DEGRADATION OF MUNICIPAL SOLID WASTE UNDER AEROBIC CONDITIONS

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ABSTRACT: The biodegradation of municipal solid waste (MSW) was investigated in simulated bioreactor landfills under aerobic conditions. The bioreactors were operated to determine the quantity of moisture and sludge that would optimize waste degradation. The leachate generated was recycled over 47 weeks, and leachate samples were collected on a weekly basis and analyzed for pH and organic concentration measured in terms of BOD and COD. Leachate recirculation and sludge addition at the rate of 855 and 85 mL/kg of waste/d in the aerobic bioreactors proved to be sufficient to enhance the MSW degradation within 27 weeks where COD concentration was about 1000 mg/L. This rate was the highest among the bioreactors. Reduction of leachate recirculation and sludge addition to 285 and 28 mL/kg of waste/d increased the stabilization period up to 45 weeks. These results revealed that the more moisture and sludge addition the more of rate biodegradation of MSW can be enhanced. Fitted empirical models indicated that COD concentration in the leachate was affected by leachate recirculation and sludge addition. However, the effect of leachate recirculation was much stronger than sludge addition.

RESUME: La dégradation biologique des déchets solides municipaux a été étudiée en simulation dans des bioréacteur en conditions aérobiques. Les bioréacteurs ont été utilisé pour determiner le taux d'humidité et de boue qui optimiserait la degradation des déchets. Le lixiviat produit a été recycle pendant 47 semaines. On a pris des échantillons de lixiviat chaque semaine et on a fait les analyses de pH et de matières organiques mesurées en terme de DBO et DCO. La recirculation de lixiviat et l'ajout de boue à un taux variant entre 855 et 85 mL/Kg de déchets/jour dans les bioréacteurs aérobiques s'avère être suffisante pour accroître la dégradation des déchets solides en moins de 27 semaines et la concentration de DCO a été d'environ 1000mg/L. Ce taux a été le plus élevé obtenu parmi tous les bioréacteurs. La réduction de la recirculation de lixiviat et l'ajout de boue à 285 et 28 mL/Kg de déchets solides/jour a fait passer la période de stabilisation de 27 à 45 semaines. Ces résultats révèlent que plus on ajoute de lixiviat et de boue, plus le taux de dégradation biologique de déchets solides peut être accéléré. Le modèle empirique qui ressort de cette expérimantation indique que la concentration de DCO dans le lixiviat a été influencée par la recirculation de ce lixiviat et l'ajout de boue. Toutefois, l'impact de la recirculation de lixiviat a été beaucoup plus fort que celui de l'ajout de boue.

1.0 INTRODUCTION

Several factors influence biodegradation of municipal solid waste (MSW). These factors can be manipulated to enhance biodegradation in a landfill environment. These manipulation techniques include moisture content management, the use of buffers, nutrient addition, reduction of waste particle size, and sludge addition. Moisture content can be most practically controlled through leachate recirculation, which is the most common enhancement mechanism used in the field. Numerous studies have been conducted to investigate the effects of leachate recirculation on biological waste stabilization, leachate quality, gas production, waste settlement, and other factors (Warith *et al*., 1999; Warith *et al*. 1998, Bae *et al*, 1998; Reinhart and Al-Yousfi, 1996; Townsend *et al.,* 1995; Pohland and Al-Yousfi, 1994). The general conclusion of all these studies was that waste stabilization could be achieved by leachate recirculation. In most cases, leachate recirculation is practiced as a novel approach to managing leachate without regard to optimize the use of landfill as a bioreactor.

The aerobic degradation of MSW is mostly covered in the composting literature but not in aerobic landfill. The addition of water and sewage sludge is also commonly used in the composting system as amendments agents. However, the addition of water does not through leachate recirculation in which this technique is usually applied in landfilling practice. Presently, there is limited information in the literature regarding the use of aerobic landfill as a method of solid waste disposal. In the aerobic landfill, the addition of air, and in turn oxygen, promotes the aerobic stabilization of the landfilled waste. This is the same process that occurs in a waste composting system. However, aerobic composting is accomplished within the landfill rather than in windrows or other methods in which composting is normally practiced. The main products of aerobic degradation are carbon dioxide, water, and heat. In the aerobic landfill, methane energy is sacrificed by the addition of air. In addition, significant waste fractions such as lignin and ligneous materials, which are not degradable anaerobically are degraded aerobically (Stessel and Murphy, 1992). Based on the study of aerobic landfill conducted by Environmental Control System Inc., methane generation has decreased by more than 98% (Vitello, 2001). It is apparent that the aerobic bioreactor landfill has some advantages over the anaerobic bioreactor landfill; however, there are very limited experimental data available to support this.

