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MODELLING THE FATE ORGANIC MATTER IN MUNICIPAL SOLID WASTE LANDFILLS AFTER THE INSTALATION OF A FINAL CAPPING SYSTEM (CASE STUDY BREITENAU LANDFILL)

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SUMMARY: The study modelling to determine fate origin matter in old landfill is carried out by using a one-dimensional model. This study aimed to exam the apriority European directive on the landfill of waste which is mandatory the landfill operator to close old landfill site in order to prevent contamination surface and ground waters by leachate. To reach this objective, the Breitenau landfill was chosen as case of study. Result of this study shown implementing of European landfill directive will not extend the maintenance period, particularly for Breitenau landfill was built special as an experimental landfill site which is filled with selected municipals solid waste. Results of this study offer grate challenge to measure the conventional landfill.

1. INTRODUCTION

The European community's coming into new century of waste management practice by establishment landfill directive on April 26, 1999 (Council Directive 1999/31/EC). This directive was mandatory to states of European Union (EU) to reduce content of biodegradable matter in municipal solid waste going to landfill by 2006, 2009 and 2016 should be less than 75, 50, and 35% of total amount of biodegradable matter produced by 1995, respectively. This directive also required for EU states to cover old existing landfill in order to prevent contamination surface and ground waters by leachate and control water precipitation entering into landfill body. This directive was most crucial policy since sanitary landfill is still the most common method use for solid waste produced from household and non-hazardous industrial waste around the world at the present time and the near future. Nevertheless, controlling water precipitation entering into landfill body may can prevent surface and underground water from contaminate by leachate, but on the other hand this method also can reduce the degradation rate of organic carbon in the landfill body may cause to extending landfill management after post-closure, especially if there is no improvement carryout after covering of landfill.

The objective of this study is to estimate the fate organic matter in old landfill, and comparing the maintenance period is required in both conditions, closing the landfill surface

without and with impermeable cover as mandatory by landfill directive. To reach this objective, a one-dimensional model of the biodegradation organic matter was developed. The model is designed able to switch the biodegradation process from aerobic to anaerobic ways and vice versa depending on the oxygen concentration. The model also included the influences environmental factors on reaction rate, such as atmospheric temperature and water precipitation. In addition, a data of pull-scale landfill is use to validated model estimation results during landfill operation and after post closure. The extending of maintenance period due to capping landfill surface with impermeable cover were estimate and comparing based on the fate organic matter inside landfill.

2. METHOD AND DATA

2.1 The Breitenau landfill

The Breitenau landfill located about 60 km from Vienna city, the capital of Austria. This landfill was specially built as an experimental site for Vienna University of Technology. The construction of the landfill was built at a former gravel mining site which was started from in 1987. Between 1987 and 1988, around 95,000 tons of MSW were disposed onto this landfill and compacted to a wet waste density of approximately 1200 kg/m^3. As the experimental site, initially the Breitenau landfill consists of three separate compartments with different covers and baseliner systems one with others (see **Figure 1**). However, by middle of 2010 the cover of all cells was sealed with impermeable sheet in order to fulfil the landfill directive requirement.

Figure 1. The Breitenau an experimental landfill of Vienna University of Technology

This landfill was chosen for the study presented due to waste was disposed onto this site only household waste which is the composition waste are known, and the landfill emissions have been continuously analyzed over a period of more than 17 years, particularly leachate emissions. The leachate discharges of each compartment are collected separately and measured by inductive

flow meters. Leachate composition (pH, electric conductivity, TOC, COD, NH_4, TKN, NO_3, NO_2, SO_4, Na, and Cl) was analyzed from 1987 until May 2005. A series data presented and use to compare model calculation results were derived from compartment I, where around 35,000 tons of MSW were landfilled onto this compartment during landfill construction (Fellner et al, 2004).

The most important information is required for modelling biodegradation organic matter in landfill site is the environmental data, such as atmospheric temperature and water precipitation. The atmospheric temperature and water precipitation data from over than 17 year were collected and used as data entry of the models.

