Pergamon

Wat. Sci. Tech. Vol. 34, No. 3–4, pp. 483–491, 1996.

0273–1223/96 $15·00 + 0·00

PII: S0273-1223(96)00615-4

PERFORMANCE ANALYSIS OF THE FULL-SCALE EGG-SHAPED DIGESTER IN TREATING SEWAGE SLUDGE OF HIGH CONCENTRATION

Y. Y. Li*, T. Noike**, K. Katsumata*** and H. Koubayashi***

* *Technical Research Institute, Ataka Construction & Engineering Co., Ltd, 2-11, Funamachi 2-chome, Taisyo-ku, Osaka 551, Japan*
** *Department of Civil Engineering, Faculty of Engineering, Tohoku University, Aoba, Sendai 980-77, Japan*
*** *Sewage Works Bureau, City of Yokohama, 1-1 Minato-cho, Naka-ku, Yokohama 231, Japan*

ABSTRACT

A full-scale investigation was conducted to evaluate the performance of an egg-shaped digestion tank in treating sewage sludge of high concentration. The experiment was continued over a half year at 36°C, and the influent concentration of sewage sludge to the digester was controlled at about 50 g/L (5%) with a centrifugal thickener. The total solids (TS) in the raw sludge contained 20% inorganic matters and 80% volatile solids (VS), which were further composed of carbohydrates (45.4%), proteins (34.8%), lipids (13.1%) and volatile fatty acids (about 9.2%). At the mesophilic egg-shaped digestion tank with the retention time of 30 days, the removal efficiencies of carbohydrates, lipids, proteins and VFA reached 75%, 50.6%, 46% and 100%, respectively, and the reduction efficiencies of TS, VS, SS, VSS were 44.2%, 56.6%, 46.6% and 61.9%, respectively. The result of gas production showed that 1 m3 of influent concentrated sludge could produce 21 m3 of digestion gas containing 61% of methane. Of all influent sludge COD, about 57% was converted to methane and as a result, 1kg of influent VS produced 0.531m^3 digestion gas. There was no noticeable scum and foaming problems in the egg-shaped digesters, although they have been continuously operated for over ten years. The metabolic activities and populations of individual trophic groups of bacteria in the digester were also elucidated in this study. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

KEYWORDS

Anaerobic digestion; activity; bacterial population, egg-shaped digester; full-scale; high solid; methane production; performance; sewage sludge; volatile fatty acid.

INTRODUCTION

As the saturation level of sewage works has increased and the discharge standards of wastewater have become more strigent, the volume and amount of sludge produced from wastewater treatment plants have increased year by year. The further handling, treatment, and disposal of sludges from municipal, as well as industrial wastewater plants, has become a complex management/economical/regulatory/ecological burden in many countries, especially in Japan. It has become an important concept that sludge treatment and disposal systems must be technically feasible, reasonably cost effective, environmentally acceptable, and implementable in the required time frame. Proper sludge management is to reuse the valuble material in the sludge for the benefit of the community.

State-of-the-art in sludge treatment in Japan

In Japan, over 50 percent of all sewage has been treated by wastewater treatment plants. As a result, the annual sludge production reached 259 million m^3 in volume and 1.5 million tons in dry weight in 1991. The state-of-the-art in slduge treatment and disposal systems operated in Japan in 1992 has been summarized as Table 1 (Watanabe, 1994). Because most big cities in Japan do not have enough land to accept the dehyrdated sludge, due to lack of space, the final disposal of sludge has become a very difficult problem. Reducing the sludge volume and recycling the usful resource in sludge have, therefore, become the basic concept in sludge management and treatment. As an effective method for reducing the slduge volume, incineration process has been widely used in Japan. As shown in Table 1, about 61% of total sludge produced from sewage treatment was treated by incineration process in 1992. In addition, anaerobic digestion process is also widely used for the stabilization of the raw sludge and for producing methane gas. As shown in Table 1, about 50% of the total amount of slduge produced in Japan was treated by the anaerobic process. The processes of TK-AD-DW, TK-AD-DA-CP and TK-AD-DW-IC treated 16.1%, 4.85% and 27.34% of total amount of sludge, respectively.