The purpose of this paper is to evaluate the use of aerobic processes for the rapid stabilization of MSW in simulated bioreactor landfills. In addition, the optimum factors of leachate recirculation and sludge addition that enhance the degradation of MSW are examined. Another aspect of this research is to evaluate the use of aerobic bioreactor landfills technology in term of the biodegradation using empirical model.

2.0 MATERIAL AND METHODS

2.1 Simulated bioreactors setup

The experimental setup consisted of six simulated bioreactor landfill models made from Plexiglas with dimensions of 150-mm in diameter and 550-mm in height. Bioreactors were operated with leachate recirculation and equipped with an outlet port at the bottom to collect leachate from the bioreactors, and an inlet port at the top of the bioreactors to distribute simulated rainfall and the recirculated leachate. The leachate from the bioreactors were collected and stored in tanks before being recycled back at the top of each reactor. Also all bioreactors were sealed using construction-type sealant in order to avoid leachate from leaks. A perforated PVC pipe with diameter of 12.7-mm used as an air distribution systems. This pipe was wrapped in a plastic mesh prior to inserting into the waste matrix and was connected to the laboratory air supply system. The configurations of the bioreactors are shown in Figure 1.

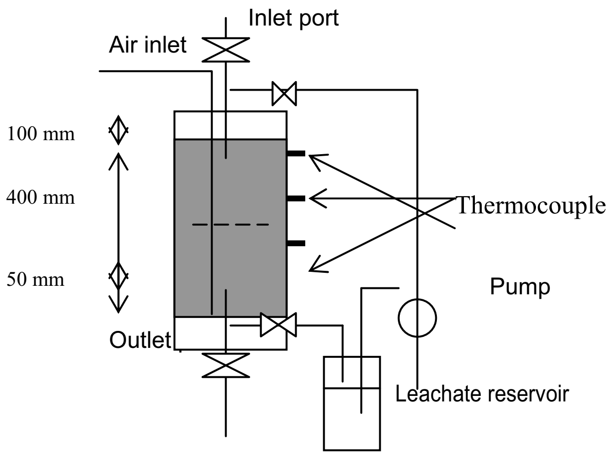

Figure 1 Configuration of Simulated Bioreactor.

The MSW used in this experiment was collected from curbside of Ottawa City in order to achieve representative sample of municipal solid waste that are normally disposed in a landfill. As is presented in Table 1, the major components of this waste were paper (36.6%), food (36.2%) and yard trimmings (27.2%). The collected waste was shredded manually to about 50 to 100-mm in diameter and was mixed before being loaded into the bioreactors. A 100-mm layer of shredded solid waste was filled and compacted to a density of 350 kg/m^3. This technique was repeated until the thickness of solid waste in each reactor reached a height of 400-mm. A supporting media, consisting of marbles (15-mm in diameter), with thickness of about 50-mm was placed at the bottom of each reactor and used as a leachate collection system. In addition, the marbles beds were used to prevent clogging of the leachate outlet at the bottom of the bioreactors. A perforated plate was placed at the top of the waste matrix to provide equal distribution of water and leachate recirculation. Approximately 2 liters of tap water was added per day to the bioreactors in order to attain field capacity. After day 4, when leachate had been generated, simulated rainfall was reduced to 2 L/wk. Leachate, then, was recycled daily at the top of the bioreactors.

