

Effect of Aeration on Fresh and Aged Municipal Solid Waste in a Simulated Landfill Bioreactor

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Municipal solid waste (MSW) is slow to stabilize under conventional anaerobic landfill conditions, demanding long-term monitoring and pollution control. Provision of aerobic conditions offers several advantages including accelerated leachate stabilization, increased landfill airspace recovery and a reduction in greenhouse gas emissions.

Air injection was applied over 130 days to bench-scale bioreactors containing fresh and aged MSW representative of newly constructed and pre-existing landfill conditions. In the fresh MSW simulation bioreactors, aeration reduced the average time to stabilization of leachate pH by 46 days, TSS by 42 days, TDS by 84 days, BOD₅ by 46 days and COD by 32 days. In addition, final leachate concentrations were consistently lower in aerated test cells. There was no indication of a gradual decrease in the concentration of ammonia, and it is likely this high ammonia concentration would continue to be problematic in bioreactor landfill applications.

This study focussed only on biodegradability of organics in the solid waste. The concentrations of the nonreactive or conservative substances such as chloride and/or heavy metals remain in the bioreactor landfills due to the continuous recirculation of leachate.

The results of this study demonstrate the potential for air injection to accelerate stabilization of municipal solid waste, with greatest influence on fresh waste with a high biodegradable organic fraction.

Key words: aerobic bioreactor, landfill simulation, municipal solid waste, waste age, leachate, stabilization

Introduction

Increased public opposition to landfill siting has frequently impeded the construction of new waste disposal facilities, requiring existing landfills to surpass their intended operating lifetimes (Stessel and Murphy 1992). As such, meeting the disposal requirements for the 23,100,000 metric tonnes of solid waste generated annually in Canada (Statistics Canada 2002) has become increasingly problematic. Furthermore, the potential for landfill leachate to impact groundwater endures long after closure when costs associated with monitoring and maintenance are no longer offset by revenue generated from the acceptance of waste.

As a result of these concerns, considerable interest has been generated in the potential for aerobic bioreactor technology to prolong a landfill's usable lifetime and reduce the duration of post-closure liability.

A bioreactor landfill is an engineered landfill in which the bioconversion of solid waste is enhanced by promoting conditions suitable to biological processes, typically through moisture addition and recirculation combined with other enhancements. Implementation of leachate recirculation has been shown to reduce the strength of landfill leachate (Warith et al. 2001; Chugh et al. 1998; Townsend et al. 1996), increase the capacity

of a landfill (Wall and Zeiss 1995; Warith et al. 2001), decrease the time to landfill stabilization (Pacey et al. 1999) and allow for more rapid reclamation of the site (Pacey 2001). MSW shredding has also been shown to enhance the rate of degradation (Komilis et al. 1999). The addition of buffer solutions and sludge enhanced MSW biodegradation in a study by Warith et al. (1999). Reduced compaction densities, modified lift designs and temperature controls can also promote biodegradation.

Aerobic biodegradation occurs at a much faster rate and to a greater extent than anaerobic conditions in a given time period (Murphy et al. 1995). However, little research has been performed on in situ aeration of landfilled municipal solid waste. Instead, studies involving aeration have typically been associated with composting or aerated static piles and not in situ landfill conditions (Murphy et al. 1995).

Stessel and Murphy (1992) found that an air delivery rate of 0.0104 m³/s or greater was sufficient to provide the air requirements for 140 kg of MSW, using leachate pH as an indicator of aerobic conditions. In a study by Leikam et al. (1999), BOD₅, COD and ammonia concentrations were reduced considerably. Leikam et al. (1999) showed degradation of organic substances approximately five times higher than under anaerobic conditions. After 50 days of aeration, the leachate nitrogen concentration was also reduced to regulatory levels. Comparatively, 400 to 500 days longer was required in

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the anaerobic bioreactors to reach similar levels. Generation of methane and the associated odour and hazards are minimal when aerobic conditions are provided (Stegmann and Splendin 1989).

Materials and Methods

Study Design

An experiment was conducted in order to examine the potential for aeration to accelerate MSW stabilization, and to determine if comparable benefits could be expected when air injection was applied to fresh and aged wastes representative of newly constructed and landfill closure conditions. Eight bioreactors were constructed with closed-loop leachate recycle systems, containing fresh or aged solid waste and subject to aerobic or anaerobic conditions. The bioreactor cells were assigned the designations AF1, AF2, AO1, AO2, NF1, NF2, NO1 and NO2 based on their respective treatment, matrix and replicate number (Table 1).

