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CHARACTERISTICS OF CRITICAL SOLID-LIQUID SEPARATION AND ITS EFFECT ON THE PERFORMANCE OF AN ANAEROBIC SEQUENCING BATCH REACTOR TREATING MUNICIPAL SLUDGE

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Abstract – Solid-liquid separation and its type greatly affected the stability and performance of an anaerobic sequencing batch reactor (ASBR) for municipal sludge digestion. Flotation thickening occurred in the mesophilic ASBR, while solid-liquid separation in the thermophilic ASBR followed gravity thickening. Hydraulic retention times (HRT) and cycle period as well as type of thickening were key parameters governing sludge thickenability and critical solids accumulation. Thickened sludge bed volume was a critical operating variable in the ASBR with gravity thickening, which had poor performance because of the loss of thickened solids, and sludge interface disruption or instability of sludge bed due to internal gas evolution. A cyclic mutual effect between thickened volume and gas production was serious in gravity thickening, whereas it was insignificant in flotation thickening.

Key words : Anaerobic Sequencing Batch Reactor, Municipal Sludge, Sludge Flotation, Solid-Liquid Separation, Thickenability

INTRODUCTION

Application of aerobic sequencing batch reactor technology to anaerobic treatment is a new concept for improving the performance and stability of conventional anaerobic processes. Aerobic digestion is a viable alternative to anaerobic digestion for sludge digestion, but Bendefield and Randall [1980] list the disadvantages most often claimed for aerobic digestion compared with anaerobic digestion, which are as follows : high power costs result in high operating costs, which become significant in large facilities; solids reduction efficiency varies with temperature fluctuation; gravity thickening following aerobic digestion generally results in a supernatant high in solids concentration; and some sludges apparently do not dewater easily by vacuum filtration after aerobic digestion. The anaerobic sequencing batch reactor (ASBR) process, which repeats a cycle including four typical discrete sequences--fill, react, settle, and draw step--can retain high concentration of slow-growing anaerobic bacteria in the reactor. Research on the ASBR has been carried out by several investigators. Satisfactory phenol degradation and suspended solids removal using the ASBR were reported by Earley and Ketchum [1988]. Dague and Pidaparti [1992] reported the ASBR for a swine waste was capable of biomass retention without any serious operational problems. Chang and Chung [1995] indicated continuous accumulation of volatile solids and biomass in the ASBR improved the treatability of a starch wastewater. Kennedy et al. [1991] and Sung and Dague [1992] proposed that use of granular sludge was good for easier operation of the ASBR. It should be noted that most of the investigators used soluble feeds and did not experience any difficulty associated with critical solid-liquid separation, which would be a key operational parameter of the ASBR treating high-solids-content waste.

The anaerobic process has been often reported to have an adverse effect on solid-liquid separation because of poor settleability of anaerobically digested sludge. Previous study also showed settleability of digested municipal sludge was more deteriorated through thermophilic digestion than was the case of mesophilic digestion [Han et al., 1994]. The most serious problem in solid-liquid separation would therefore occur in the ASBR treating a high-solids-content waste such as municipal sludge.

The objective of this study was to evaluate the performances of the ASBR under critical conditions of solid-liquid separation, caused by extremely high settleable solids in the feed and digestion temperature, for broader application of the ASBR process to various high-solids-content wastes.

MATERIALS AND METHODS

1. Reactor Setup and Feed Sludge

Laboratory-scale ASBRs, as illustrated in Fig. 1, and their corresponding completely-mixed daily-fed control reactors were operated in an environmental chamber maintained at 35 °C and 55 °C. Simultaneous operation of control runs without solid-liquid separation was essential to evaluating the performance of the ASBR because the nature of the feed varied widely

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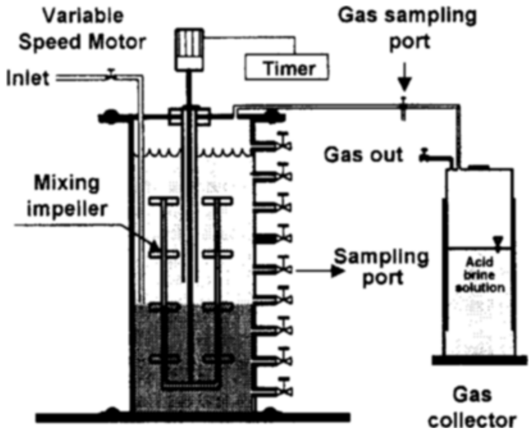

Fig. 1. Schematic diagram of ASBR system.

with time. The ASBRs and the control reactors were identical except for sampling ports on the side wall of the ASBRs. Each reactor made of plexiglas had a working volume of 4 liters with a liquid depth of 26 cm. Reactor mixing was accomplished by an impeller type mechanical mixer for highly viscous sludge.