In all bioreactors, the pH was controlled by adding sodium bicarbonate ($NaHCO_3$). Addition of buffer depended on the pH of the leachate in each bioreactor. Anaerobically digested municipal sewage sludge was added to the bioreactors through leachate recirculation system. The sludge was collected from ROPEC Wastewater Treatment Plant in Ottawa. Air was supplied to the aerobic bioreactors to maintain the aerobic conditions. The flowrate supplied of air must satisfy the oxygen demand exerted by the organic waste decomposition (stoichiometric demand). In this research, the assumption of solid waste composition is $C_{64}H_{104}O_{37}N$ (Haug, 1993). The Consequently, the oxygen demand calculated was 1.53 g O_2 /g waste (dry). This is a total quantity of oxygen that must be supplied to the aerobic bioreactors to meet the stoichiometric demand. However, in this research a safety factor of 2 was applied to avoid anaerobic pockets. A total flow rate of air was 185 L air/day.

In order to record the progress of landfill stabilization within the bioreactors, a combination of parameters concerning solid waste and leachate were monitored throughout this experiment. Leachate samples collected from the leachate outlet port were stored in a refrigerator at 4^0C prior to measurement for chemical, physical and biochemical parameters. Of particular interest in evaluating the effect of leachate recirculation, with sludge addition, on solid waste biodegradation were biochemical oxygen demand (BOD), chemical oxygen demand (COD); these were measured on a biweekly basis. BOD and COD were analyzed by procedures outlined in “Standard Methods” (5210B and 5220C, AWWA-APHA 1998).

2.2 Factorial Design

An empirical mathematical model was used to describe the effects of operating variables on the COD concentration of the leachate (process response, *E(Y)*). In this model, at a certain time, the data was fitted to the first order linear model using a factorial design. The model is expressed,

$$E(Y) = \ _0 + \ _1 x_1 + \ _2 x_2 + \ _{12} x_1 x_2 \qquad \text{Eq. 1}$$

where *E(Y)* is the expected value of the observed response, $\ _i$ is a model parameter and x_i is a coded operating variable. The model parameters were estimated using data collected according to a 2^2 factorial experimental design including two center point replicates from which reproducibility and lack of fit was evaluated.

To assess the effects of leachate recirculation and sludge addition on the biodegradation of solid waste, three scenarios providing different rates of leachate recirculation and sludge addition had been decided. . These scenarios are coded as a factorial experimental To simplify notation and subsequent calculation x_1 and x_2 in equation 1 would be dimensionless coded variables defined as follows:

x_1 = (rate of leachate recirculation-10)/5

x_2 = (sludge addition-1)/0.5

Each operating variable was tested at only two conditions. Therefore, four possible combinations of operating conditions using the coding x_1 and x_2 was derived from Table 2. The following design strategy of four combinations of operating conditions and two center point replicates, as outlined in Table 3, was put forward for this study.
design (Box et al., 1978) and according to a 2^2 factorial experimental design, the results of 2^2 factorial experimental design are outlined in Table 2.

Table 1 Composition of MSW Used in Simulated Bioreactors

Component	Total weight of MSW (wet basis)	
	(kg)	(%)
Corrugated and Kraft	0.319	12.77
Newspaper	0.174	6.97
Computer and high grade paper	0.099	3.96
Others	0.323	12.91
Fruits	0.120	4.78
Vegetables	0.239	9.56
Pasta, Rice	0.085	3.42
Bread	0.085	3.42
Meat/Fish	0.085	5.47
Diary product	0.051	2.05
Coffee/Tea	0.034	1.36
Others	0.154	6.15
Grass	0.256	10.25
Leaves	0.075	3.01
Trimmings	0.348	13.93
Total	2.50	100.00

Table 2 Different scenarios at which operating variables were investigated in the factorial design.

Type of operating variable	Levels		
	Low	Center	High
Rate of leachate recirculation (L/week)	5	10	15
Rate of sludge addition (L/wk)	0.5	1	1.5
Coded	-1	0	+1

Table 3 A 2^2 factorial design in coded variables with two center point replicates

Bioreactor Name	x_1	x_2	$x_1 x_2$
AER1	-1	-1	+1
AER2	+1	-1	-1
AER3	-1	+1	-1
AER4	+1	+1	+1
AER5	0	0	0
AER6	0	0	0

3.0 RESULTS AND DISCUSSION

The variations of pH in leachate during the experimental period are presented in Figure 2. During the initial phase, the pH in the leachate varied from 5.6-6.7 from all bioreactors in the period starting from week 1 to 5 with the exception of the AER2 and AER4 in which the pH was stabilized at about neutral (pH 7-7.5) after 3 weeks of operation. While the pH in the leachate from the AER1, AER3, AER5 and AER 6 reached between 7 to 7.5 after 10 weeks. The data show that the pH in the AER2 and AER4 reached at about neutral condition faster than in anaerobic bioreactors. This indicated that an acclimation period or initial lag time of the AER2 and AER4, where highest leachate recirculations were applied, faster than the rest of bioreactors. The leachate pH, then, was controlled by adding sodium bicarbonate ($NaHCO_3$). Therefore, the pH in the leachate samples was consistently at the range of neutral condition until the end of experimental study.