2.2 Model analogy and assumptions

In chemical processing, contact between phases to separate a compound of mixed compound (e.g. absorption, extraction, leaching, etc) or to react two or more compound to produce different compounds (e.g. catalytic reaction), are apply in many processes. These processes involve mass transfer followed with chemical reaction. The mass transfer occurs through intimate contact between the phases. In some cases, the contact between gas–liquid or liquid–liquid phases is enhanced by presence of the solid phase, so called as support media or packed-bed. The hydro-cracking of heavy petroleum feedstock in counter current fixed-bed reactor by using zeolite based catalyst (Penick, 1985) is an example of how sophisticated technology can be developed from simple analogy of the interaction between phases.

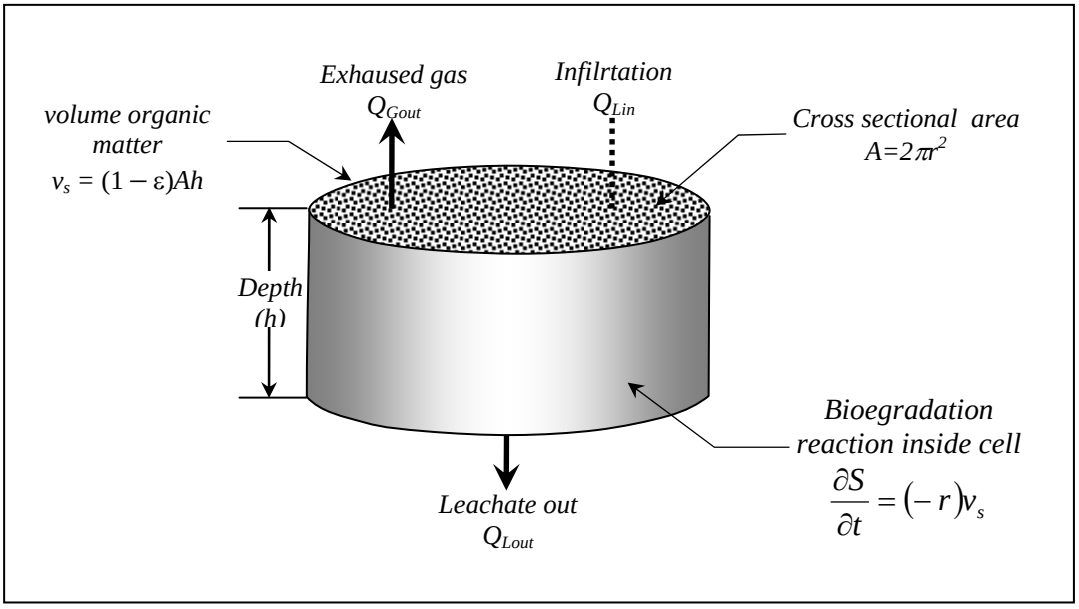

Figure 2. Schematic diagram of a landfill cell and its incoming and out flow steams.

In this study we analogue the unit cell of landfilled as one stage of packed-bed reactor. A unit cell of landfill can be defined as a system which consists of three phases, where the two phase's gas and liquid are flowing in counter current direction, and the rest is solid phase in fixed state. The flow into and out of the system were divided into three streams, where two streams represent water infiltration into the waste bulk inside landfill and leachate discharge out of landfill site, and one stream is represent landfill gas exhausted out of landfill site. During this process the biodegradation organic matters occur due to intimately contact between the phases including diffusion and/or redistribute of all components involved the system. There is no water infiltrate into waste bulk inside the landfill is assumed after landfill capped with impermeable

seal. This process can be described schematically as shown in **Figure 2**.

2.2.1 Model Description

A one-dimensional model used in this study is to represent a unit cell of landfill. This model is an extension compartment model developed by Kim et al (2007), but in this study the biodegradation process is influenced by environmental factor such as atmospheric temperature and water precipitation. For this purpose, a series environmental data were collected and used in modelling process. This model was chosen due to its flexibility to involve the influence atmospheric conditions, such as temperature and precipitation onto the biodegradation process in landfill. This model also still can improve to involve the effect of the aeration rate onto biodegradation process for simulation biodegradation organic matter of landfill equipped with aerobification.