Recent development in upgrading of the sludge digestion

Sewage sludge usually contains 1-2% of total solids, of which over 80% is organic matter. Because the sludge is not only biologically degradable, but also a good material for methane fermentation, anaerobic digestion technology has been widely used as an important process for stabilization of sludge (Ghosh, 1987; Li, 1989) and producing biogas. However, anaerobic sludge digestion has some problems which have limited its applications. Scum formation and low VS reduction are two well-known problems (Li, 1989; Ghosh, 1990). Several methods have been reported for the upgrading of sludge digestion, including thermal pretreatment (Sato, 1987; Li and Noike, 1992), two-phase process (Eastman and Ferguson, 1981; Ghosh, 1987; Ghosh, 1990; Li, 1989; Elefsiniotis and Oldham, 1994) and egg-shaped digester process. In the past decade, a total of 49 egg-shaped digesters have been built in Japan for sludge treatment. The treatment performance of these full-scale digesters, however, has not been elucidated.

The objective of this study was to clarify the performance of the full-scale egg-shaped digestion tanks in treating sewage sludge of high concentration. The experiment was conducted over a half year to measure the reduction efficiencies of various organic matter, methane production, bacterial populations and methanogenic activities of digester sludge in the full-scale digestion tank.

MATERIALS AND METHODS

Schematic of sludge treatment process with egg-shaped digester

Figure 1 illustrates the flow chart of the sludge treatment process investigated in this study. This process is located in the hokubu (Northern) sludge treatment center and involves a process sequence of thickening, digestion, dewatering, and incineration on sludge received from the five wastewater treatment plants in the northern part of Yokohama City. This system of centralized sludge treatment offers the following benefits: (1) greater efficiency in facility construction and management due to the higher economy of scale; and (2) conservation of energy and resources through comprehensive use of the energy contained in sludge. A total of 12 egg-shaped digestion tanks with individual working volume of 6800 m^3 were run to stabilize sludge and to produce digestion gas under the mesophilic conditions (36°C). The raw sludge, which has a concentration of about 2 percent (20g/L), is concentrated to about 5 percent (50 g/L) by means of centrifugal thickener, and then the concentrated sludge is used as the influent to the digester. Digestion gas is beneficially used as fuel for power generation and as auxiliary fuel for incinerators. In addition, waste heat from power generation is used to warm the sludge through a heat exchanger and as a heat source for air conditioning equipment. This investigation was focused on the performance of the egg-shaped digestion tank.

Table 1. The state-of-the-art in sludge treatment processes operated in Japan (1992)[a]

Final stabilization state	Sludge treatment Processes[a)]	Number of plants	Treated sludge Amount[c)] (1,000 tons/year)	Treated sludge Percentage (%)
Thickened sludge	TK	5	0.1	0.01
	TK-AD	**3**	**5.7**	**0.38**
	Sub total	8	5.8	0.39
Dewatered skudge	TK-DW	298	138.0	9.23
	TK-AD-DW	**195**	**240.8**	**16.10**
	AeD-TK-DW	5	0.7	0.05
	TK-TT-DW	1	1.3	0.09
	Sub total	499	380.8	25.45
Composted sludge	TK-DW-CP	68	46.8	3.13
	TK-AeD-DW-CP	1	0.6	0.04
	TK-AD-DW-CP	**57**	**72.5**	**4.85**
	Sub total	126	119.9	8.02
Dried sludge	TK-DR	12	0.1	0.01
	TK-AD-DR	**12**	**1.3**	**0.09**
	TK-DW-DR	7	1.6	0.11
	TK-AD-DW-DR	18	12.0	0.80
	Sub total	49	15.0	1.00
Incinerated ash	TK-DW-IC	133	468.7	31.33
	TK-AD-DW-IC	**57**	**409.0**	**27.37**
	AeD-TK-DW-IC	2	0.2	0.01
	TK-TT-DW-IC	5	35.4	2.37
	TK-WO-DW	1	5.1	0.34
	Others	4	7.8	0.52
	Sub total	202	926.2	61.92
Melted slag	TK-DW-ME	19	35.5	2.37
	TK-AD-DW-ME	**5**	**9.9**	**0.66**
	TK-DW-IC-ME	1	2.2	0.15
	TK-AD-DW-IC-ME	2	0.4	0.03
	Others	1	0.1	0.01
	Sub total	28	48.1	3.22
Total of all the plants		912	1495.8	100.0
Treatment plants with anaerobic digestion		**344**	**741.7**	**49.60**

a) According to Watanabe (1994).

b) TK=Thickening, DA= anaerobic digestion, DW =dewatering, AeD= aerobic digestion, TT=thermal treatment, CP =composting, DR =drying, IC=incineration, WO=wet oxidation, ME=melting.

c) Amount as total solids.

d) Ratio of sludge amount treated by which process to total sludge amount produced in Japan.