Each bioreactor contained approximately 50 L of municipal solid waste with soil cover compacted to typical landfill densities of 530 to 590 kg/m³ (wet mass). This waste density is typical of waste density placed in landfills across North America. Fresh waste samples were collected in residential Toronto and were representative of MSW as discarded. Aged waste samples were obtained from the Brock West Landfill, Ontario, Canada, and were approximately 20 years old upon collection. Cover material was irrevocably intermingled with the aged samples necessitating proportionate treatment to the fresh samples. Sorting based on percent composition (ASTM D5231-92, ASTM 2001) and shredding of the solid waste samples (7.5 cm) was required in order to minimize differences between these replicates, prevent clogging and promote leachate circulation (Warith et al. 1999). The percent composition of the fresh and aged waste including the soil cover appears in Table 2.

Four bioreactors maintained anaerobic conditions and four incorporated the air injection system presented in Fig. 1. Vertical air injection pipes were constructed

TABLE 2. Percent composition of fresh and aged MSW

Composition	Fresh MSW (%)	Aged MSW (%)
Paper	18.4	22.2
Plastic	8.5	12.6
Yard waste	0.9	2.0
Food waste	17.6	5.1
Wood	0.0	1.9
Other organics including textiles	6.3	8.0
Ferrous metals	4.1	5.1
Aluminum	2.2	2.2
Glass	3.9	1.9
Other inorganics ^a	38.0	39.0
Total (%)	100.0	100.0
Biodegradable organic fraction ^b	43.2	37.3

^aIncludes soil cover.

^bBiodegradable organic fraction = paper, yard, food and other organics assuming 100% biodegradability.

from a 39-mm (1½") diameter ABS pipe with air vents radiating out horizontally into the MSW. Each of the four aerated bioreactors received air at a rate of 0.63 L/s for 30 min at 12-h intervals (80 m³/Mg of waste/day or 45 m³/m³ of waste). This rate and duration of airflow assured a complete exchange of the air within the cell. Constant aeration was not required since the remaining headspace within each bioreactor contained excess oxygen relative to the 96-h peak microbial respiration activity (80 mg O₂/g dry matter) for fresh MSW (Leikam et al. 1999). The cell headspace and gravel layers bordering the MSW in Fig. 1 were necessary to facilitate the recirculation of leachate and encourage its even distribution throughout the bioreactor.

The bioreactors were packed and sealed on day 1 of the study. Anaerobic conditions were established and samples were brought to field capacity by day 7, when sampling was initiated. Aeration began on day 18.

Leachate was sampled (250 mL) weekly over 130 days. Design constraints made gas analysis infeasible. Moisture content was maintained at field capacity (ASTM D2216-98, ASTM 2001) through daily additions of water to maintain a constant leachate recirculation volume of 2 L/day, comparable to other leachate recirculation studies (Stessel and Murphy 1992; Chugh et al. 1998; Warith et al. 1999). The average amount of water added to the cells above replacement of the sample volume is shown in Table 3. Temperature with the test bioreactors remained within 3°C of ambient conditions. The degree of stabilization of the fresh and aged waste was determined through chemical analysis of the leachate pH, TSS, TDS, COD, BOD₅ and ammonia concentrations. The degree of stabilization of each analytical parameter was assessed individually using established guidelines where available. Pacey et al. (1999) suggests that the BOD should be less than 100 mg/L and COD less

TABLE 1. Bioreactor designation, treatment condition and matrix

Bioreactor designation	Treatment condition	Bioreactor matrix
AF1	Aerated	Fresh MSW
AF2	Aerated	Fresh MSW
AO1	Aerated	Aged MSW
AO2	Aerated	Aged MSW
NF1	Anaerobic	Fresh MSW
NF2	Anaerobic	Fresh MSW
NO1	Anaerobic	Aged MSW
NO2	Anaerobic	Aged MSW

