

(38) TREATMENT OF THICKENED EXCESS SEWAGE SLUDGE BY THERMOPHILIC OXIC PROCESS

高温・好気法を用いた濃縮余剰汚泥の処理

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ABSTRACT; Thermophilic Oxidic Process (TOP) can be applied to the treatment of highly concentrated organic wastewater. Organic matter in the wastewater is almost completely decomposed and all water of influent is evaporated by this process. In this paper, TOP was applied to the treatment of thickened excess sewage sludge. Caloricity of this sludge is not enough to evaporate all water in this sludge. Therefore, waste food oil was added to increase the caloricity for the acceleration of microbial activity and evaporation of water. The optimum operational conditions were investigated using a 20 l of reactor and cedar chips as a medium. When the mixing ratio of oil to sludge was 12% (w/w, BOD₅ concentration of mixture was 157,000 mg·l⁻¹), BOD₅ load was 6.6 kg·m⁻³·d⁻¹, moisture content of medium ranged from 50% to 60%, and aeration rate was 200 l·m⁻³·min⁻¹, temperature of medium increased to approximately 60°C, organic matter in the sludge was almost completely mineralized to CO₂ and all water in the sludge was evaporated. A minute amount of excess sludge was formed in this process.

KEYWORDS; Thickened excess sewage sludge, Waste food oil, Thermophilic Oxidic Process.

1. Introduction

In these ten years, many small sewage treatment plants have been built in rural areas of Japan¹⁾. Therefore, a lot of thickened excess sewage sludge is produced in these areas. It is necessary to develop the simple and low cost system for the treatment of this sludge. Thermophilic Oxidic Process (TOP) can almost completely treat highly concentrated organic wastewater. When air was introduced into the medium mixed with wastewater from the bottom of the reactor, the temperature of the medium rose to 50 - 65°C. Organic matter was decomposed to CO₂ and water. All water of influent was evaporated by heat which was generated during the degradation of organic matter. Higher than 90% of the input carbon was converted to CO₂ and resulted in a minute amount of excess sludge. The higher the organic matter concentration in wastewater was, the more the heat was generated and the higher the treatment efficiency could be obtained^{2,4)}. In this research, TOP was applied to the treatment of thickened excess sewage sludge. Caloricity of this sludge is not enough to evaporate all water in this sludge. Therefore, waste food oil was added to increase the caloricity for the acceleration of microbial activity and evaporation of water. Using waste food oil as the thermal energy, high temperature can be kept, high decomposition efficiency of

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organic matter also can be obtained, and all water in the sludge can be evaporated. The objectives of this research were to investigate the possibility of the treatment of thickened excess sewage sludge using TOP by addition of waste food oil and to study the optimum operational conditions, such as oil addition rate, aeration rate and BOD_5 load, etc.

2. Materials and Methods

2.1 Materials

Three materials were used in this research. The one was thickened excess sewage sludge, which was sampled from Shinzikotoubu Sewage Treatment Plant. The average concentration of TS, VS, BOD_5 , Lu (ultimate BOD) and TOC are 3.3%, 77%, $12,400 \text{ mg} \cdot \text{l}^{-1}$, $17,670 \text{ mg} \cdot \text{l}^{-1}$ and $13,000 \text{ mg} \cdot \text{l}^{-1}$, respectively. The other was waste food oil. It was taken from a restaurant of Shimane University. The concentration of BOD_5 , Lu and TOC are $1,365,000 \text{ mg} \cdot \text{kg}^{-1}$, $1,897,000 \text{ mg} \cdot \text{kg}^{-1}$ and $760,000 \text{ mg} \cdot \text{kg}^{-1}$, respectively. Cedar chips were used as a medium, the average size of it ranged from 1 to 3 mm.