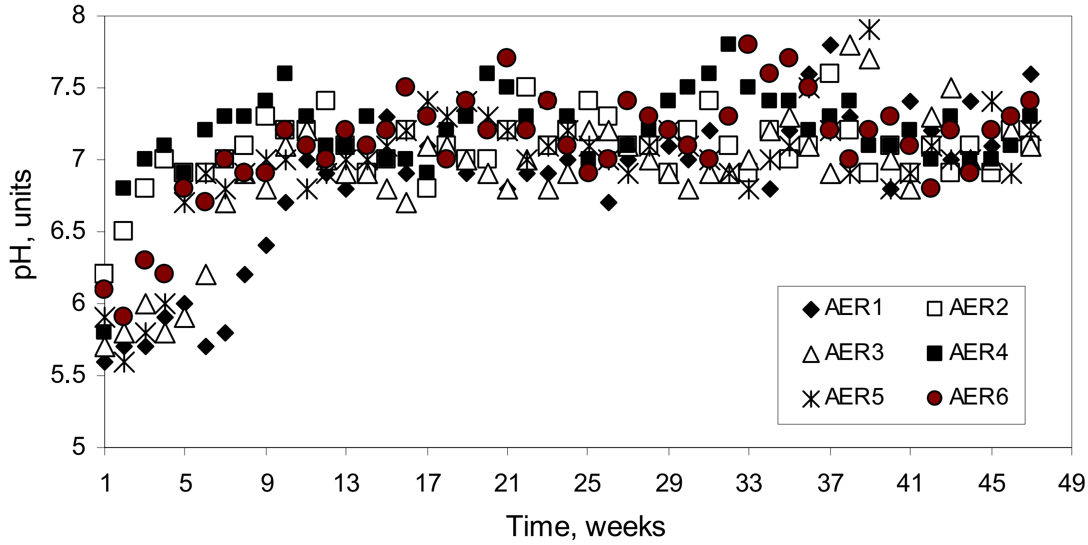

Figure 2 pH in Leachate Collected from Aerobic Bioreactors

The two parameters used to evaluate the effect of leachate recirculation and sludge addition on waste degradation were COD and BOD. Figure 3 depicts the concentration of COD in the leachate from the bioreactors. At the initial stage, the COD concentration in the leachate from AER1, AER3, AER5 and AER 6 increased slowly for a period of 9 weeks and generally remained below 10,000 mg/L. After this stage, the COD concentration increased exponentially and reached at peak value of about 40,000 mg/L for AER5 and AER6, 45,000 mg/L for AER3, and 51,000 mg/L for AER1 until 17 and 19 weeks. While, after 3 weeks of operation, the COD concentration increased exponentially and reached at peak value of about 38,000 mg/L for AER1, and 40,000 mg/L for AER3 until 13 weeks and were followed by a decrease in the COD concentration at almost constant rate until 25 weeks. It can bee seen that all curves had a similar trends, with rising part, peak concentration, and declining part. The COD concentration in the leachate from AER4 was about 1000 mg/L after 25 weeks of the operation. While, at the same period the COD concentration from the rest of bioreactors were still above 8000 mg/L. The concentration of COD trends showed that the MSW stabilization was achieved in AER4 and AER2, where the volume of leachate recirculation were 15 L/wk and the volume of sludge addition were 1.5 L/wk and 1.0 L/wk, respectively. The rates of biodegradation were 3409, 3406, 2958, 2619, 2356, and 2301 mg COD/L/wk for AER5, AER6, AER4, AER2, AER1, and AER3, respectively. These biodegradation rates were calculated from the maximum COD concentration to the point before the biodegradation rates became gradual. These results indicated that the highest rate occurred at the AER5. However, this indication can not be drawn as a conclusion of biodegradation rates of the waste since the rates was only calculated at a certain period. Therefore, the over all time to reach peak and then from peak reach to the bottom line was used to withdraw conclusions of the biodegradation rates. And according to the graph (Figure 3), it can be seen that time to attain the maximum concentration and to stabilize MSW was 11 and 25 weeks for AER4 and 19 and 43 weeks for AER1. This revealed that the highest rate of waste biodegradation was occurred in AER4 and the slowest rate was in AER1. The rate of waste biodegradation of AER4 was almost 2-fold faster than that happened in AER1. Thus, it can be concluded that the higher rates of leachate recirculation the faster waste biodegradation can be enhanced.