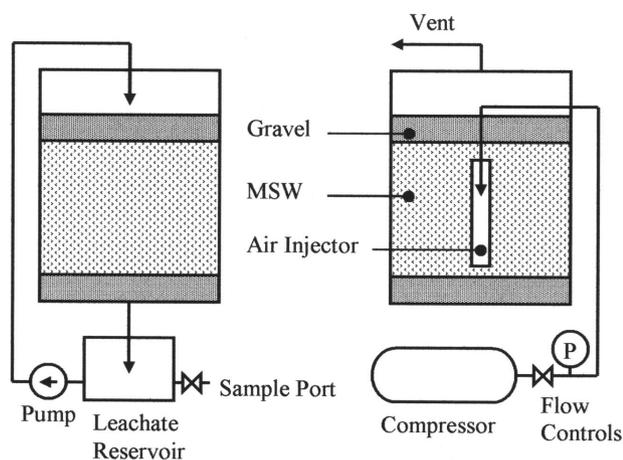


Fig. 1. Simulated bioreactor test cell leachate recycle and air injection schematic.

than 1000 mg/L when the leachate is stabilized. Similarly, the BOD/COD ratio of 0.1 or below indicates stable leachate, while values over 0.4 are readily degradable (Ehrig and Kruepeltbech 1989). No similar guideline exists for TSS, TDS and ammonia concentration. For TSS and TDS, the average concentration determined for bioreactor cells NO1 and NO2 was used as the benchmark concentration under which stability was assumed. NO1 and NO2 were selected based on their low potential for biodegradation due to waste age and lack of aeration.

A 90% reduction in leachate strength from the peak value was used to indicate stability with respect to ammonia.

Analytical methods are summarized in Table 4.

Results

pH

Throughout the study period, leachate pH in all bioreactors moved towards neutralization. Prior to aeration, a rapid drop in leachate pH was observed in the fresh MSW bioreactors, suggesting a large potential for acidification.

Aeration promoted a strong neutralizing effect in the AF1 and AF2 bioreactors. Prior to aeration, the pH of AF1 and AF2 were 5.24 and 6.05, respectively. By day 52, both AF1 and AF2 had leachate pH greater than pH 7.0. Comparatively, leachate pH did not exceed 7.0 in the unaerated bioreactors NF1 and NF2 until day 115 and day 80, respectively (Fig. 2).

Comparison of the time to stabilization between the aged waste samples suggests the aged waste was near stabilization at the study inception. Initial pH of AO1, AO2, NO1 and NO2 were 6.67, 6.55, 6.38 and 6.50, respectively. While leachate pH in the aerated bioreactors AO1 and AO2 stabilized on day 52 reporting pH above 7.0, the unaerated aged bioreactors NO1 and NO2 showed little variation in pH, and concluded the study with pH of 6.84 and 6.69, respectively.

Total Suspended Solids (TSS)

During the period prior to aeration fresh-MSW bioreactors yielded greater TSS concentrations than the aged-MSW bioreactors prior to aeration and were highly erratic (Fig. 3).

The average time required for stabilization to occur was shorter in bioreactors implementing air injection. Stabilization of leachate TSS was considered to have occurred when leachate TSS remained below the average concentration of NO1 and NO2 (50 mg/L). Applying this criterion, stabilization occurred on day 73 and day 66 in the fresh-MSW aerated bioreactors AF1 and AF2, respectively. Comparatively, NF1 required 94 days to reach a comparable TSS concentration, and NF2 remained above 100 mg/L on day 129 reporting a final concentration of 133 mg/L.

In the aged-waste bioreactors, aerated cells AO1 and AO2 stabilized (<50 mg/L) on day 45 compared to day 80 and day 66 from NO1 and NO2, respectively.

Total Dissolved Solids (TDS)

The total dissolved solids of the aged-MSW bioreactor leachate ranged from 3000 to 4450 mg/L on day 17, prior to aeration (day 18). Comparatively, the leachate samples from fresh MSW bioreactors ranged from 6750 to 11,400 mg/L (Fig. 4).

In the fresh-waste bioreactors, aeration prompted a rapid decline in TDS. AF1 TDS declined from 11,400 to 2800 mg/L after only 21 days of aeration for bioreactor cell AF1. Similarly, AF2 declined from 6750 to 3300 in the same time period.