Measurement of specific methanogenic activity

In order to measure the specific methanogenic activity (SMA) of digester sludge, a series of batch experiments were performed at 36°C using a 120-ml serum vial with 80-ml working volumes, based on the method (Li and Noike, 1989; Li and Noike, 1992) modified from the techniques proposed by Owen *et al.* (1979) and Dolfing and Bloemen (1985). The digester sludge was used as seed sludge for the batch experiment. The individual substrates used for the SMA measurements included formate, acetate, propionate, butyrate, glucose, peptone, lipid and the influent sludge.

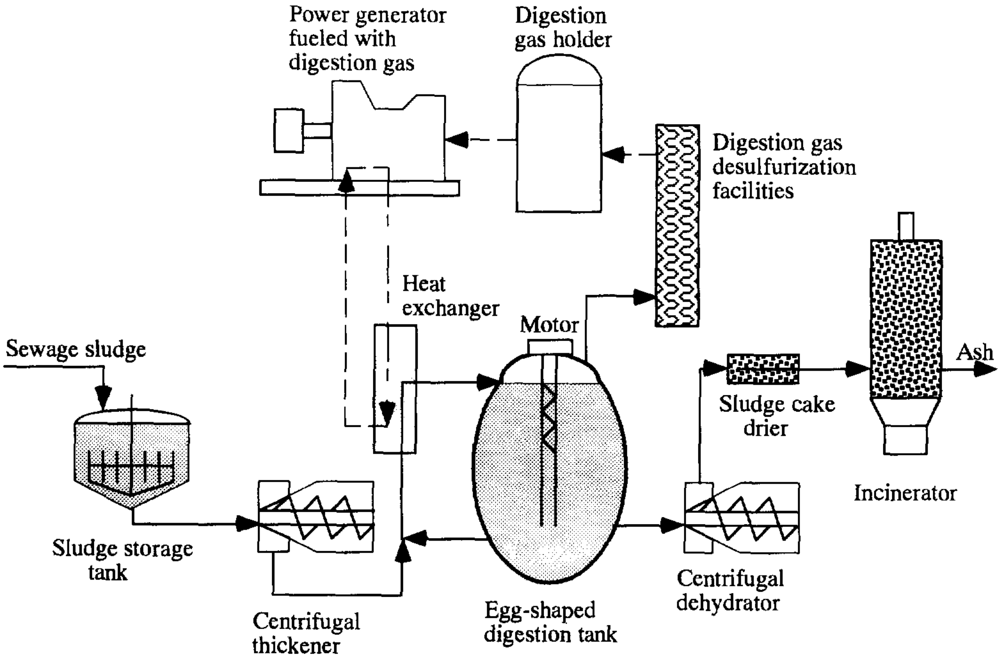

Figure 1. Flow chart of the sludge treatment process with egg-shaped digester and power generator.

Enumeration of methanogenic bacteria

The most-probable-number (MPN) method was used for the enumeration of methanogenic bacteria (MPB). The MPN tests were run in screw-capped glass tubes with butyl-rubber stoppers (Sanshin Industry Ltd., Japan) containing growth media under an anaerobic environment. The modified anaerobic techniques (Balch *et al.*, 1979; Mackie and Bryant, 1981; Chartrain and Zeikus, 1986) for the preparation and use of media were used in this study. For the MPN tests of MPB, each litre of basal medium contained: KH_2PO_4, 0.4g; K_2HPO_4, 0.4g; NH_4Cl, 1.0g; $MgCl_2$ $6H_2O$, 0.21g; $NaHCO_3$, 6.0g; yeast extract, 0.2g;Na_2S $9H_2O$, 0.25g; sodium cysteine. HCl H_2O, 0.5g; mineral solution 10 ml (Li and Noike, 1989) and vitamin solution, 10 ml (Balch *et al.*, 1979). The organic substrates in the basal medium were, respectively, 3.0 g sodium acetate for acetate-consuming MPB, and H_2/CO_2 (80/20) for hydrogen-consuming MPB. The medium was dispensed into tubes under anaerobic conditions and the head space contained a gas mixture of N_2/CO_2 (80/20), except for the MPN test for the hydrogen-consuming MPB; in that case, the gas phase was replaced with H_2/CO_2 (80/20) at 2 atm of pressure for inoculation. All tubes were incubated at 36°C for one month. The growth of bacteria was interpreted on the basis of presence of methane in the gas phase of the tube.

