–3.4	3.2	120–380	250

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affect air migration in the waste mass; gas composition remained unaltered in the same monitoring wells. As expected, clear temperature reduction was observed in the waste during moisture addition. However, the test was carried out in a small part of the aerated landfill and for a limited amount of time, therefore no quantitative assessment can be made.

The percolation through aerated waste layers enabled a faster development of leachate oxidation processes; as an example, nitrate and sulfate concentrations reached values much higher than before recirculation, up to approximately 200 and 450 mg/L respectively, in the leachate samples extracted from aeration well P8. However, the leachate extracted form P8 was actually a mixture of the leachate percolating through the aerated layers with the legacy leachate still present in the bottom part of the landfill, therefore a quantitative assessment of the impact of leachate recirculation on leachate quality was not possible.

4. Conclusions

The Airflow technology was applied to the old landfill of Modena, in the framework of a project involving the excavation of a 19 m deep trench through the landfill, for the construction of the high velocity railway line connecting Milan to Bologna. Prior to the LFM the Airflow plant was run for 6 months, enabling the enhancement of waste biological stability and the abatement of the leachate table in the excavation area.

Gas quality in monitoring wells remained unaltered during leachate recirculation tests, proving that moisture addition can be used without affecting landfill aerobization.

Undesired temperature increase in the landfill body (as well as waste dehydration) during the aeration might be controlled by means of moisture addition through leachate recirculation. Although a beneficial effect has been observed, due to technical constraints and plant limitations it is not possible to make a quantitative assessment and a proper evaluation of this issue based on the results of this project.

During LFM, with proper adjustments of flow rates and plant set-up, biogas emissions into the excavation area from the side slopes and the adjacent non-aerated landfill sectors were minimized.

The improved waste quality resulted in negligible odor emissions during the excavation and management before the eventual disposal. Actually, despite the presence of a waste thermal treatment plant in town, due to the limited amount of combustibles and the significant presence of soil-like materials, the decision was made to deposit the excavated waste in a new landfill sector, built on top of the southern part of RSU3 landfill.

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