2.2 Apparatus

Experimental apparatus is shown in Fig. 1. The reactor was a 20 l plastic cylindrical container, surrounded by styrofoam insulation. Cedar chips of which moisture content was adjusted to approximately 50% were put in the reactor (dry weight of cedar chips was 2.5 kg). It was because that in the thermophilic oxic process, the suitable moisture content of medium ranged from 40 to 65%⁵⁾. Air was supplied by using an air pump, and aeration rate was controlled by an air valve and monitored by an air flow meter. A perforated plastic plate was placed at the bottom of the reactor to support the medium and distribute air. Temperature was determined using a thermocouple that was inserted into the medium, monitored by a computer and recorded by a recorder. The reactor was placed on a scale to measure the changes of weight of medium.

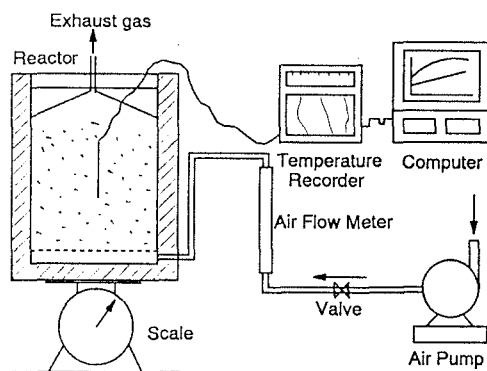


Fig.1 Schematic diagram of experimental apparatus

2.3 Operational conditions

Different aeration rates and oil addition rates were tested in order to find the optimum operational conditions. Aeration rates ranged from 50 to $500 \text{ l} \cdot \text{m}^{-3} \cdot \text{min}^{-1}$. Oil addition rates ranged from 1.25 to $7.5 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$. In order to keep the moisture content of the medium stable, the weight of sludge added was changed depending upon the weight of medium decreased during the reaction. The waste food oil and sludge were added every other day before the temperature decreased to lower than 45°C . After adding the oil and sludge into the reactor, they were completely mixed with medium by hand, and next period of reaction was conducted. Every operational condition was conducted for 14 days (7 periods), and the average data were taken.

2.4 Analysis

TS of thickened excess sewage sludge was measured according to the methods of sewage test⁶⁾. The samples of thickened excess sewage sludge and waste food oil for the analysis of BOD₅, Lu and TOC were pretreated as following: the samples were diluted from 10 to 50 times in the homogenizer cup and dispersed at 10,000 rpm for 10 minutes using a homogenizer (HM-/OSA NIPPON RIKAGAKU KIKAI, CO., LTD). After the pretreatment, BOD₅ and Lu were determined by a BOD tester (BOD TESTER, 200F, TAIYO SCIENCE OF INDUSTRY, LTD). TOC was measured by a TOC analyzer (TOC-5000, SHIMADZU CORPORATION). Moisture content of medium was determined by weight difference before and after drying at 105°C for 12 hours⁷⁾. Determination of concentration of CO₂ in the exhaust gas was carried out by glass tube detector (GASTEC Company). Oil content in the medium was determined by the method of hexane extracts⁶⁾. Total carbon (T-C) and nitrogen (T-N) in the medium were determined by C-N analyzer (SUMIGRAPH NC-90A, SUMIKA CHEMICAL ANALYSIS SERVICE LTD). Contents of P, K, Cu, Zn, As, Cd and Hg in the medium were analyzed by inductively coupled plasma emission spectroscopy (MULTI-SPECTROMETER, ICPS-2000, SHIMADZU CORPORATION) after the samples were wet digested with concentrated HNO₃ + HClO₄⁷⁾. Electrical conductivity (EC) of the medium were measured by electrical conductivity meter (CM-40S, TOA ELECTRONICS, LTD) in the 1:10 water extract. Ammonium ion (NH₄-N) in the medium was analyzed according to the standard methods for soil analyses and determination⁷⁾.

