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Release Characteristics of Nitrogen and Phosphorus in Aerobic and Intermittent Aerobic Sludge Digestion

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Abstract−Batch digestion experiments of biological sludge by continuous aeration and intermittent aeration were performed to find the release characteristics of nitrogen and phosphorus in this study. Nitrogen content of the sludge increases for the endogenous respiration period, but the content gradually decreases to the same content of raw sludge. Nitrogen removal efficiency was up to 42.7% for 34 days by the intermittent aerobic digestion of which aeration ratio was 0.25 and the removal efficiency was dependent on aeration ratio. Phosphorus does not release until the phosphorus content reaches a limit content. So, phosphorus content of sludge increases gradually to this limit. After the phosphorus content of the sludge reaches this limit, phosphorus will be released proportional to VSS reduction rate.

Key words: Sludge, Aerobic Digestion, Intermittent Aerobic Digestion, Nitrogen, Phosphorus

INTRODUCTION

With the exception of anaerobic digestion, aerobic digestion is probably the most widely used process for the stabilization of wastewater treatment sludge. Both ease of operation and relatively low capital costs have made aerobic digestion particularly attractive for small municipal wastewater treatment plants such as those common in rural areas. It has been reported that aerobic digestion has a number of advantages. Compared to anaerobic digestion, the aerobic or intermittent aerobic digestion is cited as improving supernatant quality, formation of inoffensive end-products, and relatively fast reduction rate. Moreover, intermittent aerobic digestion can be operated at ambient temperature. However, disadvantages are the higher energy costs associated with aeration requirements and pH drop as low as 3.8 [Jenkins and Mavinic, 1989]. While this low pH does not adversely affect solids reduction, it produces a number of potential disadvantages related to digested sludge characteristics and supernatant.

The concept of intermittent aerobic digestion incorporates, at regular intervals, non-aerated periods during aerobic digestion. This produces a digester which cycles between anoxic and aerobic conditions. Hashimoto et al. [1982] introduced an anoxic tank attached to traditional aerobic digestion. They showed that total nitrogen (TN) as well as VSS could be successfully removed by their separated anoxic-aerobic digestion. Jenkins and Mavinic [1989] also reported that anoxic-aerobic digestion in a single tank could save aeration cost and maintain neutral pH. But they conducted the experiments with fixed aeration cycle of 2.5 hours aeration and 3.5 hours non-aeration, so performances according to aeration ratio were not established. Digester type of SBR is widely studied in a field of anaerobic or aerobic digestion process [Hur et al., 2001; Khalili et al., 2000; Park et al., 2001]. Along with ease of installation, SBR has many advantages like ease of operation and adaptability to the changes of loading or operation conditions.

Sludge settleability or thickening is one of the important factors in digester operation. Basically, aerobic digestion process is a floc destructive process. So, median particle size is diminished and specific resistance is increased [Barbusinski and Koscielniak, 1997]. But in the anoxic-aerobic digestion, Lim [1997] reported that specific resistance of digested sludge from anoxic-aerobic digester was higher than that of raw sludge, but it was lower than that of digested sludge from continuous aerobic digester.

The main benefit of intermittent aerobic digestion is expected to power saving associated with non-aeration, neutral pH compared to aerobic digestion [Kim and Hao, 1990]. Nitrogen removal is also expected at the anoxic period.

Wastewater sludge contains nitrogen and phosphorus as well as organics. Primary sludge contains about 2.5% nitrogen and about 0.9% phosphorus while waste sludge contains about 7.5% nitrogen and about 2.5% phosphorus [Bishop and Farmer, 1978]. Wastewater sludge from the wastewater treatment plant contains nutrients like nitrogen and phosphorus. Nitrogen and phosphorus are released to the supernatant as the digestion processes and these adversely affect wastewater treatment systems [Hur et al., 1998; Park et al., 2001]. The content of nitrogen or phosphorus is not always constant and dependent on biological process, wastewater characteristics, sludge age etc. Therefore, various types of molecular formulas of the biological sludge have been proposed. For example, $C_{60}H_{87}O_{23}N_{12}P$ was proposed as a molecular formula of the biological sludge [Sherrard, 1976] and $C_5H_7O_2N$ was simply used [Kim and Hao, 1990]. At the sludge digestion processes, released organic nitrogen transformed into ammonia nitrogen by ammonification reaction. It was reported that the concentration of soluble organic nitrogen separated by 0.45 μm filter ranged from 11-17 mgl^{-1} which was much less than the ammonia nitrogen concentration, 113-230 mgl^{-1} [Hao

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and Kim, 1990]. Therefore, soluble organic nitrogen is regarded as being easily converted into ammonia nitrogen.