The feed was taken from a gravity thickener for a mixed sludge of primary and activated sludge in a municipal wastewater treatment plant. Feed sludge was collected bimonthly and stored in a refrigerator maintained at 4 °C after screening with standard sieve #8. Feed composition varied remarkably with collection time, and its volatile fraction ranged from 35.4 % to 81.7 %. Characteristics of the feed sludges for different operating conditions are given in Table 1. Each reactor was inoculated with a digested municipal sludge from a laboratory-scale mesophilic digester fed with the same feed sludge.

2. Start-up and Operation Methods

The reactors for an ASBR run were operated in completely-mixed daily-fed mode at the same operating conditions of their corresponding control reactors until they showed the same performances as those of the control runs. The ASBR had a cycle time consisting of a 30-minute fill and draw period, one- to three-day react period, and one-day thicken period. One-day thickening was adopted to minimize the loss of thickened sludge during a draw step based on a preliminary one-day thickening test in a 1 L graduated cylinder with a digested municipal sludge. Mesophilic reactors were converted to thermophilic runs by a method of direct temperature raising with subsequent digester resting [Chung and Chang, 1988]. The operating conditions of the ABSRs and control reactors are given in Table 2. The pH, ORP, COD, solids, alkalinity and volatile acids of digested sludge and clarified effluent were routinely monitored according to the APHA Standard Methods [APHA, 1992]. Dehydrogenase activity (DHA) was examined as an absorbance by a modified procedure of the TTC method.

RESULTS AND DISCUSSION

1. Relationship Between Equivalent HRT and Withdrawal Volume Ratio

The minimum equivalent HRT of the ASBR treating of a high-solids-content sludge depends upon a permissible effluent withdrawal volume in the draw step under a fixed cycle period, since the digested sludge has a large thickened volume. A permissible withdrawal volume in the draw step could be estimated by a preliminary solid-liquid separation test using a similar digested sludge. The required cycle period can be determined under a designed equivalent HRT and a withdrawal vol-

Table 1. Characteristics of feed sludges for different operating conditions

Parameters	Mesophilic runs		Thermophilic runs		
	HRT 5 days	HRT 10 days	HRT 3.3 days	HRT 5 days	HRT 10 days
pH	5.1-6.6	5.9-7	5.9-6.6	6.2-6.8	6.2-7.1
VS (g l^{-1})	9.1-17.8	7.2-15.4	6.3-18.7	8.8-13.6	6.3-18.7
COD (g l^{-1})	13.1-32.8	11.1-28.0	10.5-26.5	12.4-22.3	10.5-26.5
Volatile acids (mgHAc l^{-1})	970-3,630	150-700	160-280	180-300	30-310
Alkalinity (mgCaCO$_3$ l^{-1})	480-1,290	280-1,190	540-1,850	560-1,130	560-1,610
Thickened volume (%)[a]	30-99	24-92	50-94	60-82	41-82

[a]Thickened sludge volume after one-day thickening in a 1 liter graduated cylinder.

