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A Study on the Mass Balance Analysis of Non-Degradable Substances for Bioreactor Landfill

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Abstract

Analysis of hydrological safety as well as the determination of many substance concentrations are necessary when bioreactor systems are introduced to landfill operations. Therefore, hydrological and substance balance model was developed since it can be applied to various bioreactor landfill operation systems. For the final evaluation of the model's effectiveness, four different methods of injections (leachate alone, leachate and organic waste water, leachate and reverse osmosis concentrate, and all the above three combination) was applied to 1st landfill site of Sudokwon landfill. As a result, the water content of the hypothetical cases for four different systematic bioreactors is projected to be increased up to 35.5% in next 10 years, and this indicated that there will be no problems in meeting the hydrological safety. Also, the final Cl^- concentration after 10-yr time period was projected to be between from minimum 126 to maximum 3,238 mg/L, which could be still a decrease from the original value of 3,278 mg/L. According to the proposed model, whether the substance concentration becomes increased or decreased largely depends on the ratio of initial quantity of inner landfill leachate and the rate of injection.

Keywords: Bioreactor landfill, Leachate recirculation, Mass balance, Substance accumulation

1. Introduction

It is important to ensure the integrity of the final covering of landfill sites to reduce odor and greenhouse gas emission. However, final coverings of landfill causes a restraint on the moisture supply which results in the drying of the interior of the landfill. Considering that a landfill is essentially a large mixed biological reactor, the exclusion of water raises the problem of an extended stabilization time [1]. This impingement on the biological reaction drastically reduces the production of landfill gas, used as an energy source, lowering the value of the facility. Therefore landfill operations are now being studied as bioreactors, and this perspective in design is being applied to closed landfills in order to reducing leachate and waste water treatment cost and to shorten the stabilization period [2, 3], as well as to increase the economic feasibility of the landfill site as an energy facility by increasing landfill gas production [4, 5].

Bioreactor landfills are classified into various types depending on their scale, structure and recirculation of waste water, as well as whether they are operated aerobically or anaerobically [6]. For the long term operation of all bioreactor landfills, it is necessary to analyze the concentration of substances which cannot be emitted from the landfill through either the generation of gas or through the leachate, as increases in concentration of many such substances (e.g., Cl^-) can negatively influence the operation of the system. The change in substance concentration depends on the scale of landfill, the injection volume of waste water and the rate of substance production from waste.

The purpose of this research was to predict the long term changes of water content and the concentrations of non-degradable substances in a large scale landfill site after the introduction of a bioreactor system. The strict control of the water content in such systems can allow for the prevention of operational problems as well as improving the efficiency of the bioreactor system. A study was carried out to develop a substance concentration model which can be applied to various bioreactor landfills, and this model and methodology were applied to the 1st landfill site of Sudokwon landfill in Korea in order to further refine the parameters of bioreactor control *in situ*.

2. Materials and Methods

2.1. Accumulation Model Development

2.1.1. Mass balance equation

The bioreactor system generally has various combinations of leachate recirculation, waste water injection and leachate treatment facilities. These combinations should be reflected in constructing mass balance equation. In a large-scale landfill system,

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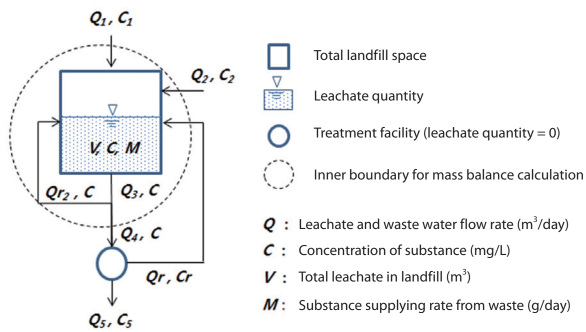

Fig. 1. Mass balance concept of bioreactor landfill for non-degradable substances.

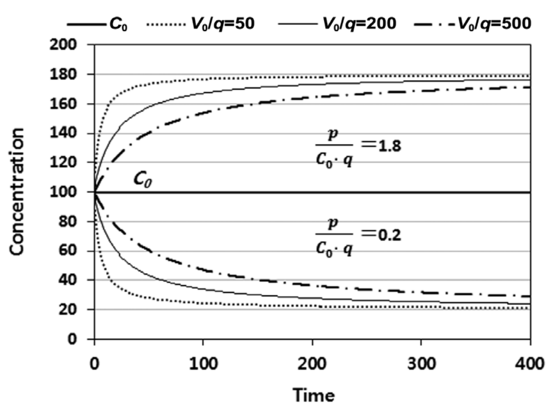

Fig. 2. Concentration change curves according to V_o/q.

secondary and irregular processes can cause a change in substance concentration, and it is impossible to recognize all these complicated phenomena. In this study, the total landfill system was constructed as shown in Fig. 1 for its mass balance analysis against non-degradable substances.