TDS was considered stabilized when the concentration was below the average concentration of NO1 and NO2 during the study period (2800 mg/L). AF1 stabilized on day 52 and AF2 stabilized on day 45 according to this criterion. However, AF1 TDS exceeded the benchmark concentration of 2800 mg/L on day 108, and

TABLE 3. Average water usage for bioreactor cells

	AF1	AF2	NF1	NF2	AO1	AO2	NO1	NO2
Usage (L/week)	0.080	0.062	0.017	0.008	0.057	0.063	0.014	0.009

TABLE 4. Methods used for sample analysis and stabilization criteria

Parameter	Method	Reference	Stability benchmark
% Composition	ASTM D5231-92	ASTM (2001)	—
% Moisture	ASTM D2216-98	ASTM (2001)	—
pH	Accumet BASIC method	Fisher Scientific Ltd.	pH 7
TSS	SM 2540D	APHA (1989)	>50 mg/L ^a
TDS	SM 2540C	APHA (1989)	>2800 mg/L ^a
Ammonia	Indophenol method	Fisher Scientific Ltd.	90% reduction ^b
BOD ₅	ASTM 5210B	APHA (1989)	>100 mg/L ^c
COD	Accu-TEST method	Bioscience Inc. U.S.A.	>1000 mg/L ^c

^aDetermined from the average concentration reported for NO1 and NO2 between day 1 and day 130.

^bFrom peak concentration.

^cPacey et al. (1999).

remained above the criteria for the remaining study duration. In the unaerated fresh-waste bioreactors NF1 and NF2, the TDS continued to increase after day 17, with peak TDS concentrations of 7950 and 9250 mg/L, respectively, on day 31. A gradual decline in TDS followed day 31, and approached stabilization with final concentrations of 3050 and 4000 mg/L.

No appreciable difference was observed in the aged-waste bioreactors, likely due to the initial high degree of leachate stabilization.

Ammonia-Nitrogen (NH₃)

The aerated bioreactors AF1 and AF2 both experienced a lag phase before expressing a period of ammonia accumulation, retention, and finally a period of ammonia reduction (Fig. 5). The time between the initial generation of ammonia and the beginning of its removal, though, was not expected, since aerobic bacteria can readily utilize ammonia as a substrate for nitrification (Burton and Watson-Craik 1998).

AF2 performed similarly to AF1, expressing a comparable final ammonia concentration. However, NF2 and AF1 reached values an order of magnitude higher than NF1 and AF2. This large variation is likely due to

differences in MSW homogeneity, despite compositional sorting (ASTM D5231-92, ASTM 2001) to reduce heterogeneity. The final ammonia concentrations on day 129 for AF1 and AF2 were 7.93 and 6.96 mg/L, respectively. Extending the study duration would have likely resulted in a further reduction in leachate ammonia concentrations.

Under anaerobic conditions, the ammonia concentration in the bioreactors was expected to rise somewhat logarithmically, with a large initial increase in ammonia concentration subsequently reaching a more constant ammonia concentration. This behaviour was noted in bioreactor NF2. Ammonia concentrations remained elevated after day 31, such that at the end of the study the ammonia concentration was reported to be 576 mg/L. There was no indication of a gradual decrease in the concentration of ammonia, and it is likely this high ammonia concentration would continue to be problematic in a landfill application. Similar observation of slow ammonia concentration decrease with time was also noted by Krueplbeck and Ehrig (1999) and by Ehrig and Krueplbeck (2001) during their study of 50 old landfills in Germany. The parameter NH₄-N showed its highest leachate concentrations during the time period

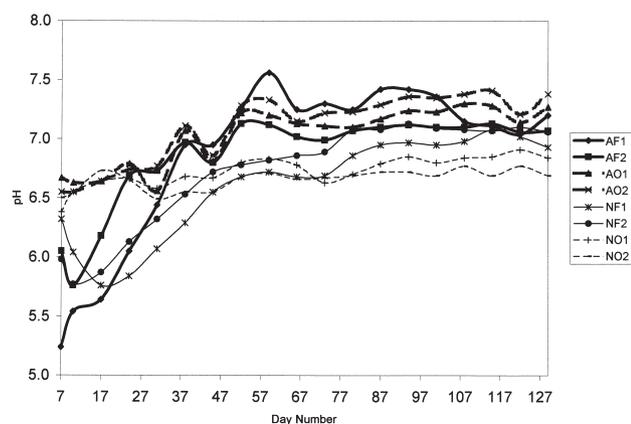


Fig. 2. Change in pH for bioreactor replicates.

