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Estimation of Landfill Stabilization using Carbon-based Mass Balance Evaluation

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ABSTRACT

In order to evaluate landfill stabilization based on organic carbon, stoichiometric analysis and a biological methane potential (BMP) test based on modeling were performed at the 2nd Sudokwon Landfill Site. Mass balance analysis through a BMP test proved to be more adaptable for evaluation, and it showed that 28.9% of landfill organic carbon was expected to remain by 2046, 30 years after landfill closure. The organic carbon ratio of total landfill waste for 2046 is forecasted as 2.9% in demolition waste and 5.1% in household waste, and, if one were to consider plastic as an organic waste, the ratios would increase to 15.9% and 28.3%, respectively. Therefore, it seems that organic matter biodegradation facilitating measures such as bioreactor landfill technology and preemptive recovery of combustible waste are necessary to shorten post closure management periods and to meet the landfill stabilization guidelines more safely.

Key words : Landfill stabilization, Mass balance, Organic carbon, Landfill gas model

1. Introduction

A landfill site employs a waste treatment method that can return waste organic matter to the soil through biological decomposition. The decomposition and stabilization processes continue long after the act of filling the site is completed. Thus, if decomposition is delayed, the management period for the landfill site might be prolonged.

Most of previous researches on landfill stabilization are based on the present evaluation of biodegradability of initial landfill waste, which can be estimated by direct sampling and analysis (Smidt and Lechner, 2005, Wu et al., 2011). These sorts of researches are currently used to determine whether to complete landfill for ex-post facto management in Korea very often. However, improvement of the running and post management procedure of the landfill beforehand by assessing the development of the landfill stabilization in the long-term is more desirable for shortening the period of ex-post facto management. Therefore, the development of a more effective mass balance analysis methodology related to the decomposition of waste in the landfill is in need.

The efficiency of landfill waste decomposition and stabilization can be broadly evaluated by mass balance analysis based on organic carbon. At landfill sites, almost all of the organic carbon compounds are released in the form of CO_2 and CH_4 (Bade Shresha and Narayanan, 2008, Majumdar et al., 2014). Thus, in order to perform mass balance calculations, suitable methodologies for estimating the quantity of landfill organic carbon changed to gaseous carbon as landfill gas must be investigated. The application of a model is then necessary to interpret the relationship between the organic carbon in the landfill and the carbon in landfill gas.

The study site, 2nd Sudokwon Landfill Site (2nd SLS), has been in operation since October 2000. By the end of 2014, 68.7×10^6 tons of waste had been disposed at this site, and it is expected to be closed at the end of 2016. For this study, the quantity of organic carbon in the landfill was estimated using two kinds of methods from 2000 to 2014. The stabilization trends were developed by projecting the organic landfill carbon and emitted gaseous carbon from 2001 through 2046. Then, calculated the remained organic carbon ratio in landfill waste in several cases to estimate possibilities of satisfying governmental guidelines on landfill stabilization.

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2. Material and methods

2.1. Landfill Quantity of Organic Carbon

Various methods are available for estimating the amount of organic carbon depending on the condition of the landfill site (Simoe and Catapreta, 2013). In this study, initially two different methods were schemed out and applied. Between these two, the more suitable one was selected, and then it was used to evaluate the long-term landfill stabilization status.

The first method (Method 1) was a stoichiometric one that calculates the theoretical maximum gaseous carbon production using data from elemental analysis (Komilis, et al., 2012). In this study, Eq. (1) (Sialve et al., 2009) was applied to all methods of estimating maximum potential CO_2 and CH_4. The sum of gaseous carbon quantity derived by Eq. (1) is equal to the quantity of landfill organic carbon eventually.

$$C_aH_bO_cN_d+\frac{1}{4}(4a-b-2c+3d)H_2O\rightarrow\frac{1}{8}(4a-b+2c+3d)CO_2 +\frac{1}{8}(4a+b-2c-3d)CH_4+dNH_3 \quad (1)$$

where *a, b, c,* and *d* is the mole ratios of carbon, hydrogen, oxygen, and nitrogen respectively, in each waste component.