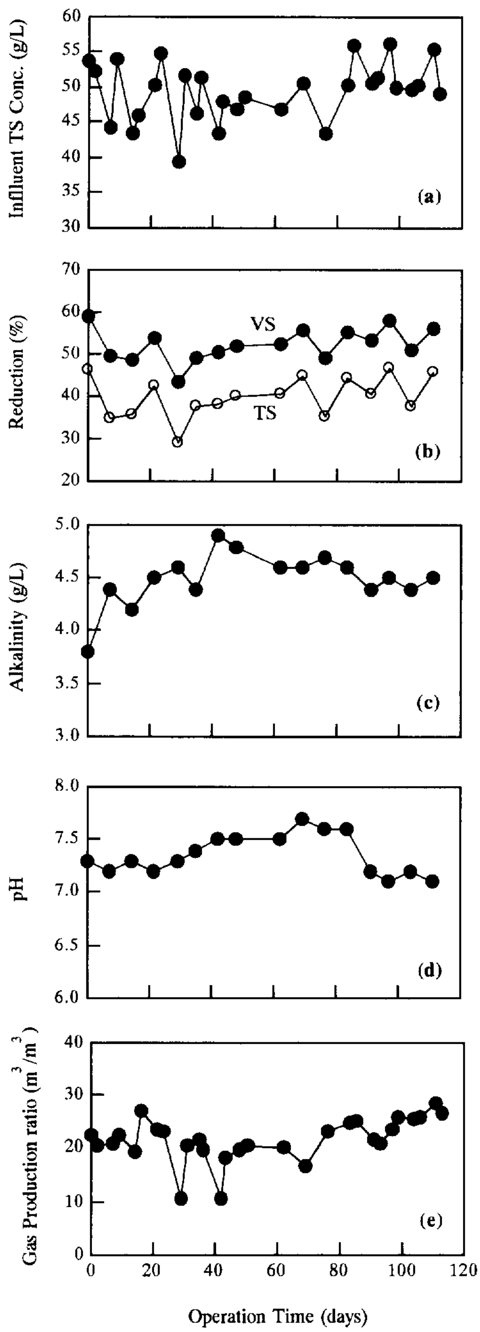

Figure 2. Variation of several operational parameters in the full-scale digester.

Analytical methods

Standard methods (APHA, 1992) were used for the measurements of COD and total solids (TS), volatile solids (VS), suspended solids (SS), volatile suspended solids (VSS), alklinity and pH. Carbohydrate concentration was measured by the anthrone-sulfuric acid method using glucose as the standard. Protein was determined by Lowry's method using albumin as the standard. Lipids were measured by the Bligh-Dyer method. The percentages of methane, carbon dioxide and nitrogen in digestion gas were analyzed by a gas chromatograph (Shimadzu) equipped with a thermal conductivity detector and a 1.5-m stainless steel column filled with activated carbon. Helium was used as the carrier gas with a pressure of 1.5kg/cm^2. The temperatures of the injection port and detector were 140°C and 120°C, respectively. Concentrations of individual volatile fatty acids (VFA) were determined by a second gas chromatograph (Shimadzu GC-8A) equipped with a flame ionization detector and a 1.5m (length) x 5mm (ID) glass column filled with Greensorb. The temperatures of the injection port and detector were 190°C and 170°C, respectively. Helium was used as the carrier gas with a pressure of 1.5kg/cm^2. In addition, hydrogen gas and air were used at the pressure of 0.6kg/cm^2.

RESULTS AND DISCUSSION

Treatment stability of the egg-shaped digester

A total of ten full-scale egg-shaped digesters were investigated in this study. The experimental data were taken weekly to demonstrate the stability of the egg-shaped digester. As an example, Fig. 2 illustrates the long period variation of several typical operational parameters, including (a) influent TS concentration, (b) removal efficiencies of TS and VS, (c) alkalinity, (d) pH and (e) gas production ratio in the digester operated at the retention time of 30 days. The influent concentration of sludge to digester was regulated to about 50 g/L (5%) with a range of 42-55g/L (Fig. 2a). The pH in digester ranged from 7.2 to 7.7 with an average of 7.3 (Fig. 2d), and the alkalinity was around 4000mglL and varied in the range of 3700-4700mg/L (Fig.2c). The reductions of TS and VS were, respectively, in ranges of 40-52% and 50-63% (Fig.2b). The ratio of digestion gas production to influent sludge volume was in the range of 18 to 31 and averaged 24 m^3 /m^3 . In addition, although the digester has been continuously operated for over ten years, there was no noticeable scum and foaming problem in any the egg-shaped digesters investigated.