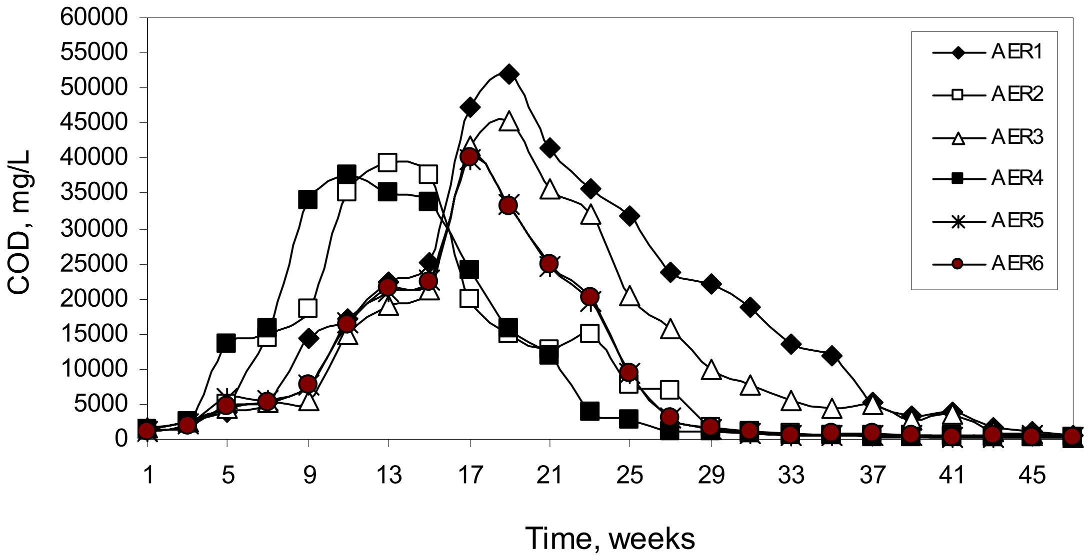

Figure 3 Concentration of COD in Leachate from Aerobic Bioreactors.

In order to study in greater detail the proportion of biodegradable organic carbon in the leachate, the concentrations of BOD were also measured. Figures 4 show the BOD concentration in the leachate from simulated bioreactors. Similar trends were observed for the BOD concentrations in the leachate from all bioreactors. Also, it was noted that the BOD data has the same characteristic as the COD concentration tends. At the beginning, the BOD concentration in the leachate from all bioreactors increased slowly for a period of 9 weeks and generally remained below 10,000 mg/L with the exception of the bioreactor AER4 which reached about 21,000 mg/L. The BOD concentration in AER4 reached its peak value of about 24,500 mg/L after 11 weeks, 27,000 mg/L for AER2 after 15 weeks and in the range 30,000 to 35,000 mg/L for the remaining bioreactors after 17 to 19 weeks. These peak values were followed by a sharply decrease in BOD concentration until approximately 27 weeks but AER1 and AER3 were until 43 weeks to reach gradual slope. The BOD concentration decreased to approximately 1000 mg/L for AER4, 4000 mg/L for AER2, and above 5000 mg/L for the rest of bioreactors after 25 weeks. Moreover, in AER1 and AER3, the BOD concentration is still above 15,000 mg/L after a period of 25 weeks. As the COD concentrations, the results indicated that the MSW stabilization was achieved in the AER4, where the volume of leachate recirculation was 15 L/wk and the volume of sludge addition was 1.5 L/week. It can be seen that the more volume leachate recirculation and sludge addition, the more rate of waste biodegradation can be achieved. This indicate that the volume of leachate and sludge addition provided to the MSW columns have a significant effect on the rate of solid waste biodegradation.