Method 1 offers advantages such as simplicity, low cost, and data productivity, because it uses chemical analysis. On the other hand, it has a tendency to overestimate the quantity of biodegradable carbon. This is because it does not consider the composite characteristics of waste and landfill site, such as non-biodegradable carbon mixed products and various decomposition hindrance factors of waste.

The second method (Method 2) employs the biogas production results of each waste component from biochemical experiments, for instance, biochemical methane potential (BMP) tests (Tolaymat et al., 2010) or lysimeter experiments (Ahmed et al., 2010, Deipser and Stegmann, 1994). Then the quantity of gaseous carbon or biodegradable organic carbon can be calculated from the inorganic carbon in CH_4 and CO_2. This method is especially suitable for estimating the potential of biogas production from easily degradable organic materials by digesters. However, decomposition in landfills usually takes place over several decades after mixed landfill of not easily degradable solid waste, so considering these landfill site characteristics, there is a difficulty in setting optimum experimental conditions. If experiment itself and the interpretation of experimental results are not adequate, there is a possibility to underestimate the maximum gaseous carbon potential.

The total organic carbon landfill quantity by Method 1 and Method 2 explained above is as Eq. (2).

$$TC_L=\sum_{i=1}^{n}\sum_{j=1}^{m}C_j\cdot W_{ij},\; C=Q_{BG}\times\frac{12}{22.4}\times10^{-3}\;\text{(Method 2)} \quad (2)$$

where TC_L is the total landfill gaseous carbon Method 1 or Method 2 (t), C is the carbon content of each waste component from elementary analysis (Method 1) or from BMP test (Method 2) (weight ratio of carbon per wet waste), W is the disposed waste to landfill site (t yr^{-1}), j is the type of waste, and i is the year of disposal, Q_{BG} is the maximum production potential of CO_2 and CH_4 from each waste by BMP test (L/g wet waste).

To compare the results from Method 1 and Method 2, the BMP test data (Sudokwon Landfill Site Management Corp., 2004) and the elementary analysis results for the same year were used for C_j in Eq. (2).

2.2. Estimation of Discharged Carbon

The total landfill gas from the 2nd SLS is derived by summing the quantities from three main sources: collection, surface emission from landfill cover (Trapani et al., 2013) and incineration by mobile incinerator. Collection and mobile incinerator data is obtained from monthly measurements, and surface emission data (2005-2014) is collected on a seasonal basis.

Among the three aforementioned data sources, surface emission data were the most difficult to obtain, and consequently have the greatest margin of error (Barlaz et al., 2009). The number of sampling spots for surface emission measurements (EPA, 1986), though it was not fixed, was total of 457 sites in 2014, as shown in Table 1.

After summing up the CO_2 and CH_4 volume of landfill gas as described above, the quantities were converted to gaseous carbon weight using Eq. (3).

Table 1. Number of surface emission monitoring spots during each season in 2014

Sampling site	Winter (2.12-14)	Spring (5.22-24)	Summer (8.15-16)	Autumn (11.12-14)	Total
Upper intermediate covering	78	74	79	69	300
Dike of collecting well	34	25	23	21	103
Slope	14	15	11	14	54
Total	126	114	113	104	457

$$TC_{LFG} = \frac{12}{22.4}\sum_{i=1}^{n}\Big[(A_i+I_i)\times\frac{273.15}{273.15+t_{LFG}}+$$

$$(Sc_i\cdot Ac_i+Sd_i\cdot Ad_i+Ss_i\cdot As_i)\times\frac{273.15}{273.15+t_{atm}}\Big] \tag{3}$$

where TC_{LFG} is the total generated gaseous carbon (t), A is the collected CO_2 and CH_4 ($m^3\ yr^{-1}$), I is the CO_2 and CH_4 incinerated by mobile incinerator ($m^3\ yr^{-1}$), *Sc, Sd* and *Ss* are the unit quantity ($m^3\ m^{-2}$) of CO_2 and CH_4 emitted through intermediate cover, dike and slope respectively, *Ac, Ad* and *As* are the area (m^2) of intermediate cover, dike and slope respectively. t_{LFG} is the landfill gas temperature (°C), and t_{atm} is the atmospheric temperature (°C).