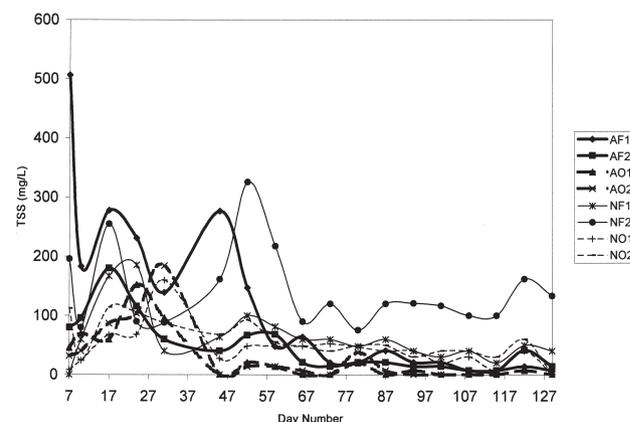


Fig. 3. Change in total suspended solids (TSS) for bioreactor replicates.

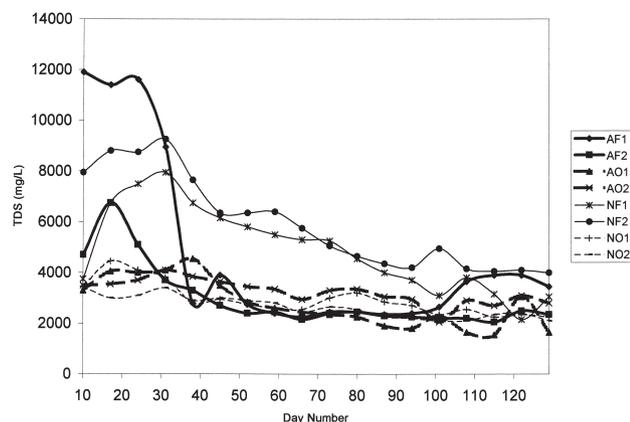


Fig. 4. Change in total dissolved solids (TDS) for bioreactor replicates.

from 11 to 20 years of the landfill operation (Ehrig and Krueplbeck 2001). Marttinen et al. (2002) reported that the landfill leachate treatment is normally focussed on the removal of organic nitrogen and ammonia nitrogen levels since both parameters are quite important for possible inhibition of methane production under anaerobic bioreactor landfill conditions. It is imperative to note that most of the nitrogen in municipal solid waste is in the ammonia forms following the degradation of proteins and amino acids (Inanc et al. 2000).

The performance of NF1 showed a somewhat erratic ammonia concentration over time. Since NF2 did not indicate a trend for future ammonia reduction, a comparison between aerobic and anaerobic degradation rates cannot be made; it can only be surmised that aeration allowed for the detoxification of the landfill leachate with respect to ammonia while the unaerated bioreactor NF2 did not.

The ammonia concentrations in the aged-waste bioreactors remained very low throughout the study, providing little information.

Biological Oxygen Demand (BOD₅)

Leachate BOD₅ initially increased continuously in the fresh-waste bioreactors (Fig. 6). The aged solid-waste bioreactors contained a smaller organic fraction than their fresh waste counterparts, and were likely comprised of more recalcitrant organics, such that the leachate BOD₅ concentration in aged waste samples was lower than BOD₅ concentrations in the fresh waste samples.

Aeration initiated a steep decline in the leachate BOD₅ for the fresh-waste samples. Stabilization in the aerated bioreactors occurred on day 59 for AF1 and on day 52 for AF2, reporting leachate BOD₅ less than 100 mg/L as similarly reported by Pacey et al. (1999), and with little fluctuation in BOD₅ concentration.