Table 2. Operating conditions

Parameters	Mesophilic runs (35 °C)				Thermophilic runs (55 °C)			
	Control	ASBR			Control	ASBR		
HRT (days)[a]	5,10	5	10	10	3.3, 5, 10	3.3	5	10
Cycle period (days)	-	2	3	4	-	2	2	3
Fill and draw period (hours)	-	0.5	0.5	0.5	-	0.5	0.5	0.5
React period (days)	-	1	2	3	-	1	1	2
Thicken period (day)	-	1	1	1	-	1	1	1
Withdrawal volume (%)[b]	20, 10	40	30	40	30, 20, 10	60	40	30
OLR[c] gCOD $l^{-1}d^{-1}$	1.1-6.6	2.6-6.6	1.1-2.2	1.1-2.2	1.6-8.0	3.2-8.0	2.7-3.6	1.6-2.2
gVS $l^{-1}d^{-1}$	0.8-3.6	1.8-3.6	0.8-1.5	0.8-1.5	1.1-5.6	1.9-5.6	1.8-2.7	1.1-1.4

[a]Equivalent HRT for the ASBR.
[b]Effluent withdrawal volume percent to working volume of the reactor.
[c]Equivalent daily organics loading rate for the ASBR.

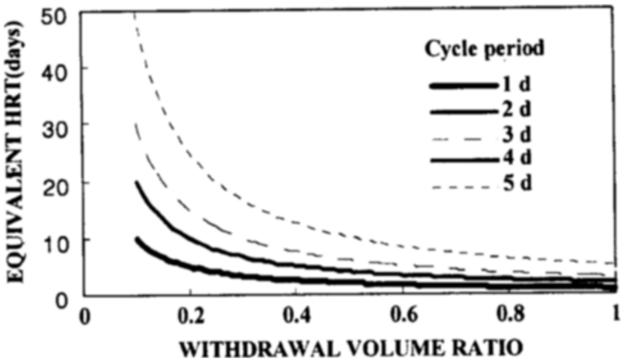

Fig. 2. Relationship between equivalent HRT and withdrawal volume ratio of the ASBR.

ume not exceeding the permissible volume. A simple equation can be derived to demonstrate a relationship between equivalent HRT, cycle period, and withdrawal volume for the ASBR process, as follows:

Equivalent HRT=Cycle period/Withdrawal volume ratio

Withdrawal volume ratio is a ratio of the withdrawal volume in a draw step to the working volume of the ASBR. Fig. 2 shows the relationship between the equivalent HRT and withdrawal volume ratio at various cycle periods. The cycle period should satisfy the react period required for stabilization of organics, and also include the thicken period required to obtain permissible withdrawal volume.

2. Overall Process Performances

Conversion of a completely-mixed daily-fed reactor to a sequencing batch reactor was easily achieved without any adverse effects. No noticeable effect of shock loading during the start-up period on process stability was observed in the ASBRs with 5- to 10-day HRT in spite of a draw and fill of 30% to 40 % of the liquid contents; whereas, a stable reaction could not be expected in the completely-mixed reactor under such an abrupt draw and fill. Start-up behaviors of the ASBRs indicate that a conventional digester could be easily converted to the ASBR without stability problems. In all reactors, no adverse effect during and after temperature shift was observed.

The performance of the ASBR could be regarded as a stabilized pseudo-steady state since no intentional attempt was provided to control solids retention time (SRT). Pseudo-steady state performances of the ASBRs and their corresponding control runs are summarized in Table 3. Chemical characteristics of the mixed digested sludge in all reactors were almost similar in the ranges, indicating ordinary digestion of the municipal sludge, except for volatile acids accumulation in the thermophilic ABSR with a 3.3-day HRT. Organics removal of the ASBRs increased at longer HRT, and lower efficiencies of the thermophilic reactors were attributed to poor solid-liquid separation of the sludge. A change in cycle period of the me-

Table 3. Pseudo-steady state performances (average values)

Parameters	Mesophilic runs					
	HRT 5 days		HRT 10 days			
	ASBR 2-day cycle	Control reactor	ASBR 3-day cycle	Control reactor	ASBR 4-day cycle	Control reactor
Sludge properties[a]						
pH	6.9	6.9	7.09	6.97	6.9	6.85
ORP (−mV)	251	251	261	290	206	199
VA (mgHAc/L)	212	270	214	225	192	182
Alkalinity (mg$CaCO_3$/L)	2,190	2,120	1,170	1,710	1,550	1,290
Organics removals						
VS removal (%)						
Digested sludge		23.2		21.0		20.4
Clarified effluent[b]	91.8	90.7	92.4	91.1	93.4	93.5
COD removal (%)						
Digested sludge		28		18		22
Clarified effluent[b]	93.7	92.8	95.2	92.0	95.4	92.2
Gas production						
GPR (L/L/d)[c]	0.67[f]	0.5[f]	0.15	0.1	0.15	0.1
Gas yield (L/gVS_{added})	0.28	0.23	0.14	0.09	0.14	0.09
CH_4 content (%)	69.5	69.0	73.2	73	73	72.6
S/L separation						
Thickened volume (V/V%)[d]	71	59	70	49	69	61
Centrifuged volume (V/V%)[e]	56	23.7	-	-	38	20