Under aerobic conditions, sludge is digested consuming oxygen and ammonia nitrogen is oxidized to nitrate nitrogen by nitrifying bacteria. Under anoxic conditions, sludge digestion is also possible because of the presence of nitrate nitrogen. Most heterotrophic organisms can use nitrate nitrogen as an electron acceptor and they use nitrate nitrogen instead of free oxygen. Therefore, this reaction is often called a denitrification reaction. When the oxygen and carbon source are not sufficient, microorganisms sustain their life by endogenous respiration consuming nitrate nitrogen.

Most phosphorus in biomass cells is located in nucleic acid, coenzyme, polyphosphate and phosphatide [Bishop and Farmer, 1978]. The amount of total phosphorus does not vary throughout the wastewater or sludge treatment system because phosphorus is not volatile material. But it is possible that soluble phosphorus is transformed to particulate phosphorus or vice versa. Bishop and Farmer [1978] concluded that phosphorus content of sludge would not changed during aerobic digestion and that the content was 1.6-1.7% before digestion and 1.9-2.0% after digestion. Matsuda et al. [1988] reported that phosphorus content of sludge for the raw wastewater sludge was 1.7%, and it increased to 2.0% after 5 days aerobic digestion and finally it decreased to 1.2-1.5%. Jenkins and Mavinic [1989] conducted aerobic digestion of sludge from the biological phosphorus removal process. They reported, based on their experimental study, that phosphorus release rate was slower than VSS reduction rate so phosphorus content of the digested sludge was higher than that of raw sludge. At present, phosphorus content seems to increase during the aerobic digestion but there are no rational reasons. Therefore, Henze [1991] supposed that lower phosphorus content biomass destroyed earlier than higher phosphorus content biomass. Jenkins and Mavinic [1989] supposed that live microorganisms would possess phosphorus in their cell under the endogenous condition because phosphorus is an essential compound for energy metabolism. Tonkovic [1998] also showed that intermittent aerobic digestion could reduce phosphorus leaching by 50% or more even if biosolids from BNR processes.

The purpose of this study is to investigate the characteristics of nitrogen and phosphorus release from the sludge under the intermittently aerated system. Transformation of nitrogenous compounds to predict the nutrient concentration of the return stream from the intermittent aerobic digestion process is another object of this study.

EXPERIMENT MATERIALS AND METHODS

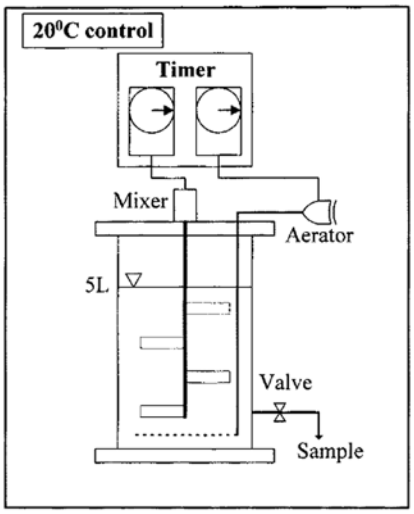
Characteristics of waste activated sludge from municipal wastewater treatment plant were varied by wastewater composition, wastewater treatment process, sludge age, sludge storage time or operation technique. So, biological sludge was used as materials in this digestion experiments to eliminate these varieties.

Biological sludge was aerobically maintained by using synthetic wastewater in the laboratory controlled to 20 °C. Synthetic wastewater was composed of powered milk, yeast extract. Sodium bicarbonate was also added as a pH buffer. Synthetic wastewater about 500 mgCODl^{-1} was added to sequencing batch reactor (SBR) to raise the biomass concentration. SBR operation strategy was as follows. One cycle time was set to 6 hours and it was split to Fill and aeration was for 4 hours, followed by settling for 50 minutes, decanting the supernatant for 10 minutes. Sludge withdrawing was not necessary in this operation. By this way, SS was increased from 500 mgl^{-1} to 4,820 mgl^{-1} for 20 days cultivation. Biological sludge was directly used for batch digestion experiment without any other treatment. Characteristics of biological sludge at the start-up of the digestion experiment are shown in Table 1. Experimental apparatus is shown in Fig. 1. A mixing device, an aerator and a diffuser were equipped to each reactor, and controlled by each electric timer. Aeration intensity was also controlled to maintain DO to 6 mgl^{-1} at the aeration period. DO concentration was less than 0.1 mgl^{-1} for the non-aeration period.