A unit cell of landfill consists of gas, liquid, and solid organic phases. The solid phase is distinguished onto organic solid, inorganic, and biomass matters. Future more, the organic solid is divides into three categories according to its biodegradability, namely easily degradable organic matter, slowly biodegradable organic matter, and non-degradable. The empirical formulas of easily and slowly degradable organic matter were described as $C_nH_aO_bN_c$ and $(C_6H_{10}O_5)_n$, respectively. The easily degradable organic matter is represented of simple carbohydrate, protein, and fats. The value of subscript n, a, b, and c of each these organic matter were determined based on typical carbohydrate, protein, and fats contain in Viennese household waste. In similar method was used to determine the value of subscript n of slowly degradable organic matter. For non-degradable solid waste consist of ash, minerals, synthetic fibre, metal, etc. While, the empirical formula of biomass is describes as $C_5H_7O_2N$ (McCarty, 1972). The typical waste composition and easily, slowly, and non-degradable fraction of Viennese household presented in **Table 1**.

Table 1. Typical Viennese municipal solid waste composition distinguished by its degradability group (Neumayer, 1999)

Waste Composition	Fraction (% dry basis)	Degradability group	Composition (% dry basis)
Paper and cardboard	14.7	Easily degradable	1.6
		Slowly degradable	61.3
		Non-degradable	37.1
Biogenic waste (including kitchen and garden waste)	20.7	Easily degradable	54.9
		Slowly degradable	35.3
		Non-degradable	9.9
Plastic	12.7	Non-degradable	99.9
Food packaging	15.8	Easily degradable	1.2
		Slowly degradable	46.1
		Non-degradable	52.9
Textile and Rubber	4.3	Easily degradable	5.1
		Slowly degradable	52
		Non-degradable	45
Wood	1.3	Easily degradable	10.1
		Slowly degradable	89
		Non-degradable	0.9
Glass	5.9	Non-degradable	100.0
Metal	6.0	Non-degradable	100.0
Residual waste	18.7	Non-degradable	100.0
Total	100.0		

In this model the oxygen content designed to is played an important role on biodegradation

organic matter. The easily- and slowly-degradable organic matter will be degraded by aerobically or anaerobically is depend on the partial pressure of oxygen. In condition the partial oxygen pressure higher than 100 Pa, the biodegradation of organic matter will occurs by aerobically, whereas if the partial oxygen pressure below than 100 Pa the biodegradation of organic matter will switch to be anaerobically.

The biodegradation pathway of organic matters inside landfill site is assumed occurs into two steps. The first stage is combination of hydrolysis and acetogenesis of organic matter. In this stage, the organic matter is converted to be intermediate product, such as CH_3COOH, H_2, NH_3 and NO_3. The second stage is oxidation and/or methanogenesis of intermediate product to be final product such as CO_2, N_2, and CH_4. A partly of intermediate product (H_2, NH_3, and NO_3) are subsequently converted into final product under either aerobic or anaerobic conditions, while the CH_3COOH can be transformed in both aerobic and anaerobic conditions. In aerobic condition CH_3COOH will be oxidize to CO_2 and H_2O, otherwise it converted to be CH_4 by methanogeneic way. The amount bacteria will growth during biodegradation process, however part of them will self decay and degraded in similar way like MSW organic matter. The rate self decay of bacteria is assumed 0.05 times of maximum specific growth rate.

2.2.2 Mass Balance Equation

The mass balance equation of easily- and slowly-degradable solid organic matter in landfill system can describe in below equations:

$$\frac{dS}{dt} = \sum \left(-r_{s,i}\right) v_{s,i} \tag{1}$$

where dS is the time variation organic matter change (kg/day); $r_{s,i}$ is disappearance rate of easily- and slowly-degradable organic matter by reaction (kg/day-m^3); and $v_{s,i}$ is volume easily- and slowly-degradable organic matter in landfill cell (m^3).

The partial pressure gas component resulted of biodegradation organic matter is determined in similar method. The time derivative of gas component is equal to summation of outflow fraction and gas resulted by biodegradation organic matter. In mathematical form, the derivative partial pressure gas component is describes in below equation:

$$\frac{v_g}{RT}\left(\frac{dP_i}{dt}\right) = \sum \left(r_{g,i}\right) - Q_{GOut}\left(\frac{P_i}{RT}\right) \tag{2}$$