V is the total quantity of leachate in the landfill. C is the concentration of non-degradable substance in leachate. M is substance supplying rate from waste to landfill. Q_1 is the infiltrating rate of precipitation through the landfill covering. Q_2 is the injection rate of organic waste water and C_2 is its concentration. Q_3 is the leachate flow rate from landfill, Q_4 is flow rate to the leachate treatment facility and Q_5 is the discharged or reused flow rate after treatment. Q_r is the flow rate of leachate recirculated from the treatment facility to landfill. Q_{r2} is the flow rate of leachate recirculated which exceeds planned treatment quantity. C_1 is, the concentration of precipitation, which is 0 and if treatment facility is employing reverse osmosis (RO) system, then C_5 is also 0. Q_1, Q_2, Q_r, Q_4, Q_5, C_1, C_2, C_r, C_5 are also constants, and Q_3, Q_{r2}, V, C, M are a function of time.

As shown in Fig. 1, mass balance is expressed in terms of V and C. If M is the function of time and m(t) is the differential function of M(t), the change of substance with time can be expressed as Eq. (1).

$$\frac{d(VC)}{dt} = Q_1C_1 + Q_2C_2 - Q_5C_5 + m(t) \tag{1}$$

Here, if the initial quantity of leachate is set to be V_0, and the system flow was assumed to be $q = Q_1 + Q_2 - Q_5$, then V can be expressed as Eq. (2).

$$V = V_0 + q \cdot t \tag{2}$$

m(t) can be changed according to V. The extent of the change is different from landfill to landfill, case by case, and additional research is needed in order to establish these ranges, based on the input, scale, age, and design of the landfill. In this study m(t) was supposed to increase linearly by V/V_0. If the modified function is expressed as $m_2(t)$ then, it can be expressed as Eq. (3).

$$m_2(t) = m(t) \cdot \frac{V}{V_0} = m(t) \cdot (1 + \frac{q}{V_0} \cdot t) \tag{3}$$

If Eq. (4) is substituted into Eq. (1), and is then integrated, Eq. (5) which is the function of substance concentration can be described as follows.

$$p = Q_1C_1 + Q_2C_2 - Q_5C_5 \tag{4}$$

$$C = \frac{V_0C_0 + p \cdot t + M(t)}{V_0 + q \cdot t} \tag{5}$$

M(t): integrated function of $m_2(t)$

In Eq. (5) the ratio of $p{\cdot}t$ + M(t) to $q{\cdot}t$ determines the change in substance concentration with time. If M(t) is decreasing or $p{\cdot}t \geq$ M(t) and time goes to infinite, the concentration of substance in leachate approaches to p/q, and its concentration level approaches to $(p/q)/C_o$. Among all factors in Eq. (5), V_0/q, which the rate of changed concentration, is the most important. As shown in Fig. 2, the middle line is the initial substance concentration. The upper three concentration lines are approaching 1.8 and lower three lines are approaching to 0.2. As V_0/q increases, the convergent curve becomes gradual. That is to say that the size of the landfill becomes greater compared to the injection rate q, and that the convergent rate is then reduced.

If the water content is increased by leachate recirculation and the total dry weight of waste, W_d, the specific water content ratio, w_t, can be expressed as Eq. (6). Substitution of Eq. (6) into Eq. (2), consideration of V, becomes Eq. (7). When the landfill size is relatively small compared to the input quantity, the operational time and method should consider the specific water content of landfill for structural safety. In that case, the time to reach safe water content ratio can be obtained by Eq. (7).

$$w_t = \frac{V}{W_d + V} \tag{6}$$

$$t = \frac{w_t \cdot W_d - V_0 \cdot (1 - w_t)}{(1 - w_t) \cdot q} \tag{7}$$

2.1.2. Input factor V_0, m(t)

Landfill management has three hydrological phases from the start of the landfill start to post landfill management period as shown in Fig. 3. Stage A is the landfill operation period and the leachate generation increases according to waste addition. The maximum value (Q_{max}) of the leachate flow rate was reached before the final covering, as during the progression of dumping, precipitation and moisture in waste were the source of leachate. Stage B is that period in which leachate generation is diminishing with time as waste dumping has been suspended and precipitation is reduced after the final covering. In stage C leachate generation is kept constant (Q_{bal}) in long term because of the hydrological balance between precipitation infiltration and leachate discharge.