Four sets of reactors were used in this study; the operational conditions are shown in Table 2. To investigate the effect of aeration ratio, R1-R3 were operated as intermittent aerobic digester and R4 was as a continuous aerobic digester. Aeration ratio means the fraction of aeration period to 1 repeat cycle. Cycle was fixed to 12 hours

Table 1. Characteristics of the biological sludge at the start-up and 34 days digestion

Constituent	Start-up (mgl^{-1})	After 34 days digestion (mgl^{-1})			
		Intermittent aeration			Continuous aeration
		R1 (φ=0.25)	R2 (φ=0.50)	R3 (φ=0.75)	R4 (–)
pH	4	8.2	8.1	7.1	4.8
Alkalinity(as $CaCO_3$)	500	302	253	70	7
TCOD	6,790	2,340	2,120	2,120	1,340
SCOD	3.4	18	16	14	26
TS/TVS	5,140/4,370	2,730/1,950	2,650/1,920	2,870/1,910	2,550/1,470
SS/VSS	4,820/4,340	2,300/1,900	2,210/1,810	2,070/1,790	1,580/1,370
TKN	260	120	110	110	90
NH_4^+-N	-	-	-	-	3
NO_2^--N	-	0.1	-	-	-
NO_3^--N	0.1	29	40	110	140
TN	260	150	150	220	230
TP	62	59	62	65	63
PO_4^{-3}-P	0.3	3.8	6.7	10.0	12.9



R1, R2, R3 and R4

Fig. 1. Schematic diagram of the batch digestion apparatus.

to exclude the effect of aeration interval. The batch digestion experiments were continued for 34 days and pH, alkalinity, TCOD, SCOD, SS, VSS, TKN, NH_4^+-N, NO_2^--N, NO_3^--N, TP, PO_4^{-3}-P were checked every 4 to 5 days according as Standard Methods [APHA, 1992]. Deionized water was added daily to preset level for the compensation of evaporation loss. And all the data were adjusted for the sampling loss.

RESULT AND DISCUSSION

1. Nitrogen Release and Transformation

For the first 3-6 days, VSS reduced rapidly (Fig. 2) but the decrease of organic nitrogen almost did not show. It was reported that nitrogen content of the digested sludge from aerobic digestion was increased slightly more than that of raw sludge [Eikum et al., 1974]. Otherwise, Mavinic and Koers [1982] reported that nitrogen content did not change in the aerobic sludge digestion process based on the experiment. In their experiment, initial nitrogen content of the sludge was 0.080 $gN(gVSS)^{-1}$ and the content of the digested sludge was 0.070-0.085 $gN(gVSS)^{-1}$. This idea was supported by Hao and Kim [1990]. The IAWQ Activated Sludge Model adopted this idea that nitrogen content of biomass is constant during synthesis or lysis of biomass [Henze et al., 1995]. So, it was possible that

$$\frac{dN_S}{dt}=-i_{NBM}\frac{dX}{dt} \quad (1)$$

and i_{NBM} is always constant.

where N_S =soluble nitrogen concentration, $(mgN l^{-1})$;

i_{NBM}=nitrogen content of biomass, $[mgN(mgVSS)^{-1}]$;

X =biomass concentration, $(mgVSS\ l^{-1})$

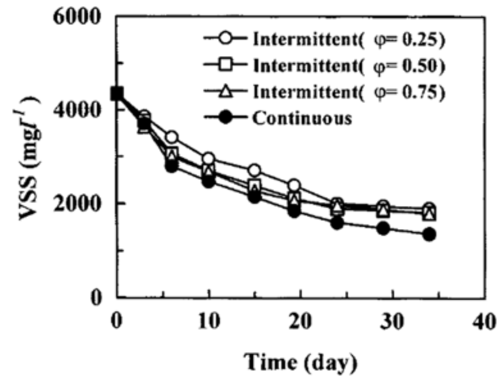


Fig. 2. VSS reduction during the batch digestion (φ=aeration ratio).