The BOD₅ concentrations in the unaerated bioreactors declined at a slower rate, and did not drop below

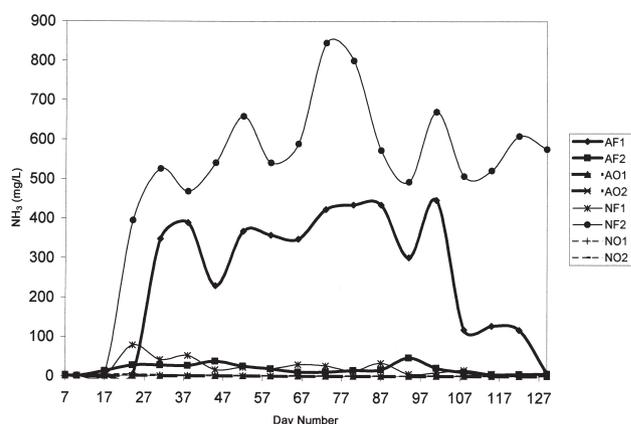


Fig. 5. Change in ammonia concentration for bioreactor replicates.

the stabilization criteria of 100 mg/L as suggested by Pacey et al. (1999). However, little fluctuation in the leachate BOD₅ occurred after day 94 for NF1, at which point the BOD₅ was 137 mg/L. The final BOD₅ for NF1 on day 129 was 127 mg/L. NF2 showed little fluctuation after day 80, with a BOD₅ of 308 mg/L. The final BOD₅ for NF2 was 303 mg/L.

These results indicate that there is a strong potential for air injection to rapidly reduce the carbon content and oxygen demand in landfill leachate. Additionally, the results suggest that MSW samples in the aged bioreactors were predominantly stable or already close to stabilization at the beginning of the study.

Chemical Oxygen Demand (COD)

In both the aged- and fresh-waste bioreactors, aeration rapidly reduced the chemical oxygen demand after a rapid increase was noted over the prior anaerobic phase.

The COD in the aerated fresh-waste bioreactors was reduced to less than 10% of the peak concentration on day 59 and day 31 for AF1 and AF2, respectively, which

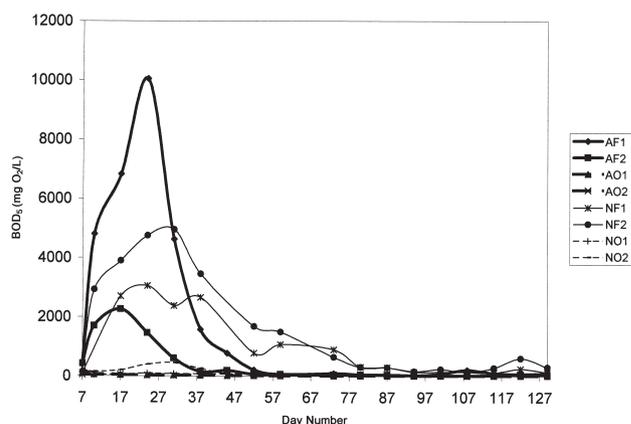


Fig. 6. Change in biological oxygen demand (BOD₅) for bioreactor replicates.

corresponds to a benchmark criteria (<1000 mg/L) suggested by Pacey et al. (1999). Anaerobic bioreactors NF1 and NF2 reached the same benchmark on day 94 and 80, respectively. Final leachate COD values in the aerated bioreactors were also lower than the anaerobic bioreactors as depicted in Fig. 7. The final COD ranged from 131 to 196 mg/L in the four aerated bioreactors, while a range of 26 to 720 mg/L was measured for the anaerobic conditions. These results indicate that aeration accelerated the COD reduction rate in both fresh and aged-waste bioreactors, and also reduced the final COD concentrations.

The aged MSW had a significantly lower potential for COD generation than the fresh-waste bioreactors. However, the leachate from the four aged-waste bioreactors all reached COD levels above 1000 mg/L prior to aeration. AO1 and AO2 stabilized on day 24 and 45, respectively, with COD values of 351 and 307 mg/L. The final COD values for these bioreactors were 131 and 164 mg/L, respectively. The unaerated bioreactors stabilized later than the aerated bioreactors, on day 24 for NO1 and day 73 for NO2. The stabilized concentrations in these bioreactors were 262 and 450 mg/L for NO1 and NO2, respectively.

Discussion

Overall, the influence of aeration had very promising effects on stabilization of leachate from fresh MSW. Prior to aeration, leachate BOD₅ and COD concentrations increased dramatically in the fresh-waste bioreactors. An immediate reversal of this trend occurred once aeration began.