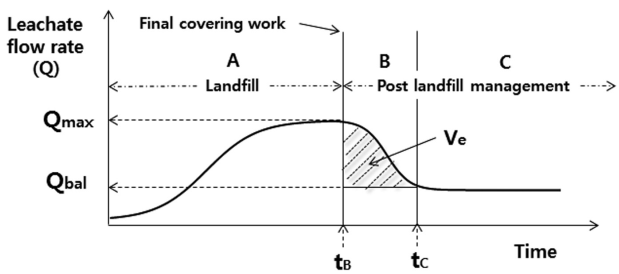

Fig. 3. Hydrological characteristics of landfill throughout operational stages.

V_e is the discharged quantity of leachate after the final covering which has been accumulated. V_0 is the total leachate quantity in the landfill when the landfill bioreactor operation begins. If the bioreactor system is introduced at t_B, Q_1 becomes less than Q_5 and Q_1 is equal to Q_5 at t_C. When the bioreactor system was introduced at t_C, and the water content was measured at t_B, V_e should be deducted from the leachate quantity at time t_C as Eq. (8) and it can be considered to be equal to V_0 at t_C.

$$V_{0tC} = V_{0tB} - \int_{tB}^{tC}(Q - Q_{bal})\,\mathrm{d}t = V_{0tB} - \sum_{i=1}^{n}(Q_i - Q_{bal}) \quad (8)$$

V_{0tC}: leachate quantity at time t_C
V_{0tB}: leachate quantity at time t_B
i: month or day
n: total month or day from t_B to t_C
Q_i: leachate flow rate of each month or day from t_B to t_C
Q_{bal}: balanced leachate flow rate at stage C

V_0 is the theoretical total quantity of leachate in waste. This is obtained by multiplying the waste quantity in landfill with water content ratio. However, this total leachate quantity comprises three types of leachate, including slowly-leaking-leachate locked in hygroscopic property waste like paper and wood, relatively-rapid-leaking leachate between waste mass and that which is rapidly removed through leakages. Hence, it is difficult to evaluate the total volume of leachate in a landfill on determinations of substance concentration. V_0', as substance concentrations are directly related to leachate quantity and water balance, is as Eq. (9).

$$0 < \frac{V_0'}{V_0} \leq 1 \quad (9)$$

V_0'/V_0 varies depending on the structure of the landfill, waste characteristics, landfill method and the injection method of the bioreactor landfill. If the leachate is injected into the landfill contacting all waste particles evenly, V_0'/V_0 may approach 1. As V_0'/V_0 approaches 1, V_0/q becomes greater. The rate of change of the concentration is decreased as shown in Fig. 2. That is to say, since the structure of the landfill cannot be modified, V_0'/V_0 should rely on the installment and operation of the bioreactor facility.

After applying the bioreactor system, V_0' can be obtained by multiplying the mean leachate flow rate by the retention time t_d as shown in Eq. (10). Retention time can be calculated using leachate flow rate against injected quantity or using a tracer substance.

$$V_0' = Q_1 \cdot t_d = Q_3 \cdot t_d \quad (10)$$

m(t) differs depending on the landfill structure, waste characteristics and the substance to be analyzed, and it is more difficult to decide an adequate m(t) in large scale landfills, as results of laboratory experiments cannot be applied directly. Actual data accumulated during a long term study is better for the actual application. m(t) can be considered as a time function of the supply rate of a substance from landfill waste.

2.2. Application to Landfill

2.2.1. Landfill for case study

The 1st landfill site of the Sudokwon landfill opened in February 1992, and an approximate 64 million tons of municipal, construction and industrial waste had been treated as of October 2000 when it ceased operation. Design information relating to the 1st landfill site is shown in Table 1, and it is now in the post management period. Landfill gas from the site has been used to supply a power plant (50 × 10^6 W) and leachate has been discharged after treatment.