3. Results and Discussion

3.1 Amounts of sludge treated

The effects of aeration rate on temperature and amounts of sludge treated are shown in Fig. 2. As the aeration rate was increased, the temperature of the medium kept at approximately 60°C in the initial and then decreased. The amounts of sludge treated increased, reached the maximum and then decreased in each oil addition rate. This means that high temperature was kept at low aeration rate because heat loss caused by aeration was low. The amounts of sludge treated did not reach high because water vapor taken out by aeration from the medium was low. Conversely, if the aeration rate was high, heat loss caused by aeration was high and high temperature was not kept,

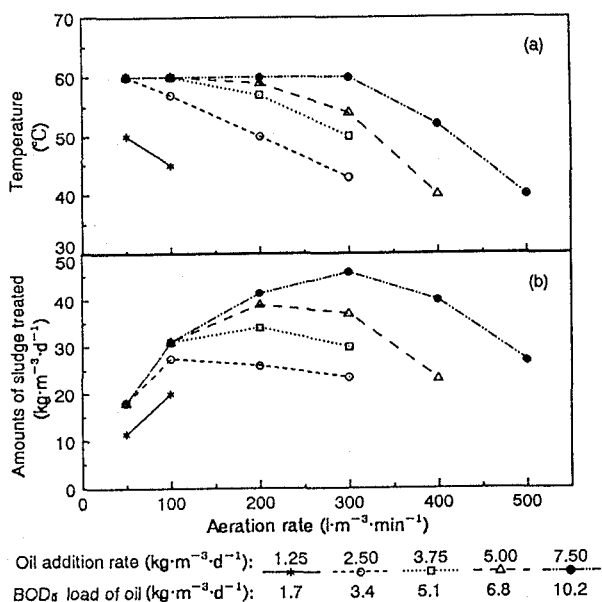


Fig. 2 Effects of aeration rate on temperature (a) and amounts of sludge treated (b)

water evaporated was low and the amounts of sludge treated did not reach high. From Fig. 2, it also can

be seen that with increasing oil addition rate, the maximum amount of sludge treated increased and the optimum aeration rate was also increased. This means that in each oil addition rate, there has an optimum aeration rate which can keep high temperature and the maximum amount of sludge treated.

Fig. 3 shows the effects of mixing ratio of oil to sludge (BOD_5 concentration of mixture) on temperature and amounts of sludge treated. In each fixed aeration rate, with increasing the mixing ratio of oil to sludge, the temperature rose and then became stable at approximately 60°C , and the amount of sludge treated also increased and then became stable. This result indicates that the water vapor taken out by aeration from the medium was limited by aeration rate. This stable value of sludge treated was the maximum

amount of sludge treated in this fixed aeration rate. At the fixed mixing ratio of oil to sludge, the temperature kept at approximately 60°C in the initial and then became decrease with increasing the aeration rate. Meanwhile, the amounts of sludge treated increased, reached the maximum and then decreased. This means that in each mixing ratio of oil to sludge, there had a corresponding optimum aeration rate to get high temperature and the maximum amounts of sludge treatment capacity. In other words, the higher the mixing ratio of oil to sludge (BOD_5 concentration) was, the more the heat was generated and the higher the amounts of sludge treated could be gotten under the suitable aeration rate. Therefore, to reach the maximum amount of sludge treated, the mixing ratio of oil to sludge must be increased and the aeration rate must be adjusted. But, increasing the mixing ratio of oil to sludge is costly.

In order to find the optimum mixing ratio of oil to sludge, each points of the maximum amount of sludge treated in each mixing ratios of oil and sludge were be linked and a new curve was drawn on Fig. 3 (b). The slope of this curve was high before point A and then became low after point A. This means that the amounts of sludge treated increased rapidly in the initial and then increased slowly with increasing the mixing ratio of oil to sludge. This result indicates that point A was the optimum operational condition. The mixing ratio of oil to sludge of point A was 12% (BOD_5 concentration was $157,000\text{ mg}\cdot\text{l}^{-1}$), oil addition rate was $4.44\text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$, amounts of sludge treated was $37.00\text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ (BOD_5 load was $6.6\text{ kg}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$) and aeration rate was $200\text{ l}\cdot\text{m}^{-3}\cdot\text{min}^{-1}$. Temperature reached approximately 60°C . Oil and sludge added were almost completely treated.