A BOD/COD ratio is used to study the fraction of the biodegradable organic carbon in the leachate. Figures 5 show the change in BOD/COD ratio in leachate collected from all bioreactors over time. The BOD/COD ratio ranged from 0.05 to 0.85, where the lowest and the highest were found in AER4 and AER5, respectively. It was documented (Kjeldsen et al., 2001, Townsend, 1996; Pohland, 1980) that the BOD/COD ratio in the leachate lies between 0.02 to 0.87 for all stages of solid waste biodegradation. A ratio of 0.4-0.80 implies the presence of highly biodegradable components in the leachate. At the initial stage, in this experiment, the BOD/COD ratio ranged from about 0.2 to 0.9 for all bioreactors until 9 weeks. Then the BOD/COD ratio was scattered with the ranged of about 0.6 to 0.8 for AER1, AER3, AER5 and AER6 until 35 weeks. While, at the same time, the BOD/COD ratio in AER4 and AER2 decreased gradually. The BOD/COD ratio decreased after 35 weeks of operation, indicating that the biodegradable fraction is decreasing compared to the non-biodegradable fraction. At the end of operation, the BOD/COD ratio was ranged between 0.05 to 0.15 with the exception of AER1 and AER3 where had ranged from 0.35 to 0.4. The lowest BOD/COD ratio was found in AER4 at the end of operation. This indicated that most of biodegradable organic matter was stabilized in AER4 which received highest leachate recirculation and sludge addition. In contrast, the BOD/COD ratio remained above 0.35 for AER1 and AER3 that indicated the biodegradable fraction of organic matter in the leachate is still elevated compared to waste non-biodegradable fraction.

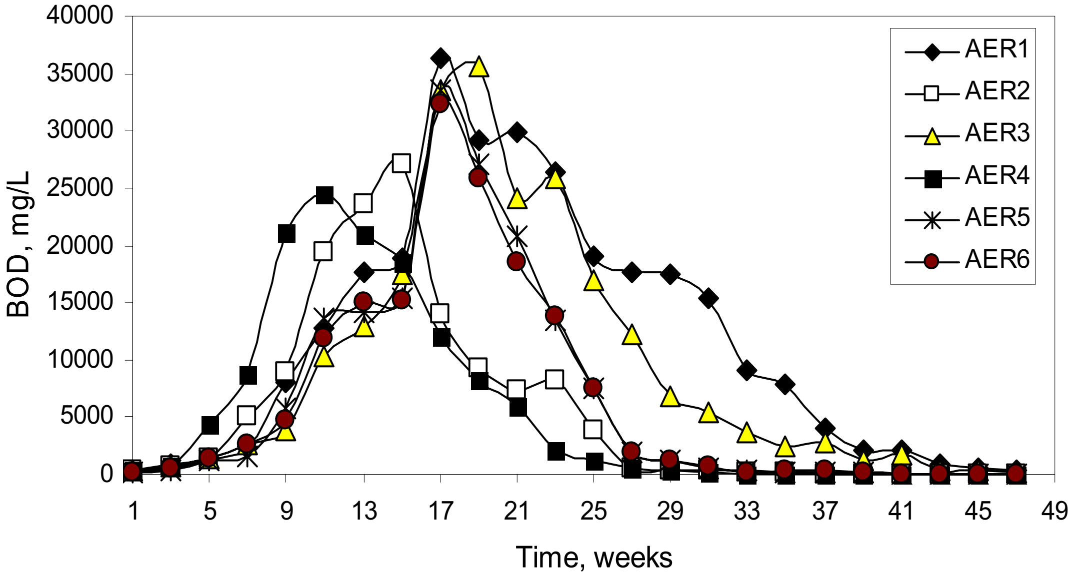

Figure 4 Concentration of BOD in Leachate from Aerobic Bioreactors.