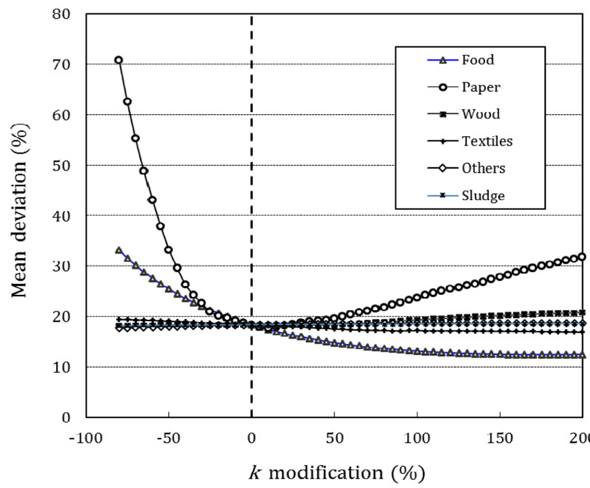

Fig. 1. Sensitivity analysis results for each waste component.

2.3. Long-term Expectation

2.3.1. Model Logic

Generally, first-order decay model is used to predict CH_4 production from landfill waste (Amini et al., 2012). The same logical structure of that model can be applied to estimate the amount of emitted gaseous carbon in CO_2 and CH_4. In this model, the maximum gaseous carbon production potential C (the same value in Eq, (2)) and reaction constant k determine the pattern of gaseous carbon generation (De Gioannis et al., 2009, Faour et al., 2007) as described by Eq. (4):

$$TC_E = \sum_{i=1}^{n}\sum_{j=1}^{m} C_i\cdot W_{ij}(1-e^{-k_j\cdot t}) \tag{4}$$

where TC_E is the accumulated gaseous carbon emission quantity by time elapsed (t), k is the reaction constant, t is the number of elapsed years after landfill (yr), j is the type of waste, and i is the year of disposal.

2.3.2. Reaction Constant k

Deciding k value to adopt for each waste component is necessary for using first order decay model (Aguilar-Virgen et al., 2014, Meraz et al., 2004). To find a compatible k value and to calibrate the model, a sensitivity analysis (Chun, 2010, Meima et al., 2008) for each waste component was done, and the optimal k was deduced by iteration.

The results of sensitivity analysis based on default k value (Intergovernmental Panel on Climate Change, 2007) are as shown in Fig. 1. Paper and food waste have a great influence on the differences between the modelled and measured data, and other waste components have meagre influences.

Considering the results of the sensitivity analysis, the combination of k values which showed minimum deviation between modelled and measured data (6.4% in Method 1 and 7.6% in Method 2 during 2005-2014) are applied.

Under all setting conditions as shown in Table 2, the mass balance evaluation of landfill organic carbon was conducted from 2001 to 2046 considering the fact that the post-management period of a landfill site after closure is set to be 30 years in Korea.

Table 2. Model parameters of Method 1 and Method 2 for long-term estimation of landfill organic carbon emission

		Food	Paper	Wood	Textile	Others	Solidified sludge
Method 1	C (Mg C/Mg wet waste)	0.19	0.38	0.39	0.47	0.36	0.22
	k (yr^{-1})	0.389	0.022	0.004	0.019	0.022	0.004
Method 2	C (Mg C/Mg wet waste)	0.11	0.23	0.11	0.20	0.10	0.02
	k (yr^{-1})	0.185	0.060	0.030	0.060	0.145	0.055