It is possible to use this treatment process for small sewage treatment plant. For example: in the treatment capacity of $1,000\text{ m}^3\cdot\text{d}^{-1}$ sewage treatment plant, the weight of thickened excess sludge

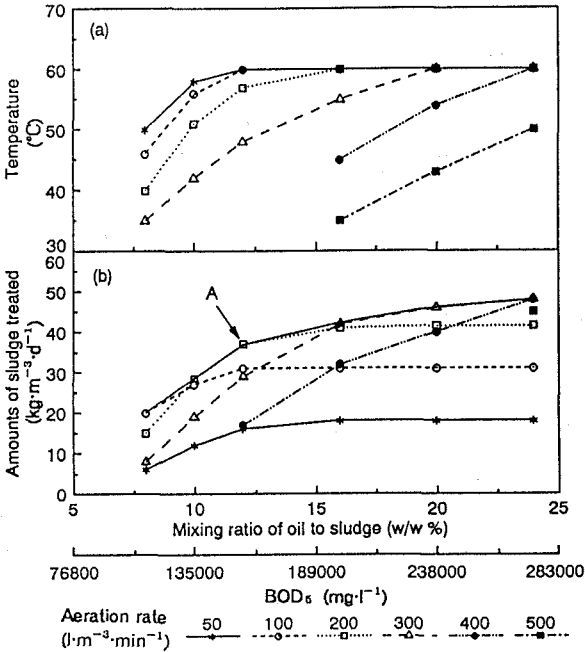


Fig. 3 Effects of mixing ratio of oil to sludge on temperature (a) and amounts of sludge treated (b)

produced was approximately $4,000 \text{ kg} \cdot \text{d}^{-1}$, at the 3% of TS. Waste oil needed was approximately $480 \text{ kg} \cdot \text{d}^{-1}$. It only need approximately 120 m^3 volume of reactor for the treatment of this amount of sludge.

3.2 Changes in temperature and weight

Fig. 4 shows the changes in temperature and total weight of medium during one period (two days) of reaction under the optimum operational condition ($n = 7$). Before adding oil and sludge, total weight of medium was 5.0 kg and temperature was 45°C . After adding the oil and sludge and mixed them with medium, total weight of medium increased to 6.66 kg and the temperature decreased to 30°C . When new period of reaction was started, the temperature increased from 30°C to 60°C during the first 10 hours, kept at approximately 60°C for 20 hours, and then decreased to 45°C at the 48 hours. Total weight of medium was returned to 5.0 kg . 1.66 kg of sludge and oil added was almost completely treated during one period of reaction.

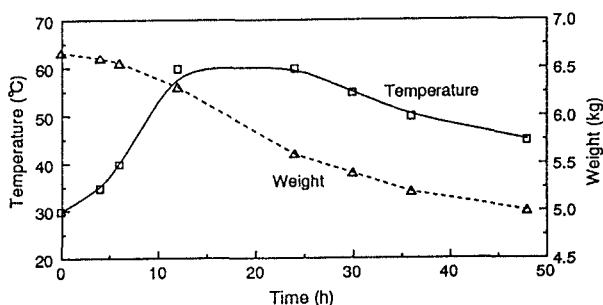


Fig. 4 Changes in temperature and total weight of medium during one period of reaction

Mixing rate of oil to sludge: 12% (BOD_5 : $157,000 \text{ mg} \cdot \text{l}^{-1}$). Oil and sludge addition rates: 4.44 and $37.00 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$ (0.18 and $1.48 \text{ kg} \cdot 2\text{d}^{-1}$, BOD_5 load: $6.6 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$). Aeration rate: $200 \text{ l} \cdot \text{m}^{-3} \cdot \text{min}^{-1}$.