Table 1. Design structure and landfill waste of Sudokwon landfill site 1st landfill

General	Total area (m^2)	2.51 × 10^6
	Block number	17
	Block size (aver.) (m)	400 × 400
Structure	Bottom layer	Original ground (silt)
	Slope (mm)	1.5 (HDPE sheet)
	Waste layer (m)	4.5
	Intermediate covering (m)	0.5
	Total height (8 layer, waste and intermediate covering) (m)	(4.5 + 0.5) × 8 = 40
Final covering	Gas venting layer (cm)	30
	Low permeability layer (cm)	45
	Drainage layer (cm)	30
	Vegetation layer (cm)	60 (soil)
	Gradient (%)	2
Landfill waste	Municipal & domestic waste (ton)	41,145,956
	Facility waste (ton)	8,360,668
	Construction waste (ton)	14,862,328

HDPE: high density polyethylene.

2.2.2. Substance for analysis

Cl^- was selected as a substance for concentration analysis. According to a previous study [7], over 99% of carbon is removed from landfill through artificial collection and surface emission of landfill gas. On the contrary, salts such as Cl^- were not removed from landfill but accumulated throughout bioreactor operation. The excessively high concentration of salts can negatively influence anaerobic digestion and leachate treatment. Cl^- is a relatively stable substance in landfill and acts as an indicator for concentration analysis of other salts.

3,278 mg/L, the average value in stage C, was applied as the initial Cl^- concentration of C_0, 1,800 m^3/day, the planned quantity of digestion for food waste water by Sudokwon Landfill Site Management Corporation (SLC), was applied for Q_2. According to RO system (300 ton/day, 75% recovery rate) in SLC, 959 m^3/day was applied for Q_5 which is 75% of the recovery amount of Q_4. 3,778 mg Cl^-/L, the digestion concentration of food waste water after digestion, was applied for C_2.

2.2.3. Case study for bioreactor landfill

During 10 years of bioreactor operation at the 1st landfill site, the changes of water content and Cl^- concentration were analyzed. For the comparison, between diverse operation types, the leachate, RO concentrate and food wastewater after digestion were analyzed for hydrological and Cl^- concentration changes as shown in Table 2.

3. Results and Discussion

3.1. Hydrological Analysis

3.1.1. Initial quantity of leachate V_0 in landfill

The 1st landfill site shows three stages of hydrological periods from the beginning to the present as shown in Fig. 4. Among these, the stage B period can be divided into B1; construction time of final covering after ending of dumping waste, and B2; before obtaining hydrological balance, or the period after construction of final covering. B1 and B2 can be considered as stage B.

Since there is no water content data for stage C of the 1st landfill site, that of the 2nd landfill site, which is similar in scale to the

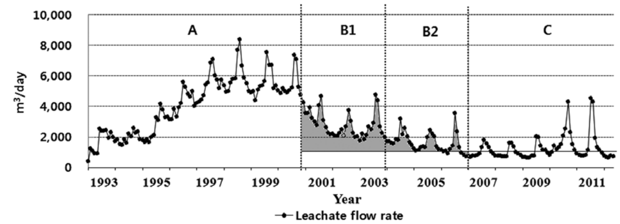

Fig. 4. Hydrological characteristics of 1st landfill throughout operational stages.

1st landfill site, was substituted. Total 61.2 × 10^6 ton of waste has been processed until July 2012 in the 2nd landfill. This landfill capacity is almost the same as that of 1st landfill site. The average percentage water content of stage A for the 2nd landfill site was 26.7% [8]. This value can be converted to leachate quantity retained in for the 1st landfill site, giving a value of 17,103,876 m^3. As previously stated, if the leachate quantity of V_e accumulated is removed from the total leachate quantity of 2,269,896 m^3 at stage B1 and B2, the estimated V_0 is 14,833,980 m^3 and the water content is 24.0% at present. In order to calculate the retention time of leachate in the 1st landfill site, which is necessary to estimate V_0', the results of four month study were used [9]. According to Eq. (10), V_0' is 153,480 m^3. Compared to the total amount of leachate inside the landfill site, the ratio of the actual leachate in the short-term cycle to total quantity was found to be relatively small. This indicated that the injection method enhancing the contact probability of leachate and waste would be an important parameter affecting the retention time in landfill.

3.1.2. Changes in water content over time

Water content change during four cases of bioreactor landfill operation which was supposed to be introduced to 1st landfill site is shown in Fig. 5. Water content was changed from 24% to 29.3% for case1, 35.5% for case 2, 25.2% for case 3, and 32.3% for case 4 after 10 years. Though there were differences depending on each case, the maximum water content was under 36% throughout the 10 years of operation.