where v_g is volume of gas equal to pore fraction in landfill cell (m^3); R is the universal gas constant (m^3 Pa/kmol K), T is the cell temperature (K); P_i is partial pressure *i-th* gas component inside landfill cell (pa); $r_{g,i}$ is *i-th* gas constituent resulted from organic solid decomposition (kg/day-m^3); and Q_{gOut} is volumetric landfill gas discharge from cell (m^3/d). For liquid phase, the concentration of liquid is assumed homogenous in whole landfill part. The mass balance of each liquid constituent in liquid phase is in below equation:

$$v_L\left(\frac{dC_i}{dt}\right) = \sum \left(r_{l,i}\right) - Q_{LOut} C_i \tag{3}$$

where v_L is the volume of liquid phase (m^3); C_i is concentration of *i*-th constituents in liquid phase (kg/m^3), $r_{l,i}$ is *i-th* liquid constituent resulted from organic solid decomposition (kg/day-m^3); and Q_{LOut} is volumetric of leachate dischrage of cell (m^3/d). For the biomass, the time derivative of biomass concentration is equal to summation biomass growth and self decay. In mathematical form, the derivative biomass concentration is describes in below equation:

$$\frac{dx}{dt} = \sum \left(R_{G,i} - R_{D,i} \right) \tag{4}$$

where dx is is the time variation biomass change (kg/m^3); and $R_{G,i}$ and $R_{D,i}$ are represent rate biomass growth and self decay of easily- and slowly-degradable organic matter (kg/m^3 day).

2.2.3 Biodegradation Pathway

The biodegradation of organic matter, multiplication and self-decay of microorganisms, and decomposition of intermediate product derived by partial oxygen, as shown in Figure 3. In total, 21 pathway of biodegradation organic matter may occurs. For example, if the oxygen partial pressure exceeds 0.001 MPa, the biodegradable organic matter and self-decayed biomass will degradate by aerobically. Partly of CH_3COOH will oxidized to be CO_2 and H_2O, and nitrifier bacteria will involve to convert NH_4-N to be NO_3 and NO_2. On the other hand, if the partial pressure oxygen less than 0.001 MPa, the biodegradation biodegradable organic matter and self-decayed biomass will degradate by anaerobically, and methanogenic bacteria will take place to convert CH_3COOH to be methane.

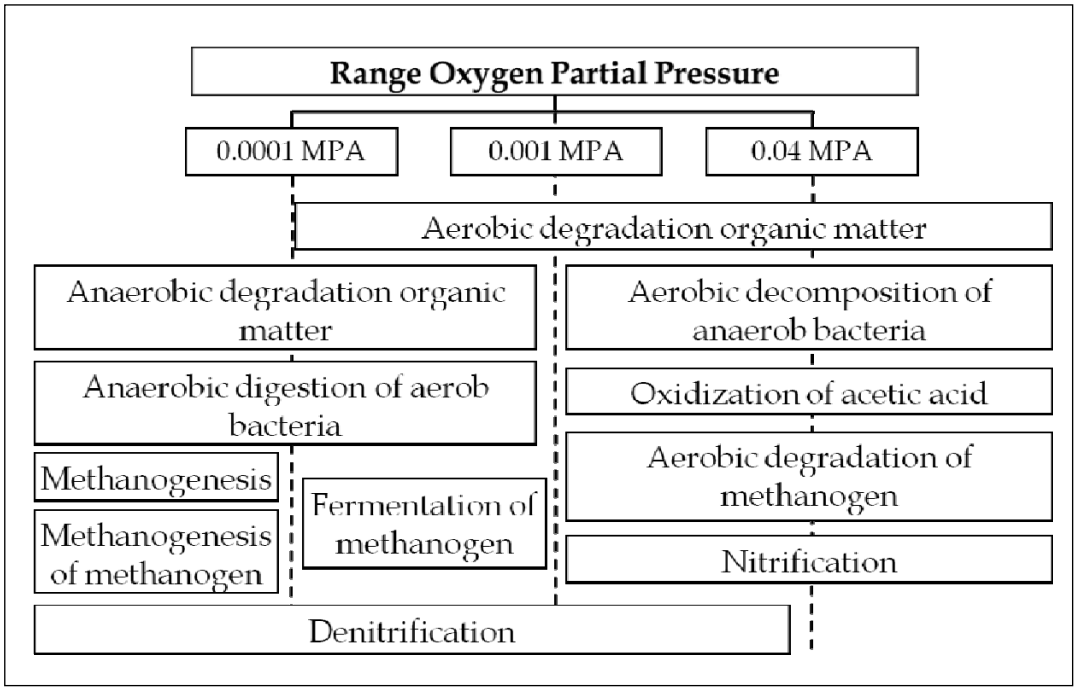

Figure 3 Biodegradation pathway of organic matter (Tojo, unpublished report)