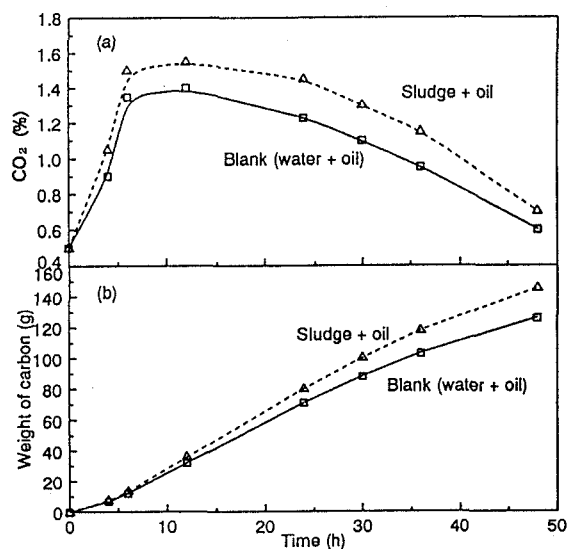


Fig. 5 Changes in CO_2 concentration and cumulative weight of carbon in exhaust gas during one period of reaction

Mixing rate of oil to sludge: 12% (BOD_5 : $157,000 \text{ mg} \cdot \text{l}^{-1}$). Oil and sludge addition rates: 4.44 and $37.00 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$ (0.18 and $1.48 \text{ kg} \cdot 2\text{d}^{-1}$, BOD_5 load: $6.6 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$). Aeration rate: $200 \text{ l} \cdot \text{m}^{-3} \cdot \text{min}^{-1}$.

3.3 Carbon balance

During one period of reaction, the changes of CO_2 concentration and cumulative weight of carbon in exhaust gas are shown in Fig. 5 ($n = 7$). The oil addition rate was same in both of tests and blank was using water instead of sludge. Although the same quantities of CO_2 were generated in both of tests during the decomposition of oil process, CO_2 concentration in exhaust gas was higher when using oil and sludge than blank (shown in Fig. 5 (a)). This means that the difference of CO_2 concentration in exhaust gas between two tests was caused by decomposition of sludge. Using the data of CO_2 concentration in exhaust gas, total weight of cumulative carbon evolved in exhaust gas was calculated. Fig. 5 (b) shows the changes of cumulative weight of carbon in exhaust gas during one period of reaction. The difference of cumulative weight of carbon evolved in exhaust gas between sludge and blank was approximately 19.00 g in one period of reaction. The weight of TOC added was 19.24 g in

1.48 kg of sludge. This result indicates that the organic carbon in the sludge was almost completely decomposed (98.8%).

3.4 Thermal balance

During biological reaction process, organic matter was decomposed and heat was generated. Water in the thickened excess sewage sludge was evaporated by this heat. It is necessary to investigate thermal balance in the process of the treatment of this thickened excess sewage sludge. In this research, thermal balance was investigated under the optimum operational condition that was gotten in the before. During one period of reaction, the thermal balance was described by the following equation⁸⁾:

$$q_r = q_a + q_w + q_l + q_s \tag{1}$$

- q_r ——— Heat generated by the decomposition of organic matter;
- q_a ——— Sensible heat removed by aeration;
- q_w ——— Latent heat removed by evaporation of water;
- q_l ——— Heat loss from wall of the reactor;
- q_s ——— Sensible heat change of oil and sludge added.

where q_r can be calculated as

$$q_r = Q_o(Lu_oW_o + Lu_sV_s) \tag{2}$$

where Q_o is the amount of heat generated per kg of oxygen consumed. The value of Q_o was taken as 3,300 kcal·kg-O₂⁻¹⁹⁾. Lu_o and Lu_s are the ultimate BOD of oil and sludge. W_o and V_s are the weight of oil and volume of sludge added.