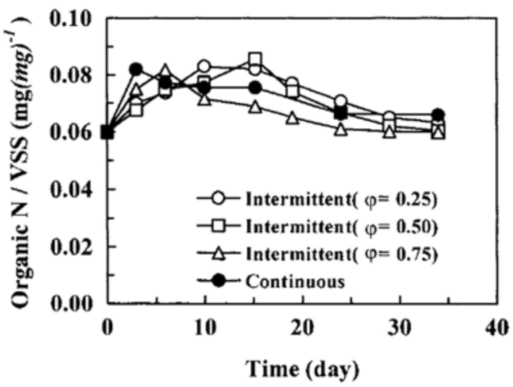


Fig. 3. Nitrogen content of the sludge during the batch digestion (φ=aeration ratio).

Under the starvation condition, organisms consume their own protoplasm for the sustenance of life, and relatively weaker organisms die and are destroyed gradually. In the Death-Regeneration Model, destruction fragments are considered as being produced as the heterotrophic organisms die and these destruction fragments are used again by the other heterotrophic organisms [Dold et al., 1980]. By the results of this experiment, VSS reduction for the first few days is absolutely endogenous reduction, and nitrogen within the cell is not released rapidly from the biomass in this stage. It makes nitrogen content of biomass increase. Fig. 3 shows that nitrogen content increased from 6% up to 8% during the endogenous period and it gradually decreased to the content of the raw sludge. This phenomenon was not only observed in continuous aerobic digestion but also intermittent aerobic condition. Therefore, it can be concluded that nitrogen content of biomass is increased for the endogenous respiration period. VSS reduction versus nitrogen release is

Table 2. Operational condition of the each reactor

Reactor	Aeration time	Non-aeration time	Aeration ratio (φ)	Remarks
R1	3 hr	9 hr	25	Intermittent aeration, repeat
R2	6 hr	6 hr	0.5	Intermittent aeration, repeat
R3	9 hr	3 hr	0.75	Intermittent aeration, repeat
R4	-	-	1.0	Continuous aeration

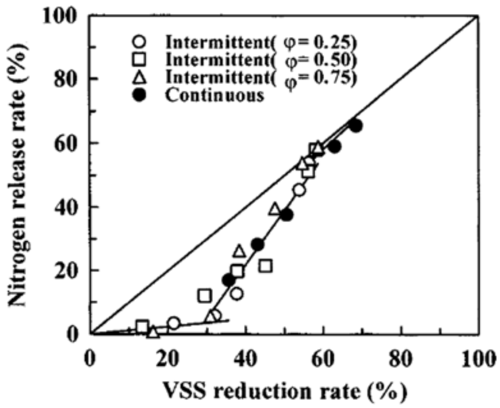


Fig. 4. Relation between VSS reduction rate and nitrogen release rate (φ=aeration ratio).

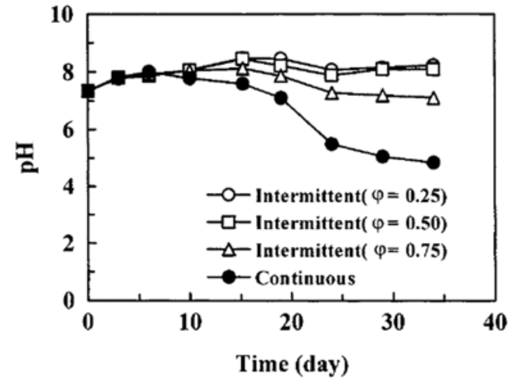


Fig. 6. pH variations under the batch digestion (φ=aeration ratio).

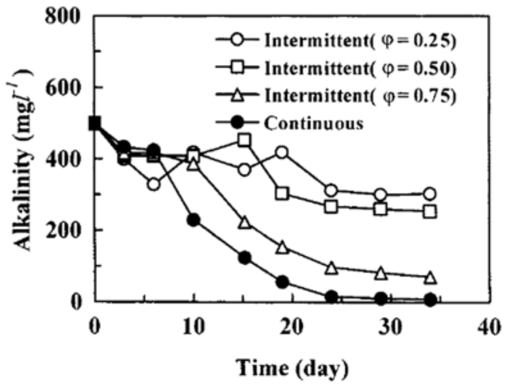


Fig. 7. Alkalinity variations under the batch digestion (φ=aeration ratio).