[a]Digested sludge of the ASBR was withdrawn at the end of react step.
[b]Based on the supernatant in a 100 ml graduated cylinder for the control. Based on the clarified effluent for the ASBR ; subnatant for mesophilic run, supernatant for thermophilic run.
[c]Equivalent daily gas production rate for the ASBR.
[d]Thickened sludge volume after one-day thickening in the ASBR, and in a 100 ml graduated cylinder for the control.
[e]Centrifuged volume of mixed digested sludge after centrifugation at 2,500 rpm for 5 minutes.
[f]Due to increase in organics loading rate on account of night soil included in feed sludge.

Table 3. Continued

Parameters	Thermophilic runs					
	HRT 3.3 days		HRT 5 days		HRT 10 days	
	ASBR 2-day cycle	Control reactor	ASBR 3-day cycle	Control reactor	ASBR 4-day cycle	Control reactor
Sludge properties[a]						
pH	7.17	7.22	7.2	7.2	7.26	7.21
ORP (-mV)	242	248	204	209	212	223
VA (mgHAc/L)	1,110	369	222	164	132	99
Alkalinity (mgCaCO$_3$/L)	2,360	2,230	2,540	2,460	2,160	2,400
Organics removals						
VS removal (%)						
Digested sludge		22.6		18.5		12
Clarified effluent[b]	65	83		81	88	90
COD removal (%)			78			
Digested sludge		31		20		22
Clarified effluent[b]	65	83.7	81	85	87	90
Gas production						
GPR (L/L/d)[c]	0.81	0.92	0.56	0.35	0.27	0.17
Gas yield (L/gVS$_{added}$)	0.23	0.25	0.26	0.17	0.17	0.11
CH$_4$ content (%)	65.2	65.4	67	68	69	68
S/L separation						
Thickened volume (V/V%)[d]	70	79	53	86	65	89
Centrifuged volume (V/V%)[e]	34.8	21.9	36.8	20.4	38.9	20

sophilic ASBR did not significantly affect the performance. Mesophilic ASBRs always had higher organics removal than those of their corresponding controls; whereas thermophilic ASBRs have had lower removals than those of control runs due to poor settleability, resulting in solids loss during a draw step, which was reflected in smaller thickened volumes of digested sludge in the thermophilic ASBRs than those in controls as listed in Table 3. Average thickened volumes of the mesophilic ASBRs were larger than those of the thermophilic ASBRs, and the thermophilic control reactors had larger thickened volume than those of the mesophilic control runs because of poor solid-liquid separation in the thermophilic controls. Analysis of standard deviations indicated that performance stability of the mesophilic ASBR was better than that of the thermophilic run.

Variations in the gas production presented as equivalent gas production from the ASBR per gas production from the control run are shown in Fig. 3 and Fig. 4. A remarkable increase in gas production was observed in the ASBRs the operation mode was changed from completely-mixed daily-fed to SBR operation, even though the reactors for the ASBR run showed slightly lower gas production than the control runs during the period of completely-mixed operation. Reduction in gas production just after start-up of the thermophilic ASBR with a 3.3-day HRT was attributed to high solids loss as a consequence of an increase in withdrawal volume. The increase in average gas production rate from the ASBR compared with the control run at the HRT of 5 days and 10 days was 25-50 % and 55 %, respectively, regardless of digestion temperature. Approximately 40-62 % and 5-20 % of total gas production in a cycle was produced during a one day react period and one-day thicken period, respectively.