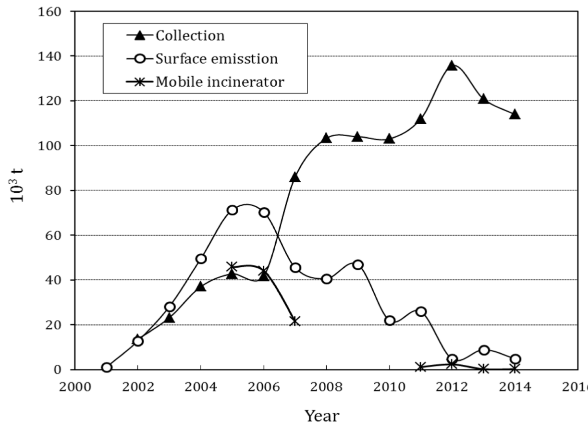

Fig. 2. Trends of emitted gaseous carbon from three major sources from 2001 to 2014.

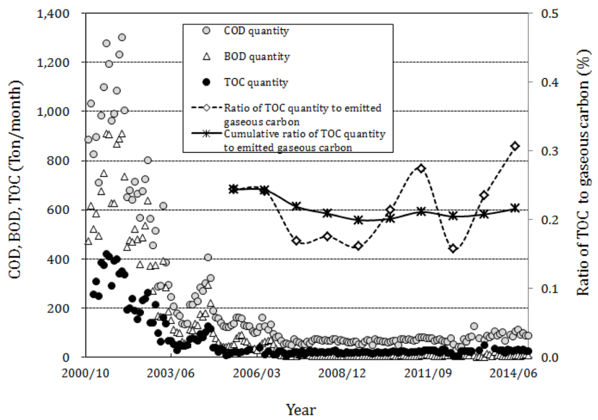

Fig. 3. Effluent quantity of organic carbon through leachate and its ratio to gaseous carbon emitted (2005~2014).

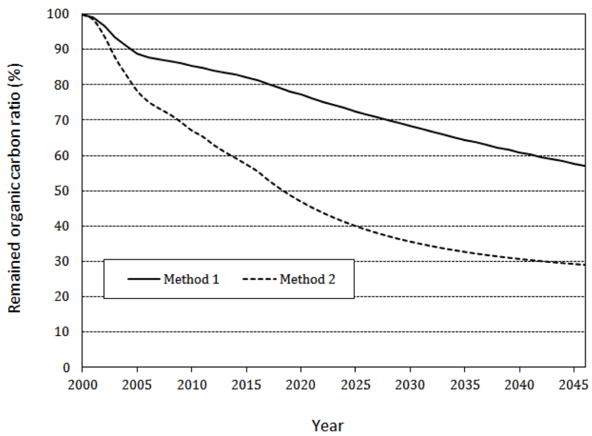

Fig. 4. Long-term estimation on the ratio of remained organic carbon in 2nd Landfill Site by Method 1 and Method 2 from 2001 to 2046.

3. Results and discussion

3.1. Total Landfill Organic Carbon and Discharged Carbon

The total quantity of organic landfill carbon from 2000 to 2014 was 9,976 × 10^3 t in Method 1 and 4,505 × 10^3 t in Method 2. There is a considerable difference in the calculated amounts of organic carbon. This indicates the importance of selecting an appropriate *C* for long-term prediction of gaseous carbon emissions.

The total quantity of emitted carbon was 1,571 × 10^3 t; 64.5% from collection, 28.3% from surface emission, and 7.2% from the mobile incinerator as shown in Fig. 2. The quantities emitted via collection and surface emission appeared to have an inverse relationship. This is likely because fortifying the landfill cover and collection for odour control results in the reduction of surface emission.

As shown in Fig. 3 the carbon emanating in the form of leachate during this period accounts for only under 0.4% of emitted gaseous carbon. Thus, when evaluating the behaviour of organic carbon or calculating mass balance, it is appropriate to consider landfill gas only.