The term q_a can be calculated as

$$q_a = C_aV_a(T_{out} - T_{in}) \tag{3}$$

where C_a is the average specific heat of air. V_a is the total volume of air supplied by aeration. T_{out} and T_{in} are the average temperatures of exhaust gas and atmosphere. The value of T_{out} and T_{in} were taken as 50°C and 20°C, respectively.

The term q_w can be calculated as

$$q_w = Q_wW_w \tag{4}$$

where Q_w is the latent heat of evaporation of water. W_w is the weight of water evaporated during one period of reaction.

The term of q_l can be calculated as

$$q_l = 48(T - T_a) / [1/(\alpha_1A_1) + \delta_1/(\lambda_1A_{1,e}) + \delta_2/(\lambda_2A_{2,e}) + 1/(\alpha_2A_2)] \tag{5}$$

where T and T_a are the average temperatures of medium and atmosphere. The value of T and T_a were taken as 55°C and 20°C, respectively. A_1 and A_2 are the interfacial areas between medium and reactor wall and insulator and atmosphere, they were 0.42 m² and 2.27 m², respectively. $A_{1,e}$ and $A_{2,e}$ are the effective surface area of the reactor wall and insulator, they were 0.42 m² and 1.18 m², respectively. δ_1 and δ_2 are the mean thickness of reactor wall and insulator, they were 0.003 m and 0.2 m, respectively. λ_1 and λ_2 are thermal conductivity of reactor wall and insulator.

Table 1. Constants used for calculation

$Q_o = 3,300 \text{ kcal} \cdot \text{kg-O}_2^{-1} \text{ } ^9)$
$C_a = 0.33 \text{ kcal} \cdot \text{m}^{-3} \cdot \text{ } ^\circ\text{C}^{-1} \text{ } ^9)$
$Q_w = 566.3 \text{ kcal} \cdot \text{kg}^{-1} (55^\circ\text{C})$
$C_o = 0.6 \text{ kcal} \cdot \text{kg}^{-1} \cdot \text{ } ^\circ\text{C}^{-1}$
$C_w = 1.0 \text{ kcal} \cdot \text{kg}^{-1} \cdot \text{ } ^\circ\text{C}^{-1}$
$\alpha_1 = 1,000 \text{ kcal} \cdot \text{h}^{-1} \cdot \text{m}^{-2} \cdot \text{ } ^\circ\text{C}^{-1}$
$\alpha_2 = 25 \text{ kcal} \cdot \text{h}^{-1} \cdot \text{m}^{-2} \cdot \text{ } ^\circ\text{C}^{-1}$
$\lambda_1 = 0.95 \text{ kcal} \cdot \text{h}^{-1} \cdot \text{m}^{-1} \cdot \text{ } ^\circ\text{C}^{-1}$
$\lambda_2 = 0.025 \text{ kcal} \cdot \text{h}^{-1} \cdot \text{m}^{-1} \cdot \text{ } ^\circ\text{C}^{-1} \text{ } ^8)$

α_1 and α_2 are the heat transfer coefficients of medium and air.

The term of q_s can be calculated as

$q_s = (W_oC_o + W_sC_w)(T - T_s)$ (6)

where W_o and W_s ($W_s \doteq V_s$) were the weight of oil and sludge added, and C_o and C_w are their specific heats.

The constants used for the calculation are summarized in Table 1, and the results of calculation are shown in Table 2. It shows that the heat generated was nearly the same as the heat consumed. In other words, under the optimum operational condition, the thermal balance can be gotten, the organic matter in the wastewater can be almost completely decomposed and the water in the wastewater can be almost completely evaporated.

3.5 Changes in characteristics of medium

Fig. 6 illustrates the changes in weight and moisture content of the medium during the operation for 90 days. The operational conditions were the same as these of previous experiments. During the operation for 90 days, cumulative sludge and oil added was 74.7 kg. However, no drain occurred and the weight of medium was nearly unchanged. Moisture content of the medium had a little decreased because some indecomposable matter and a minute amount of excess sludge remained in the medium. The dry weight of excess sludge remained in the medium was approximately 0.6 kg. If the moisture content of medium was kept at approximately 60%, the weight of medium would increase from 6.66 to 7.7 kg.