A sudden increase in the water content could negatively affect the safety of the slope of the landfill site. Therefore, when the water content exceeds a certain level, it is necessary to remove

Table 2. Data set used to estimate Cl^- changes in 1st landfill by bioreactor in all theoretical cases

	Case 1	Case 2	Case 3	Case 4
C	$\frac{V_0C_0 + M(t)}{V_0 + Q_1 \cdot t}$	$\frac{V_0C_0 + Q_2C_2 \cdot t + M(t)}{V_0 + (Q_1 + Q_2) \cdot t}$	$\frac{V_0C_0 + M(t)}{V_0 + (Q_1 - Q_5) \cdot t}$	$\frac{V_0C_0 + Q_2C_2 \cdot t + M(t)}{V_0 + (Q_1 + Q_2 - Q_5) \cdot t}$
Q_1	1,279	1,279	1,279	1,279
Q_2	-	1,800	-	1,800
Q_5	-	-	1,279 × 0.75 = 959	1,279 × 0.75 = 959
V_0	14,833,980	14,833,980	14,833,980	14,833,980
V'_0	151,480	151,480	151,480	151,480
C_0	3,278	3,278	3,278	3,278
C_1	0	0	0	0
C_2	-	3,778	-	3,778
C_5	-	-	0	0

Case 1: recirculation of all leachate, Case 2: case 1 + injection of digestion waste water (food waste water), Case 3: case 1 + recirculation of reverse osmosis concentrate (75% recovery rate), Case 4: case 3 + injection of digestion waste water (food waste water).
Unit: Q, m^3/day; C, mg/L; V, m^3.

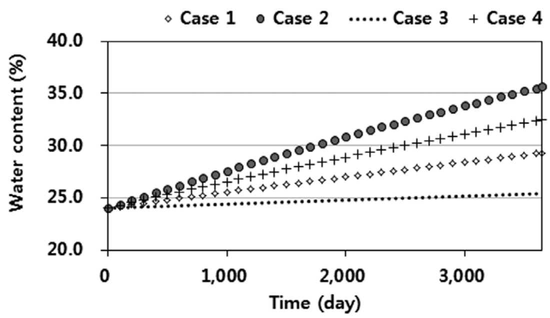

Fig. 5. Water content changes by cases of bioreactor operation in 1st landfill.

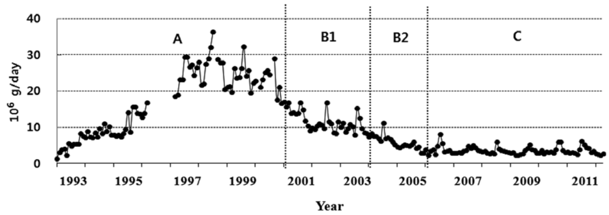

Fig. 6. Leachate flow rate multiplied by Cl^- concentration of 1st landfill.

moisture as leachate, and to manage this balance carefully. However, on the bases of a water content of 35.5%, hydrological problems were not expected during the operation of the 1st landfill bioreactor. This result also indicated that the introduction of the bioreactor system to the landfill could decrease the cost of leachate treatment process.

3.2. Analysis on the Change of Cl^- Concentration

3.2.1. Cl^- supplying rate in landfill

Fig. 6 shows the leachate flow rate multiplied by the Cl^- concentration during January 1993–May 2012 of 1st landfill site. In stage C (January 2007–May 2012), the Cl^- supply rate was declining slowly, and with 65 monthly mean measured data as a sample, the trend-line $y = 4,795.1 \times t^{0.13}$ (t, month) was used for long term prediction by trend analysis. After it was modified by multiplying V/V_0, as shown in Eq. (3), the integrated function of M(t) was achieved as Eq. (11).

$$M(t) = 5,511.6 \cdot t^{0.87} + \frac{4,795.1\ q}{1.87\ V_0} \times t^{1.87} \tag{11}$$

3.2.2. Cl^- concentration change with time

Without application of bioreactor landfill system, Cl^- concentration will be diminished from the initial 3,278 to 1,898 mg/L after 10 years. With operation of bioreactor landfill, p/q, the convergent value for Cl^- concentration, was 0 mg/L for cases 1 and 3, 2,209 mg/L for case 2, 3,208 mg/L for case 4. Cl^- concentration change in four cases of bioreactor landfill operation for the next 10 years is shown in Fig. 7. In all cases, except for case 4 (3,238 mg/L) the initial concentration of 3,278 mg/L was significantly diminished. Among those, case 1 showed greatest diminution and its concentration was 126 mg/L. When compared to the results of a non-bioreactor facility, cases 2 and 4 showed relatively high concentrations of Cl^-.