3.2. Landfill Stabilization Evaluation

The long-term expectation of organic carbon behavior using Eq. (4) with parameters in Table 2, from 2001 to 30 years after landfill work ends in 2016, is shown in Fig. 4. In Method 1, 81.4% of the total amount of landfill organic carbon, was estimated to be remained in 2016, and 57.1% remained by 2046. According to Method 2, 55.4% and 28.9% respectively. The discrepancy in the ratios of remain-

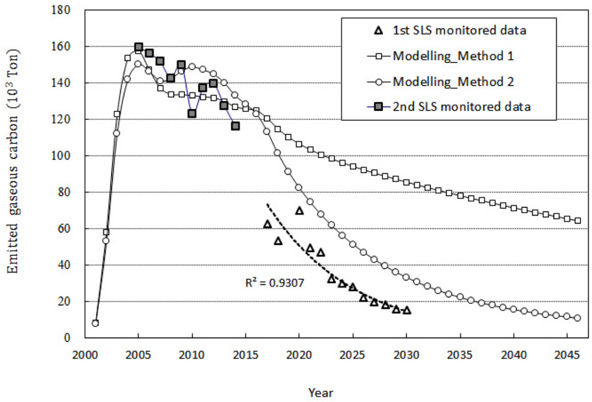

Fig. 5. The comparison of modeling results of 2nd SLS (by Method 1 and Method 2) to the post-closure monitored data of 1st SLS.

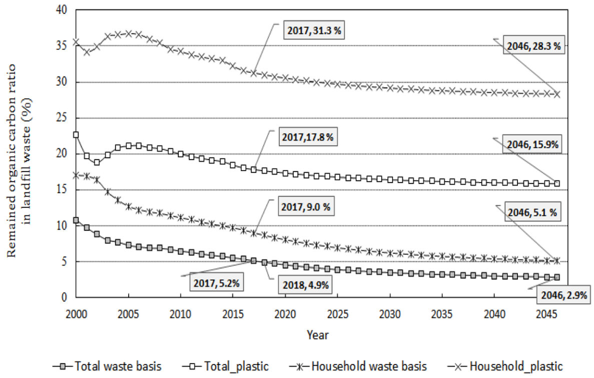

Fig. 6. The estimation of remained organic carbon ratio of waste in four cases from 2000 to 2046.

ing organic carbon calculated using Methods 1 and 2 reached 28.2 percentage points, $4{,}716 \times 10^3$ t in absolute quantity, in 2046. Therefore, it is necessary to verify which method conforms better to the actual data.

The calibration and verification for modeling can be completed by minimizing the gap between modeled and monitored data as explained above. However, these methods cannot be applied to a future estimation. Instead, a comparison of the emissions pattern to that of the closed landfill with similar size and characteristics is a productive methodology; hence, the gaseous carbon emissions data of 1st Sudokwon Landfill Site (1st SLS) (eight-layer sandwich construction method, 64.0×10^6 ton of landfill waste, closed in 2000), which is adjacent to the 2nd SLS, were used for comparison. Fig. 5 shows the modeled gaseous carbon weight emitted from the 2nd SLS and 1st SLS based on actual data. The monitored gaseous carbon data from the 1st SLS was shifted and re-plotted from 2000-2014 to 2017-2031 for comparison with the modeled data of the 2nd SLS after landfill closure. As shown in Fig. 5, the post-closure trend line for the 1st SLS is more similar to the modeled data of Method 2 but varies greatly from Method 1. The discrepancy may be resulted from the fact that Method 2 does not consider the conditions in a landfill site or the characteristics of waste in biodegradability, and therefore it might overestimate the gaseous carbon quantity. Thus, adopting Method 2 for the evaluation of the stabilization of the 2nd SLS is appropriate. Nevertheless, Method 1 offers several advantages, so increasing the method’s adaptability through additional research is necessary.

The analyzed remained organic carbon ratio in landfill waste post closure is illustrated in Fig. 6. Case 1 represents the remained organic carbon ratio of total landfill waste; Case 2 represents the remained organic carbon ratio of household landfill waste; Case 3 represents the remained organic carbon ratio (include plastics) in the total landfill waste; and Case 4 represents the remained organic carbon ratio (include plastics) in household landfill waste. The landfill waste is a dry base, and the amount of emitted carbon was deducted from waste quantity.