The change of chemical compositions in medium is shown in Table 3 during the operation for 90 days. Total carbon in the medium was a little increased because the content of oil had a little increase. Total weight of oil added was 8.1 kg during 90 day's operation, and weight of oil remained in medium was 0.19

Table 2. Heat generated and consumed in one period (kcal)

Heat generated		Heat consumed				
q_r	q_a	q_w	q_l	q_s	total	
1215	114	810	244	50	1218	

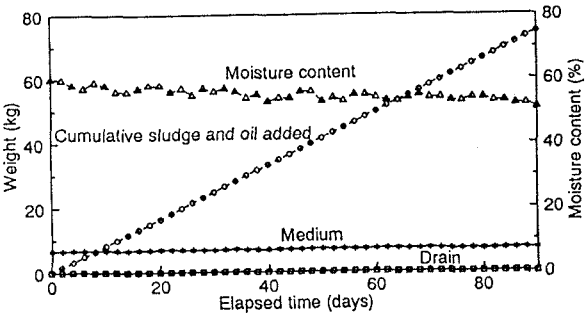


Fig. 6 Changes in weight of medium, drain, cumulative sludge and oil treated and moisture content for 3 month

Mixing rate of oil to sludge: 12% (BODs: 157,000 mg·l⁻¹). Oil and sludge addition rates: 4.44 and 37.00 kg·m⁻³·d⁻¹ (0.18 and 1.48 kg·2d⁻¹, BODs load: 6.6 kg·m⁻³·d⁻¹). Aeration rate: 200 l·m⁻³·min⁻¹.

Table 3. Changes of chemical compositions in medium during the operation for 90 days

Time	Oil	C	N	P	K	Cu	Zn	As	Cd	Hg	NH ₄ -N	EC
(days)		(g·kg ⁻¹)					(mg·kg ⁻¹)					(dSm ⁻¹)
0	0	491	11.6	4.3	3.5	24.9	85	1.5	0.20	0.28	310	0.223
30	50	529	13.6	6.2	3.3	30.2	114	1.7	0.25	0.30	751	0.228
60	63	539	15.6	10.7	3.4	33.4	119	1.9	0.33	0.31	753	0.231
90	75	548	19.1	11.0	3.5	37.9	152	1.9	0.47	0.31	753	0.235

kg at the 90 day. The decomposition rate of oil was 97.7%. $\text{NH}_4\text{-N}$ content increased at the first stage and then became stable. It was because that NH_3 was produced during the decomposition of organic matter process. The NH_3 was absorbed by medium at the initial and then the medium was saturated. N, P, K, Cu, Zn, As, Cd and Hg contents in the medium increased because these elements that the sludge contained were difficult to be decomposed and remained in the medium. EC was increased because the inorganic matter in the sludge also remained in the medium. These materials almost did not affect the physical properties of the cedar chips during the operation for 90 days. These results indicate that cedar chips are the suitable medium for TOP and can be used for a long time.

4. Conclusions

In this research, TOP was applied to the treatment of thickened excess sewage sludge by addition of waste food oil. The results can be summarized as follows:

(1) Thickened excess sewage sludge can be almost completely treated with addition of waste food oil. Organic matter in the sludge was almost completely decomposed to CO_2 and all water in the sludge was evaporated by the heat generated during the degradation of organic matter. A minute amount of excess sludge was formed in this process.

(2) The optimum operational conditions of this process are as follows: a). The mixing ratio of oil to sludge was 12% (BOD_5 concentration was $157,000 \text{ mg} \cdot \text{l}^{-1}$); b). Oil addition rate was $4.44 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$ and amounts of sludge treated was $37.00 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$ (BOD_5 load was $6.6 \text{ kg} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$); c). Aeration rate was $200 \text{ l} \cdot \text{m}^{-3} \cdot \text{min}^{-1}$.

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