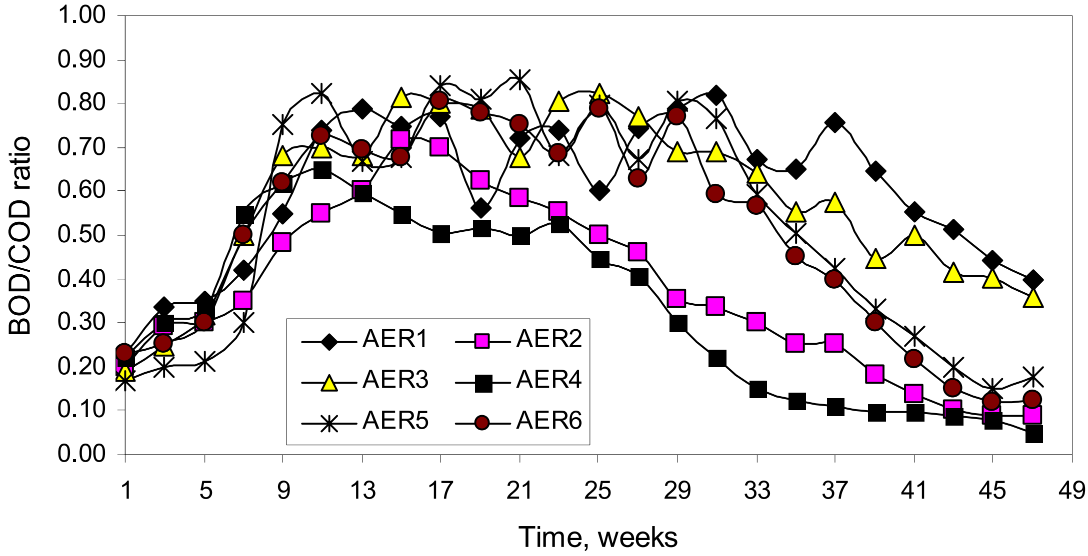

Figure 5 BOD/COD ratio in Leachate from Aerobic Bioreactors.

Empirical model in equation 1 was fitted to the COD process responses for the 4 experimental runs presented in Table 3. A pure error variance for the different responses was examined using results from 2 runs of center points replicates. It should be noted that the empirical model was determined at a certain time of operation due to the processes unsteady state.

4.0 CONCLUSIONS

1. MSW in simulated bioreactor landfills was stabilized within 27 to 45 weeks. The combination of leachate recirculation and sludge addition at the rate of 855 and 85 mL/kg of waste/d, which was the highest rate, exhibited a biodegradation of MSW faster than at the rate of 570 and 57 mL/kg of waste/d, which was the medium rate, or 285 and 28 mL/kg of waste/d, which was the lowest rate.
2. Addition of air at the rate of 84 L/kg of waste/d to the aerobic bioreactors landfill was found to have a positive effect on the rate of biodegradation of MSW.
3. Leachate recirculation and sludge addition enhanced conditions such that there was a rapid increase and was followed by a rapid decrease of COD and BOD concentrations in the leachate.
4. The fastest time to reach the maximum concentration of COD was 11 weeks after operation for the AER4, and the latest was 19 weeks for both AER1 and AER3. In addition, the fastest time to reach the stabilization, with the COD concentration about 1000 mg/L, was 27 weeks and the latest was 45 weeks.
5. The empirical models indicated that the biodegradation of MSW was affected by leachate recirculation and sludge addition. However, leachate recirculation had more significant effect compared to sludge addition.

ACKNOWLEDGMENT

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Table 3 Parameter estimates and fitted model from 2^2 factorial design for COD responses

Time, week	Parameter				Equation
	$\beta0$	$\beta1$	$\beta2$	$\beta12$	
5	6663.61	2514.09	2275.79	1999.16	Y = 6663.61 + 2514.09 X1 + 2275.79 X2 + 1999.16 X1X2
11	26186.19	10213.81	23.68	1176.32	Y = 26186.19.19 + 10213.81 X1 + 23.68 X2 + 1176.32 X1X2
19	31985.75	-16641.48	-1424.19	1817.63	Y =31985.75 - 16641.48 X1 - 1424.19 X2 + 1817.63 X1X2
25	15743.91	-10432.44	-4072.79	1515.42	Y = 15743.91-10432.44 X1 - 4072.79 X2 + 1515.42 X1X2

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