As shown in Fig. 6, the total landfill waste in Case 1 was comprised of demolition waste containing a large portion of incombustibles; hence, by considering the figures alone, the ratio is expected to decrease to less than 5% in 2018, only two years after landfill closure. In actuality, 50.7% of landfill organic carbon will still remain and a further 21.8% might be degraded and converted to gaseous carbon by 2046. Case 2 could be compared to a scenario in which a landfill is composed of only household waste. Immediately after landfill closure, the ratio is calculated as 9.0%, and in 2046, although the ratio will approach 5%. Cases 3 and 4 have very high ratios in 2046, 15.9% and 28.3%, respectively, because plastics are included in the organic carbon calculations. Of course, because of the daily covering soil, above ratios of organic matter in each case become lower. This means the ratio of each case greatly affected by landfill operating way and sampling method.

The current guideline in Korea for a stabilized landfill site is less than 5% of organic matter or less than or equal to

20 N*l* gas productivity per gram of dried waste. These criteria are based on negative environmental impacts and ground instability caused by additional biodegradation of waste. At the same time, the European Union Waste Directive (1999) preemptively limits landfilling of waste containing more than 5% organic carbon or a heat value greater than 1,433 kcal/kg; the former is for environmental protection and increased land utility, and the latter for energy recovery from waste. The legislative process in Korea integrates pre-regulation of landfill waste. For effective legislation, it would be helpful to improve the stabilization guideline for clarity, such as including a target index for organic matter or organic carbon, deciding whether to include or exclude plastic in that category, and so on.

Additionally the fraction of remaining carbon is not only from not easily biodegradable waste; it is to some extent due to the relative dryness of the inner landfill environment (Ferguson, 1993). Therefore, processes to expedite waste decomposition and to shorten the post management periods, such as the use of bioreactor landfill technology (Valencia et al., 2009) are necessary for landfill management. In connection with new integrated legislation, combustible waste including organic matter must be recovered before landfill disposal, because proactive measures are most effective under any circumstances.

4. Conclusions

Landfill stabilization based on organic carbon was estimated using two methods. The BMP test method proved more appropriate than the stoichiometric method. Mass balance analysis projected a remaining 28.9% of landfill organic carbon by 2046, 30 years after landfill closure. In the same year, the organic carbon ratio was forecasted as 2.9% in total landfill waste a low figure owing to the high volume of incombustibles in demolition waste and 5.1% in household waste. If plastic is considered in the organic waste calculations, the ratios increase to 15.9% and 28.3%, respectively. Therefore, biodegradation facilitating measures and recovery of combustible waste are necessary to shorten post closure management periods and to meet the landfill stabilization guidelines with a certainty.

Nomenclature

a, b, c, and d : mole ratios of carbon, hydrogen, oxygen, and nitrogen in each waste component

TC_L : total landfill gaseous carbon [t]

C : carbon content of each waste component [weight ratio of carbon per wet waste]

W : disposed waste to landfill site [t yr^{-1}]

Q_{BG} : quantity of CO_2 and CH_4 of each waste by BMP test [L/g wet waste]

TC_{LFG} : total generated gaseous carbon [t]

A : collected CO_2 and CH_4 [m^3 yr^{-1}]

I : CO_2 and CH_4 incinerated by mobile incinerator [m^3 yr^{-1}]

Sc : unit quantity of CO_2 and CH_4 emitted through intermediate cover [m^3 m^{-2}]

Ac : total area of intermediate cover [m^2]

Sd : unit quantity of CO_2 and CH_4 emitted through dike [m^3 m^{-2}]

Ad : total area of dike [m^2]

Ss : unit quantity of CO_2 and CH_4 emitted through the landfill slope [m^3 m^{-2}]

As : total area of the slope [m^2]

t_{LFG} : landfill gas temperature at the measurement spot [^{o}C]

t_{atm} : atmospheric temperature [^{o}C]

TC_E : accumulated gaseous carbon emission quantity by time elapsed [t]

k : reaction constant [yr^{-1}]

t : number of elapsed years after landfill [yr]

Subscripts

j : type of waste

i : year of disposal

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