shown in Fig. 4. If the content of nitrogen is constant like Eq. (1), then observed data should be plotted on the diagonal line in Fig. 4. But, data are almost located below the diagonal line. Therefore i_{NBM} in Eq. (1) is not constant, but the content of nitrogen of biomass is increased for the endogenous stage. It means that nitrogen release rate is smaller than biomass reduction rate. After the endogenous stage, nitrogen release rate is greater than VSS reduction rate and is gradually similar to the content of raw biomass. If nitrogen release rate is considered to be dependent on VSS reduction rate, then nitrogen release rate is about 12% of VSS reduction rate where VSS reduction rate is below 35%. Nitrogen release rate is almost 1.7 times of VSS reduction rate after the endogenous stage, and the rate is gradually decreased to VSS reduction rate. TN reductions are shown in Fig. 5. TN reduction was 11.5% for the 34 days batch aerobic digestion. But TN reduction was 42.7%, 42.3%, 15.4% for the intermittent aerobic digestion of which the aeration ratio was 0.25, 0.5 and 0.75, respectively. The reason for lower TN reduction at φ=0.75 than φ=0.5 or 0.25 is the relatively short anoxic period. Released ammonia nitrogen was easily transformed to nitrate nitrogen, and a part of nitrate nitrogen was accumulated in the reactors as nitrate nitrogen.

pH and alkalinity changes are shown in Fig. 6 and Fig. 7. Released organic nitrogen could be easily transformed to ammonia nitrogen [Hao and Kim, 1990] and ammonia nitrogen is oxidized to nitrate nitrogen by nitrifying bacteria under the aerobic condition. Nitrification reaction is an alkalinity consuming reaction and about 2 mole of alkalinity is needed to oxidize 1 mole of ammonia nitrogen like Eq. (2). The reason for the pH drop in the aerobic digestion process is that alkalinity consumption rate is greater than the alkalinity generation rate and this is a weak point of the aerobic digestion process. Ammonia nitrogen is expected to accumulate in the reactor after the depletion of alkalinity because of the inhibition of nitrification.

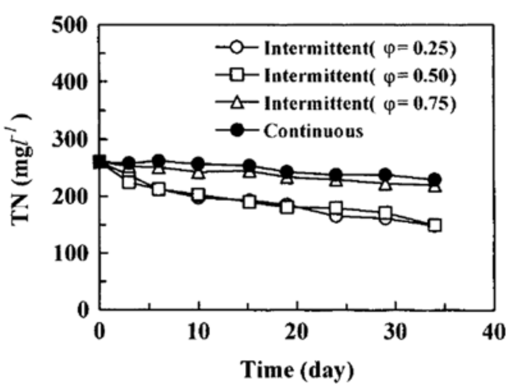


Fig. 5. Nitrogen reduction during the batch digestion (φ=aeration ratio).

$$NH_4^+ + 1.86O_2 + 1.98HCO_3^- \rightarrow 0.02C_5H_7O_2N + 0.98NO_3^- + 1.04H_2O + 1.88H_2CO_3 \quad (2)$$

Under the anoxic condition, sludge digestion is also possible because of the presence of nitrate nitrogen. Most heterotrophic organisms can use nitrate nitrogen as an electron acceptor and they use nitrate nitrogen instead of free oxygen. When the oxygen and carbon source are not sufficient, microorganisms sustain their life by endogenous respiration consuming nitrate nitrogen. So it would be called endogenous nitrate respiration (ENR) [Kim and Hao, 1990]. ENR reaction is an alkalinity production reaction like Eq. (3).

$$C_5H_7O_2N + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_4^+ + OH^- \quad (3)$$

pH or alkalinity was also decreased in the intermittent aerobic, but the rate of decrease was slower than continuous aerobic digestion. For the 34 days digestion, alkalinity reduction per unit VSS reduction was 0.086 mg $(mg)^{-1}$, 0.098 mg $(mg)^{-1}$ for aeration ratio of 0.25, 0.5 respectively. However, this value for the aeration ratio

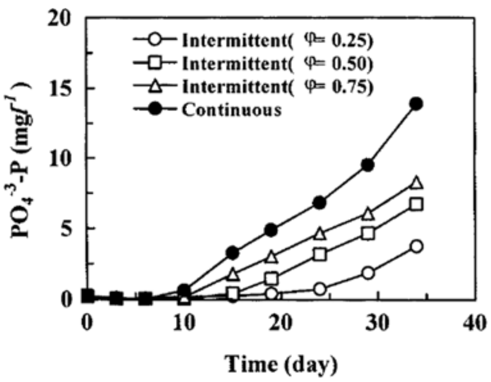


Fig. 8. Soluble phosphorus variation during the batch digestion (φ=aeration ratio).

of 0.75 was 0.176 mg $(mg)^{-1}$ which was about the same value of the continuous aerobic digestion, 0.179 mg $(mg)^{-1}$. It shows that intermittent aerobic digestion where the aeration ratio is less than 0.5 is an alkalinity saving process.