This result was in opposition to the generally accepted concept that a substances concentration may increase by leachate recirculation. Precipitation infiltration can dilute the leachate in landfill, but substance supply from waste and injection of the leachate can compensate for this dilution. However, the rate of substance supply from waste declines with time, and so, not all substances are concentrated by leachate recirculation and the injection of waste water.

3.2.3. The change rate of Cl^- concentration

Fig. 8 shows the Cl^- concentration change in next 10 years according to Eq. (9) for V_0'/V_0. The bigger the V_0'/V_0 the smaller the gradient to convergence value p/q. The extension of retention time by injecting leachate and waste water into landfill evenly can gradually change the substance concentration with time. If salt concentration is increased, it could have a negative impact

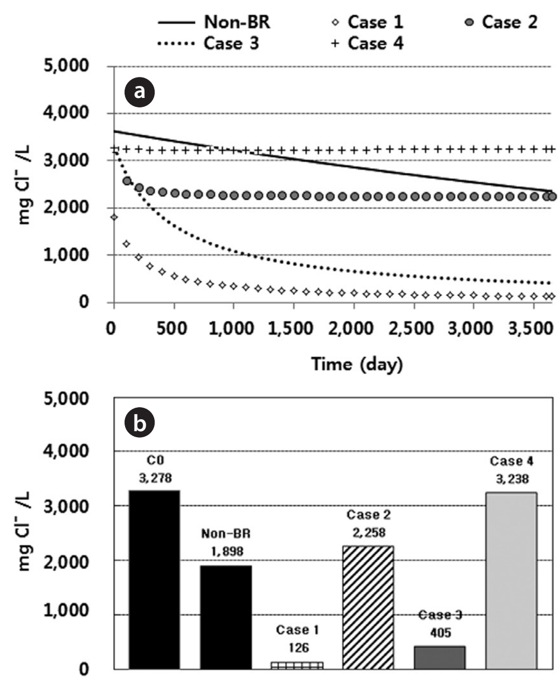

Fig. 7. Change trends of Cl^- concentration and their final concentration by cases (a) Cl^- concentration change (b) Cl^- concentration after 10 years. BR: bioreactor.

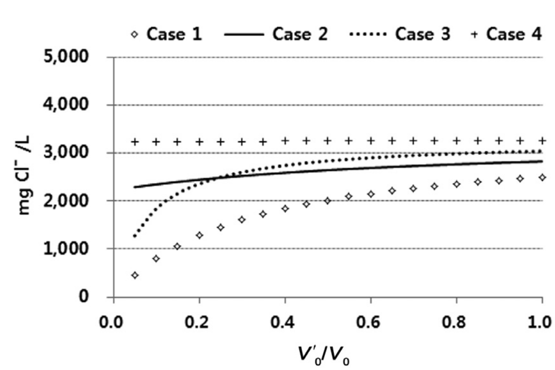

Fig. 8. Cl^- concentrations after 10 years in each V_0/q.

on the effectiveness of the leachate waste treatment. In the case of the 1st landfill site, since it showed a gradual decrease of substance concentrations and a high retention of leachate it can be concluded that salt concentrations will not cause any significant problems.

4. Conclusions

A substance concentration model was applied to the bioreactor operation of closed landfill – the 1st landfill site of Sudokwon landfill in Korea. Four types of injection cases including leachate, leachate with organic waste water, leachate with RO concentrate and leachate with organic waste water and RO concentrate were theoretically introduced.

The water contents were calculated to increase to a maximum of 35.5% from the initial content 24% over the next 10 years. Therefore, the bioreactor landfill operation should not cause any hydrological problem.

When bioreactor systems are not applied to landfills, the concentration of Cl^- is estimated to reach 1,898 mg/L in next 10 years. The estimated concentrations of Cl^- were from 126 to 3,238 mg/L in the case bioreactor introduction. Also, in all cases, the concentrations of Cl^- were determined to be attenuated with time, from the initial concentration of 3,278 mg/L.

In a bioreactor landfill, as the ratio of leachate quantity which is related with hydrological circulation becomes large, the Cl^- concentration change becomes gradual. So, the even recirculation and injection of leachate or wasted water are important for reducing the changes in substance concentration.

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