3. RESULTS AND DISCUSSION

Since the Breitenau landfill was operated in very short period (from 1997 till 1998), the biodegradation of organic matter in landfill site is assumed occurs only by anaerobic way. This assumption was made based on fact that the oxygen capability to diffuse into compacted solid waste is declined significantly by compaction load. In case of Breitenau landfill the municipal solid waste was compacted to a wet density up to 1200 kg/m^3.

3.1 Leachate Quality

Leachate quality is the most important parameter to estimate the landfill emission and its impact to the environment. Behind landfill gases which contribute for approximately 5% of global greenhouse gas emission (IPCC, 2006), leachate emission is the main reason for the European commission to established landfill directive.

Figure 4 is presents the important parameter of leachate resulted from model calculation, pH, COD and total nitrogen. From this figure we can see that the concentration of COD and total nitrogen in leachate is increase exponentially in the beginning landfill operation. The peak COD concentration is around 27,000 mg/L was achieved after 1000 days landfill operate, while the high concentration total nitrogen is around 1200 mg/L was achieved between 1000 to 2000 days after landfill operated.

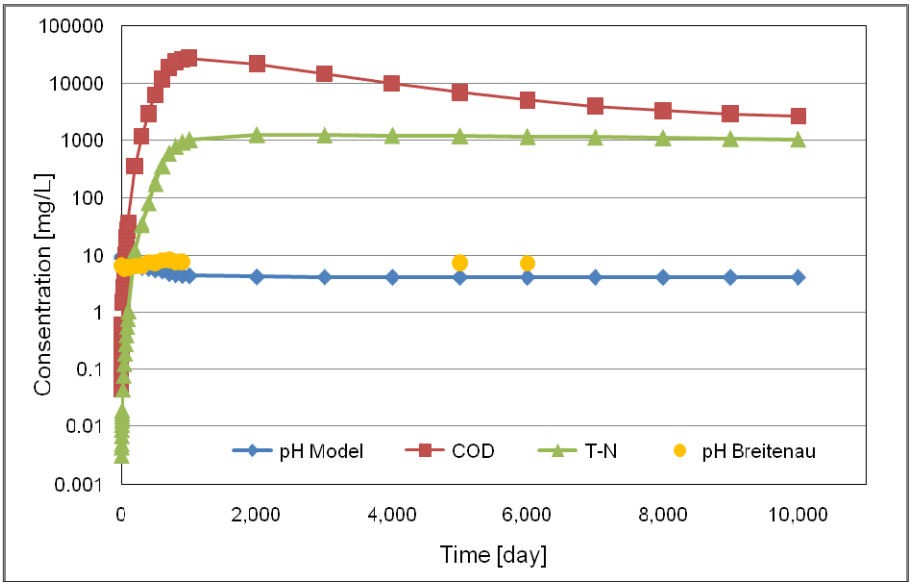

Figure 4 Model calculation results of some parameter and measuring data of Breitenau landfill

Figure 4 we can also see the comparison between pH model calculation and measure from Breitenau landfill. The highest pH value of model calculation was around 9.7. This figure much higher compare to the initial set-up and measure results. The initial set-up of pH used in the model was 7, but its increasing immediately in the beginning biodegradation process. Afterward the pH of leachate gradually decreases up to 4.2. This may caused by increasing concentration acetic acid which is produce as intermediate product of organic matter degradation.

The range pH model calculation was little bit wide compare to the measuring results which is in range between 5.9 up to 8.2. Another differences is the measure pH increase from the beginning until two year landfill operation, then decrease gradually without a very high increase in short duration. However, this data cannot be used as absolute reference since the available data was very limited and the data collection was conducted in irregular period.