2. Phosphorus Release

Phosphorus would be released from the cell as the death and lysis of microorganisms. Total phosphorus concentration maintained the start-up concentration within the experimental error range, but soluble phosphorus concentration increased gradually as shown in Fig. 8 because of cell destruction. However, the increasing rate of the soluble phosphorus concentration was not directly proportional to the VSS decreasing rate. VSS reduced to 68%, 62%, 62% and 57% of the initial concentration at the aeration ratio of 0.25, 0.5, 0.75 and 1.0 after 10 days digestion. But phosphorus release was so low that its concentration was only 0.2 mgl^{-1}, 0.0 mgl^{-1}, 0.2 mgl^{-1} and 0.6 mgl^{-1}, respectively.

Variations of the phosphorus content of the sludge are shown in Fig. 9. Phosphorus content was continuously increased from 1.5% at the start-up condition and steadily increased to 3.3-3.9% for the 34 days digestion. Phosphorus content of the sludge increased gradually for the intermittent aerobic digestion and this increase was also observed in the continuous aerobic digestion. It implies that this phosphorus storage phenomenon is not only caused by phosphorus accumulating organism's (PAO's) activity. Therefore, it can be supposed that phosphorus content of the sludge is increasing under the aerobic digestion or intermittent aerobic digestion. In the Activated Sludge Model [Dold et al., 1980; Henze et al., 1995], it is assumed that phosphorus release rate or synthetic rate is directly proportional to the VSS reduction rate. However, this assumption should not be applied to continuous or intermittent aerobic digestion.

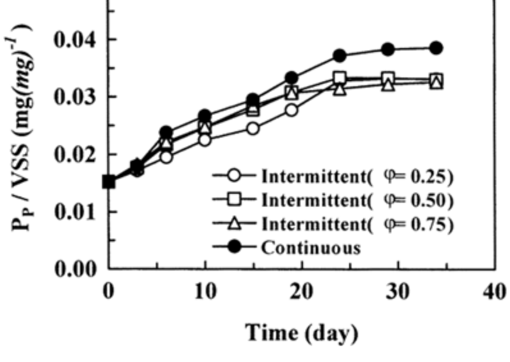


Fig. 9. Phosphorus content of the sludge during the batch digestion (φ=aeration ratio).

It is important that phosphorus content is not increased beyond the limit content. As mentioned above, it seems that phosphorus release is not directly proportional to VSS reduction rather that phosphorus release is retarded. Retardation means that phosphorus is accumulated into the sludge until it reaches some phosphorus content limit while aerobic or intermittent aerobic digestion is processed. Based on this experiment (Fig. 9), the limit phosphorus content is about 3-3.5% of biomass in intermittent aerobic digestion and is about 4% of biomass in continuous aerobic digestion. But, this value may be changed depending on the type of sludge, digestion temperature, or sludge age etc. Beyond the limit of phosphorus content, phosphorus will be released proportionally to VSS reduction rate.

CONCLUSIONS

After the experimental study of the biological sludge digestion by continuous aeration and intermittent aeration, some conclusions are reached as follows.

At the earlier stage of aerobic or intermittent aerobic digestion, nitrogen content of the sludge increases temporary in this endogenous respiration stage because nitrogen is not immediately released from the biomass. But for long digestion time, nitrogen content is recovered to the initial value. Intermittent aerobic digestion is a nitrogen removal process compared with aerobic digestion. For the 34 days digestion, up to 42% of total nitrogen is removed by the intermittent aerobic digestion of which aeration ratio is 0.5 or less and the removal efficiency is dependent on aeration ratio.

Phosphorus is released as the sludge digests, but phosphorus release rate is much slower than VSS reduction rate up to the limit phosphorus content of sludge. Limit phosphorus content of biological sludge is about 3.5-4% of VSS and this is not always constant. As the digestion continued beyond the limit phosphorus content of sludge, phosphorus will be released proportional to VSS reduction rate.

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