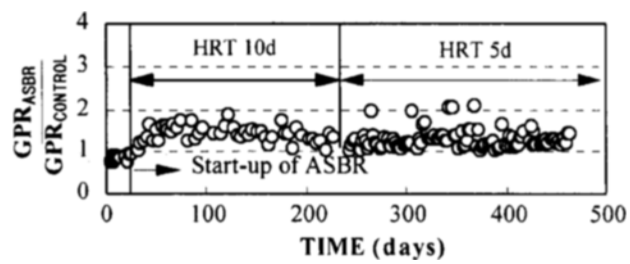

Fig. 3. Changes in gas production ratio of the mesophilic ASBR to the control run.

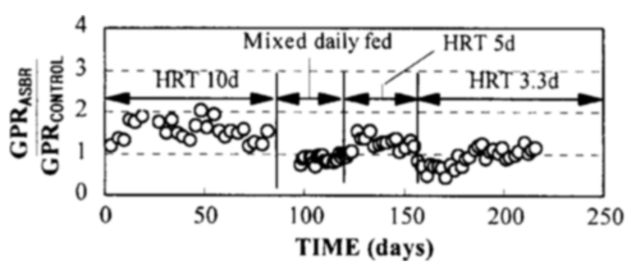

Fig. 4. Changes in gas production ratio of the thermophilic ASBR to the control run.

3. Evaluation of Solid-Liquid Separation

3-1. Thickening Behaviors

Good solid-liquid separation of digested sludge is essential to retaining biomass and meeting the predetermined withdrawal volume without significant loss of solids. Flotation thickening always occurred in the mesophilic ASBRs whereas gravity thickening was a predominant solid-liquid separation process in the thermophilic ASBRs, although reactor performances were not relatively different. The digested sludge of the control runs al-

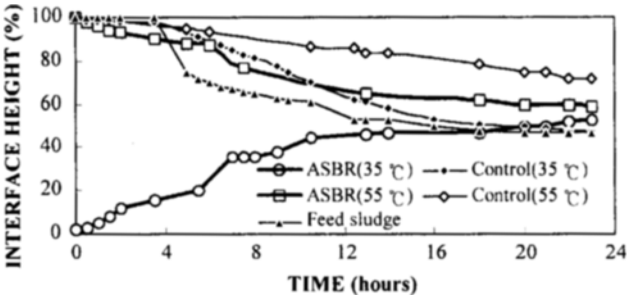

Fig. 5. Interface thickening curves of the digested sludge and feed sludge.

ways followed gravity thickening regardless of temperature, and this thickening behavior clearly supported the new hindered sedimentation theory developed by Yim and Kwon [1997]. Typical interface thickening curves of the sludges for a one-day thicken period after operation at 10 to 20 cycles at a 10-day HRT are plotted in Fig. 5. Flotation thickening was attributed to entrapment of gas bubbles to the digested sludge, resulting in lower specific gravity of the sludge enough to float the sludge bed. Specific gravity of the settled thermophilic sludge was consistently maintained above 1.015 at any operating HRT. Floating velocities of the sludges in the mesophilic ASBRs were faster than settling velocities of the sludges in the thermophilc ASBRs. An adverse effect of thermophilic digestion on sludge settleability was also observed in a study [Han et al., 1994]. Average initial settling velocities of the sludges in the mesophilic control runs were 1.3 times faster than those in the thermophilic controls.

3-2. Solids Accumulation and Their Vertical Profiles

Solids accumulation was remarkable in all ASBRs during the start-up period, and directly affected by settleable solids of the feed sludge. Approximate solids accumulation rates based on solids mass balance during start-up period at the HRT of 10, 5, and 3.3 days were 3.0-3.3, 4.5-5.1, and 6.8-7.1 gVS per cycle, respectively. Observed maximum net increase in thickened sludge volume was 10 to 20 % of the reactor volume during a cycle at any operating condition. Settleabilty of digested sludge in the thermophilic ASBRs was deteriorated as solids accumulated. Solids accumulation in the ASBR was governed by effluent withdrawal volume prescribed by a designed HRT and cycle period rather than influent solids concentration after sufficient build-up of the sludge bed, because solids accumulated above a predetermined level for effluent withdrawal should be carried away during a draw step. Average SRTs based on the effluent total solids of the ASBRs at various operating conditions were 7 to 25 times longer than those of the control runs. Solids accumulation was accompanied by biomass accumulation, which was observed with an increase in the DHA. The DHAs of mixed sludges in all ASBRs were strongly correlated with solids concentrations and centrifuged sludge volumes. The increase in gas production from the ASBRs, as shown in Fig. 3 and Fig. 4, can be explained by a combined synergistic effect of simultaneous accumulation of biomass and remaining biodegradable solids, and continuous degradation of accumulated organics. Solids concentrations and DHAs of mixed sludge in the ASBRs at various operating conditions