3.2 The Landfill Gas Composition

The biogas resulted from biodegradation organic matter inside landfill also considered in this study. The gas type was consider consist of CO_2, CH_4, O_2, N_2, H_2, and other gas distinguished as trace. Figure 5 shows the concentration gas produced of biodegradation organic matter by gas type in period 1000 days. As noted, the model calculations results cannot comparing to the landfill emission due to neither gas production rate nor composition data collected during the Breitenau landfill operation.

As mentioned in the previous section, due to very short period landfill operation and low ability oxygen infiltrate into waste, the biodegradation of organic matters is assumed occurs only by anaerobic way. Therefore, CO_2 and CH_4 are expected as the main composition of landfill gas. The simulation results shows that the main concentration of landfill gas in the beginning biodegradation organic matter is CO_2, it can believed since the main product of easily-degradable organic matter are short-chain fatty acid and CO_2. CO_2 also produced during anaerobic oxidation of soluble carbohydrate in absence of methanogenic bacteria (Weolin, 1979; Weoline, 1982).

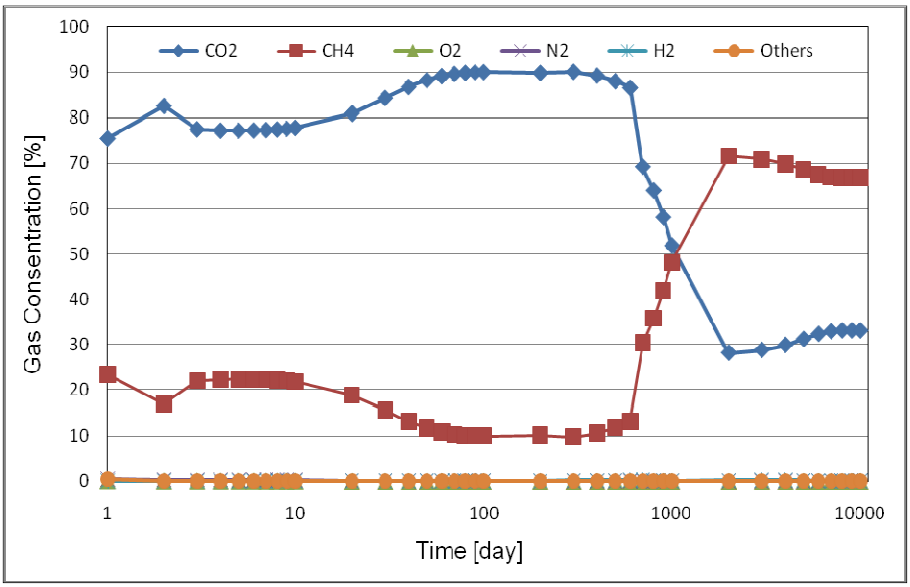

Figure 5 Consentration of landfill gas

The CO_2 concentration later on decline significantly after reached the peak in the second year landfill operation. On the hands, the CH_4 concentration increasing almost two fold in period second until third year landfill operation. During this period could be the optimum condition for methanogenic bacteria, where almost easily-degradable organic matters have been converted to be intermediate product which the essential substrate is required for methane formation.

3.3 The Fate Organic Matters

This sub-section is dealing with the fate organic matter inside the landfill body after certain time biodegradation process. This sub-section become important since the key point of this study is to criticize the European waste management directive which is mandatory to the states members to seal the old landfill by impermeable cover. As mentioned in previous section, this directive become crucial policy since sanitary landfill is still the most common method for handling solid waste produced from household and non-hazardous industrial waste around the world at the present time and the near future.

As initial assessment, the rest organic matters inside compartment I of Breitenau landfill were estimate in this study. This landfill was specially built as an experimental site for Vienna University of Technology by 1987. This landfill also requires sealing its surface with impermeable cover in order to fulfil the landfill directive. Since the purpose of this landfill as an experimental site, the waste was landfilled onto landfill site only household waste which is the composition of waste dominantly degradable organic matters. Therefore, this landfill can be good example to know whether the landfill directive is appropriate rule if not followed with any improvement. Other ways, implement this directive would be sending the waste management

problem to the future generation.

The Breitenau landfill was sealed with impermeable cover by middle of 2010 after around 17 post closures. Since the water can infiltrate into waste bulk inside landfill, it is believed the biodegradation organic matters still occurs during this period. However, because of its heterogeneity and the complexities organic matter the biodegradation is running in very slow rate. Figure 6 present the model calculation results of easily- and slowly-biodegradable organic matter inside Breitenau landfill.