In the fresh-waste bioreactors, aeration accelerated the stabilization of leachate pH, BOD₅ and COD by an average of 46, 46 and 32 days, respectively, in comparison to the anaerobic bioreactor cells. Final leachate concentrations of BOD₅ and COD were consistently lower. In addition, neutralization of leachate pH reduces the potential for accumulation of soluble pollutants such as heavy

metals in the leachate. Leachate pH was neutralized more rapidly under aeration. Thus aeration prevents the system from reaching pH extremes. Heavy metals and/or conservative contaminants tend to be stored and adsorbed to other parts of solid waste fractions in the landfilled waste (Kruemplbeck and Ehrig 1999) due to the closed loop system and leachate recirculation employed in bioreactor landfills. The accumulation of heavy metals may have a negative effect on the microbial biodegradation of the organic waste in bioreactor landfills.

Final TSS and TDS concentrations were lower in the fresh waste results, where the averaged results of the replicates suggest stabilization occurred on day 47 for TSS and day 49 for TDS. Comparatively, in the anaerobic fresh-waste cells, only NF1 met the stabilization criteria for TSS.

At the conclusion of the study, the ammonia concentration in the anaerobic fresh-waste bioreactor NF2 was 576 mg/L and showed no signs of further attenuation. The ammonia concentration in aerated cells gradually declined.

All aged-waste bioreactors had initial BOD₅/COD ratios below 0.1, which is considered to be stable as noted by Pacey et al. (1999). Other parameters support this conclusion. Because the aged waste was near stabilization at the beginning of the study, the overall potential to demonstrate accelerated waste stabilization through air injection was diminished.

The fresh MSW samples displayed a BOD₅/COD ratio near 0.6, suggesting a much larger biodegradable organic fraction. As fresh waste can expect to have BOD₅/COD ratios near 0.9 (Ehrig 1989), the fresh MSW leachate may not have reached its full concentration prior to sampling and analysis.

Conclusions

Aeration rapidly reduced the pollution potential of both leachate produced from aged and fresh waste samples. Greater benefits were realized in the fresh-waste bioreactors. The aged waste was already significantly stabilized at the commencement of the study, such that the benefits provided through aeration were limited due to the low concentration of the readily biodegradable organic fraction of the aged wastes.

Aeration accelerated the neutralization of the leachate pH and decreased both the time to leachate stabilization and final stabilized leachate concentrations for all analytical parameters. Ammonia detoxification was the limiting factor for overall stabilization. While ammonia accumulation in fresh-waste bioreactor cells was not anticipated (as the study proceeded) biotransformation of the ammonia led to its eventual removal from the aerobic systems.

Based on the results of this study, further investigation of the potential for aerobic bioreactor technology to rapidly stabilize municipal solid waste should be conducted at the pilot scale. The benefits of accelerated sta-

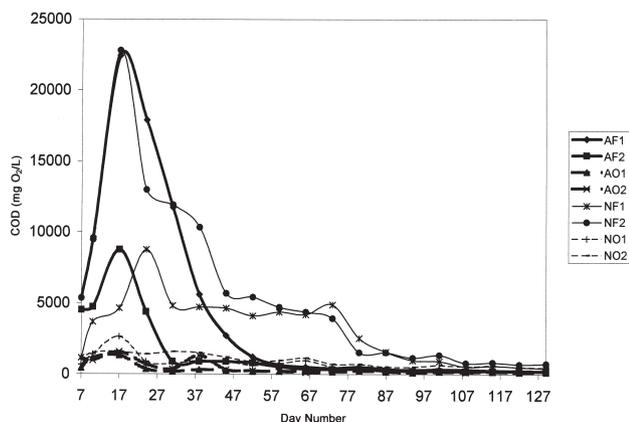


Fig. 7. Change in chemical oxygen demand (COD) for bioreactor replicates.

bilization, reduced leachate strength and improved settlement in the aged-waste bioreactors were not substantial enough to suggest aeration for landfills of this age. However, aeration of MSW of an intermediate age may still prove beneficial, such that further study is recommended with MSW samples representing various stages of waste stabilization.

Research in this area could lead to the determination of the maximum waste age at which the relative benefits of aeration are significant enough to recommend aeration for implementation.

Simulated waste samples are recommended to assure sample homogeneity. Additionally, cost benefit analysis of aeration versus long-term monitoring of landfills until they reach stabilization could shed light on the usefulness of waste aeration applications.

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