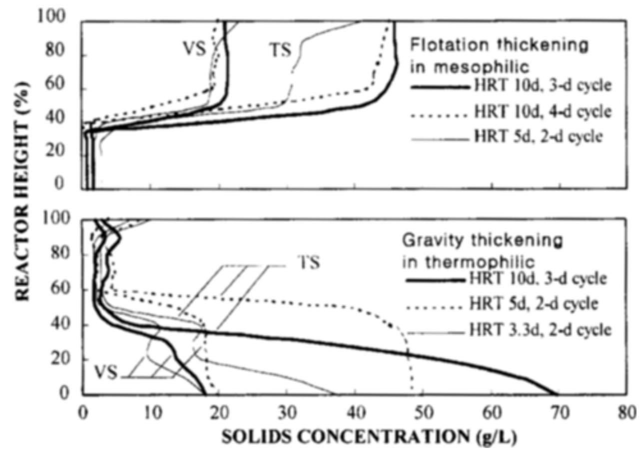

Fig. 6. Typical solids profiles at thicken step of the ASBRs.

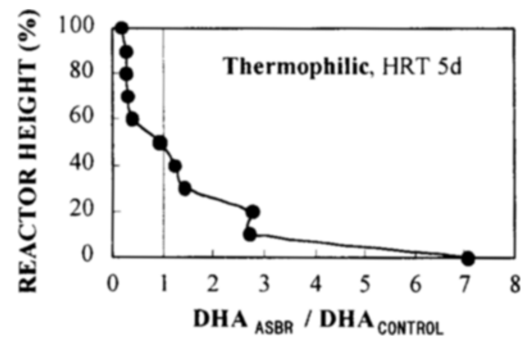

Fig. 7. Typical DHA profile in the thermophilic ASBR.

were 1.9-2.6 times and 1.6-3 times higher than those of the control runs, respectively. The centrifuged volumes of mixed sludge in the ASBRs were also maintained 1.6-2.3 times larger than those of the sludge in the control runs.

Vertical distribution of solids concentration in thickened sludge bed and clarified effluent in the ASBR dramatically changed at the solid-liquid interface, as shown in Fig. 6. Solids concentration profiles in the mesophilic ASBRs clearly demonstrate the flotation thickening of digested sludge. No noticeable difference in solids concentration was observed within the floated sludge bed, while there was a distinct difference in vertical solids distribution in the settled sludge bed. The HRT and cycle period affected the solids profile, especially in gravity thickening, as a result of the decrease in total solids mass in the sludge bed due to higher solids loss at shorter HRT and longer cycle period. The thermophilic ASBR with a 10-day HRT had a unique profile of a stratified solids distribution vertically different in physicochemical characteristics such as specific gravity and organic content. The volatile solids fraction at the bottom of its sludge bed was quite lower than those in the others, because of fixed solids accumulation probably due to a higher digestion efficiency at longer HRT and increased temperature. A typical distribution of microbial activity at the end of the thicken step is shown in Fig. 7, expressed as a ratio of DHA in the ASBR to the activity of mixed sludge in the control reactor. Thickened sludge had dramatically higher microbial activity than clarified effluent in the ASBRs. The DHAs of clarified effluent at any ASBR were below 6 % of that of the

Table 4. Evaluation of thickenability in the ASBRs

Parameters	Flotation thickening			Gravity thickening		
HRT (days)	10	10	5	10	5	3.3
Cycle period (days)	3	4	2	3	2	2
Concentration ratio[a]	25.2	20.7	14.3	9.7	9.2	7.67
Mass ratio[b]	42.2	34.6	19.9	13.8	13.9	13.5
Thickening ratio[c]	0.7	0.6	0.6	0.7	0.6	0.4

[a]Ratio of total solids concentration in thickened sludge to that in clarified effluent.
[b]Ratio of total solids mass in thickened sludge to that in clarified effluent.
[c]Ratio of thickened sludge volume at the end of thicken step to reactor working volume.