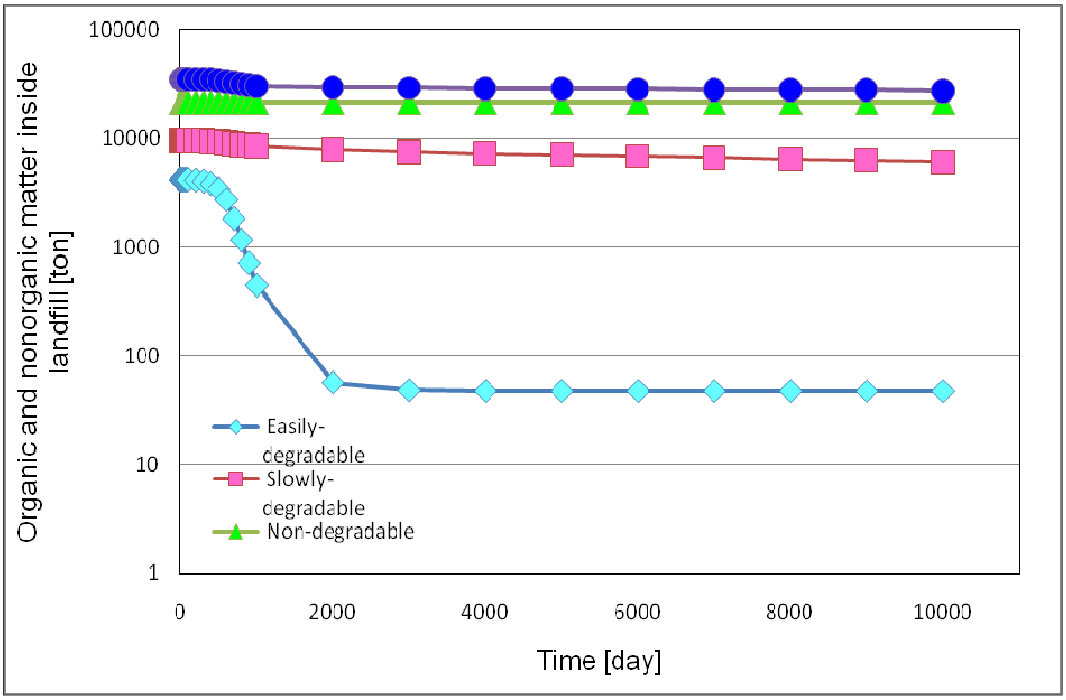

Figure 6 Concentration the fate easily- and slowly-degradbale organic matter over time simulation period

The model calculation results shows the easily-degradable organic matter was degraded rapidly in the beginning until the third year landfill operation. Almost 90% of easily-degradable organics matter was degraded during this period. After this period, the biodegradation rate of organic matter was very slow. In average the biodegradation organic matter was run at rate around 1% per year. In term of slowly-degradable organic matter, the biodegradation rate was run in quite stable during whole time. The biodegradation rate was run at rate less than 1% per year. Comparing with other cellulose degradation study have been reported, this figure are in range degradation rate of cellulose pulps under fully controlled condition (Mitcheel, 1951; Ding and Wang, 2008). Moreover, results of this study also shows that the implement landfill directive to the old landfill after 17 years post closure will not will not extend the maintenance period. It can believe since almost easily organic matter already degraded during operation and post-closure. Based on the model calculation results for 25 years biodegradation period, the amount of easily- and slowly-degradable inside Breitenau landfill will not exceed than 1% compare to amount of easily- and slowly-degradable without sealed by impermeable covers.

5. CONCLUSIONS

One-dimensional models have been developed for estimate the fate of organic matter inside

landfill after post closure. The simulation was carried out for 25 years biodegradation process. The simulation conducted under anaerobic condition. A model calculation result was validated with the available data. Although the validated can be done only part of landfill parameter, the simulation results are close to actual condition. For instant, the pH simulation result is comparable to the measured. Simulation also addressed to estimate the extending maintenance period due to implementation European directive on waste management. Results of this study shows the seal landfill surface with impermeable cover will not extend the maintenance period, particularly for Breitenau landfill which is special landfill was built for experimental purposes.

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