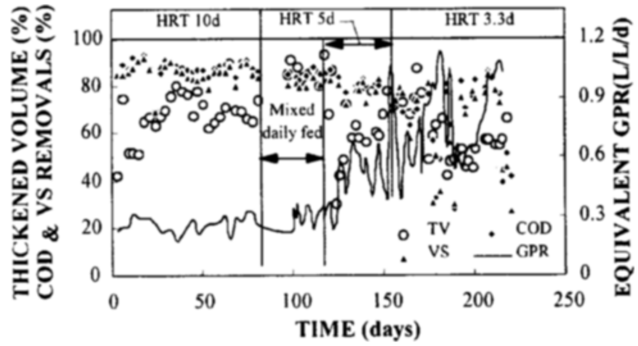

Fig. 9. Performance response to changes in thickened volume in the thermophilic ASBRs.

mixed sludge at the end of the react step. The DHAs and their profiles clearly showed the ability of the ASBR process to retain higher concentration of active biomass.

3-3. Quantitative Evaluation of Thickenability

Sludge thickenability in the ASBR could be evaluated as a ratio of concentration or mass of solids in the thickened sludge to that in the effluent as listed in Table 4. The ratios clearly demonstrate that flotation thickening in the mesophilic ASBR is more effective in thickenability than gravity thickening in the thermophilic ASBR, regardless of the thickening ratio. One of the reasons for poor thickenability of gravity thickening was the instability of the settled sludge bed by internal gas evolution during the thicken step regardless of thickened sludge volume. An increase in HRT and a decrease in the cycle period improved sludge thickenability irrespective of effluent quality, and this is remarkable in flotation thickening.

4. Impact of Critical Solids Build-up on Process Performance

4-1. Performance Response to Solids Accumulation

Solid-liquid separation, particularly critical accumulation of solids at the end of the thicken step of the ASBR, had a profound effect on the process performance. Performance responses of the mesophilic and thermophilic ASBRs to changes in thickened sludge volume are illustrated in Fig. 8 and Fig. 9, respectively. Thickened sludge bed volume increased as the cycle progressed, and consequently reached a critical level, which is above predetermined level for effluent withdrawal. Organics removals based on subnatant of the mesophilic ASBRs were maintained relatively stable regardless of HRT and thickened sludge volume, as shown in Fig. 8. However, the removals based on supernatant of the thermophilic ASBRs decreased with shorter HRT, and significantly fluctuated with a variation of the thickened sludge volume particularly at an HRT of 3.3 days, as shown in Fig. 9. Unstable and lower removals of the thermophilic ASBRs were caused by loss of thickened sludge bed volume, exceeding a predetermined level for effluent withdrawal, and intermittent disruption of settled sludge interface and rising of settled solids by internal gas evolution irrespective of thickened volume, or unstable sludge bed and its expansion by continuous gas evolution during the thicken step. These behaviors resulted in loss of organic solids and biomass during the draw step, leading to subsequent decrease in gas production and SRT. Lower organics removals and smaller thickened volume in the thermophilic ASBRs than those in the control runs, as listed in Table 3, clearly demonstrate a significant effect of such an unstable sludge bed. Whereas, flotation thickening was insensitive to interface disruption of the thickened sludge bed since sludge once floated was only compressed by continuous gas evolution. Analysis of ratios of DHA and VS in the ASBR to those in the control run showed a balance between biomass and organics worsened with gravity thickening at shorter HRT, whereas enough biomass balanced on accumulated organics to be removed could be retained through flotation thickening.

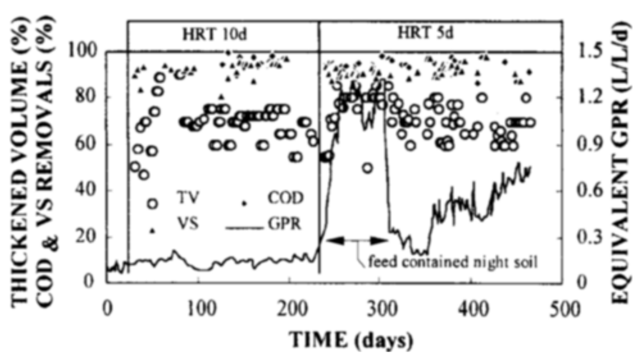

Fig. 8. Performance response to changes in thickened volume in the mesophilic ASBRs.

The SRTs of the mesophilic ASBRs were always above 1.4 times longer than those of the thermophilic runs due to a difference in capacity of solids and biomass capture. The SRT and HRT were strongly correlated at all ASBRs, and cycle period also affected the SRT. Increased withdrawal volume at shorter HRT and longer cycle period resulted in higher loss of solids and consequent shorter SRT. As a result, process performance of the ASBR for municipal sludge digestion primarily depended on the critical condition of solids accumulation. Thickened sludge volume at gravity thickening was a more critical operating variable than was the case of flotation thickening.

4-2. Analysis of Gas Production Response to Critical Solids Accumulation

In order to obtain an insight into the critical condition concerned with a mutual effect between solids accumulation and gas production, the response of gas production to changes in thickened sludge volume at gravity thickening in the thermophilic ASBRs is plotted in Fig. 10. It clearly shows that gas

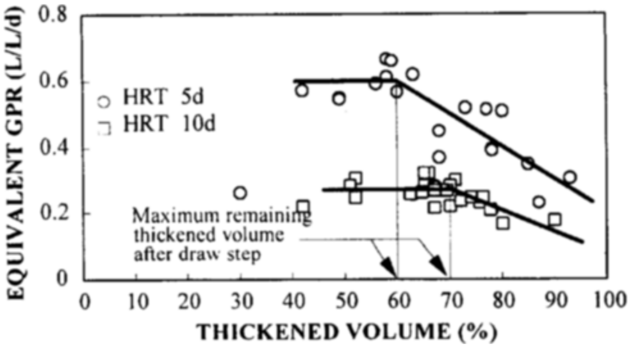

Fig. 10. Relationship between thickened sludge volume at preceding cycle and gas production at following cycle throughout the operation of the thermophilic ASBR.

production at a following cycle significantly decreased after shock loss of biodegradable organics and biomass during a preceding draw step if solids accumulation during preceding cycles exceeded a predetermined level for effluent withdrawal. After shock loss of solids and biomass at a preceding cycle, gradual increases in solids accumulation and gas production were observed during the following cycles until the thickened volume reached a critical level. Increased gas evolution was also accompanied by an instability of the settled sludge bed. Subsequent fluctuations of thickened volume and gas production occurred periodically as the cycle repeated. Such a cyclic mutual effect between critical solids accumulation and gas production was a peculiar feature of the gravity thickening. This behavior was insignificant in the thermophilic ASBR with a 3.3-day HRT, since its effluent withdrawal level of 60% of liquid depth always overlapped with the thickened sludge bed. Gas production from the mesophilic ASBR was relatively independent of thickened volume since gas evolution could further compress a floated sludge bed, and effluent was withdrawn below the floated sludge bed.

CONCLUSIONS

The performance of the ASBR for municipal sludge digestion clearly showed that stability of the ASBR process in treating a high-solids-content waste could be greatly affected by critical conditions of solid-liquid separation. Sludge thickenability and solids accumulation as well as process performance were significantly governed by HRT, cycle period, and type of thickening.

Flotation thickening in the mesophilic ASBR showed better sludge thickenability and consequent superior performance than gravity thickening in the thermophilic ASBR. Poor performance with gravity thickening was caused by loss of thickened solids above a critical level for effluent withdrawal and intermittent disruption of settled sludge interface by internal gas evolution, or an unstable sludge bed and its expansion by continuous gas evolution. Thickened sludge volume at gravity thickening was a critical operating variable, although it was not in the case of flotation thickening. A dynamic mutual effect between critical solids accumulation and gas production resulting in loss of solids was a peculiar feature of gravity thickening, while it was insignificant in flotation thickening. Sludge thickenability was improved with longer HRT and shorter cycle period regardless of effluent quality, and this was especially remarkable in flotation thickening.

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