Table 2. Summary of operational data of full scale digester during steady-state condition

	Influent (concentrated sludge)		Effluent (digested sludge)	
	Average	Range	Average	Range
Environmental factors				
pH	5.43	5.16 - 5.85	7.29	7.1 - 7.4
NH_4^+-N (mg/l)	390	288 - 488	1110	1080 -1110
Alkalinity (mg/l as $CaCO_3$)	595	465 -693	3750	3460 -3820
Sludge concentrations				
Total solids (g/l)	50.2	46.1 - 52.7	28.0	26.6 - 28.7
VS (g/l)	39.9	37.5 - 42.7	17.3	17.0 - 17.5
SS (g/l)	47.2	41.9 - 50.0	25.2	23.6 - 26.7
VSS (g/l)	40.4	37.3 - 41.9	15.4	14.1 - 16.1
Total COD (g/l)	61.1	55.4 -67.2	26.0	21.6 - 31.2
Chemical composition				
Carbohydrates (g/l)	18.1	17.8 - 18.5	4.52	4.14 - 5.20
Proteins (g/l)	13.9	11.0 - 18.0	7.50	6.72 - 8.76
Lipids (g/l)	5.24	4.68 - 5.62	2.59	2.21 - 2.95
Volatile fatty acids				
Acetate (mg/l)	1340	890 - 1900	ND	ND
Propionate (mg/l)	1750	1310 - 2190	ND	ND
Isobutyrate (mg/l)	97	40 - 203	ND	ND
Butyrate (mg/l)	450	298 - 560	ND	ND
Isovalerate (mg/l)	50	0 - 77	ND	ND
Digestion gas production				
Total gas yield (m^3/m^3-influent sludge)			21.2	19.0 - 24.5
Gas composition CH_4 (%)			60.8	60.0 - 62.0
CO_2 (%)			37.0	35.0 - 38.2
N_2 (%)			2.2	1.1 - 4.3

Summary of the treatment performance

Table 2 summarizes the average of operational data obtained from 3 full-scale digesters during steady-state condition. The influent TS concentration was about 5%, of which about 80% was organic matters. Influent SS, VSS, and total COD were 47.2 g/l, 40.4 g/l and 61.1 g/l, respectively. The environmental factors of pH, alkalinity and NH4+-N concentration in the digester varied, respectively, in the ranges of 7.1-7.4, 3460-3820 (mg/L) and 1080-1110 (mg/L). As summarized in Table 3, with the mesophilic egg-shaped digestion tank, the removal efficiencies of carbohydrates, lipids, proteins and VFA reached 75%, 50.6%, 46% and 100%, respectively, and as a result, the reduction efficiencies of TS, VS, SS, VSS were 44.2%, 56.6%, 46.6% and 61.9%, respectively. The results showed that 1 m^3 of influent concentrated sludge could produce 21 m^3 of digestion gas containing 61% methane, and that 57% of the total COD in sludge was removed.

Table 3. Reduction of different components in sludge

Components	Reduction of different components in various sludge (%)				
	This study	Mixed sludge[a)]	Mixed sludge[b)]	Primary sludge[c)]	WAS[c)]
TS	44.2	-	-	-	-
VS	56.6	29.7	38	-	-
Total COD	57.4	-	-	66.0	28.7-51.7
SS	46.6	-	-	59.6	-
VSS	. 61.9	-	-	68.6	25.4-48.8
Carbonhydrates	75.0	27.3	76.0	84.9	30.0-40.5
Lipids	50.6	25.1	65.0	63.0	31.4-53.0
Proteins	46.0	27.1	32.0	53.9	37.3-48.8

a) From Ghosh et al (1987): mesophilic digester at the retention time of 15 days;
b) From Saito (1985) : full-scale mesophilic digester at the retention time of 10-20days;
c) From Li and Noike (1990) : bench-scale mesophilic digester at the retention time of 20days;
d) From Li (1989): maximum reduction efficiencies of waste activated sludge at mesophilic condition

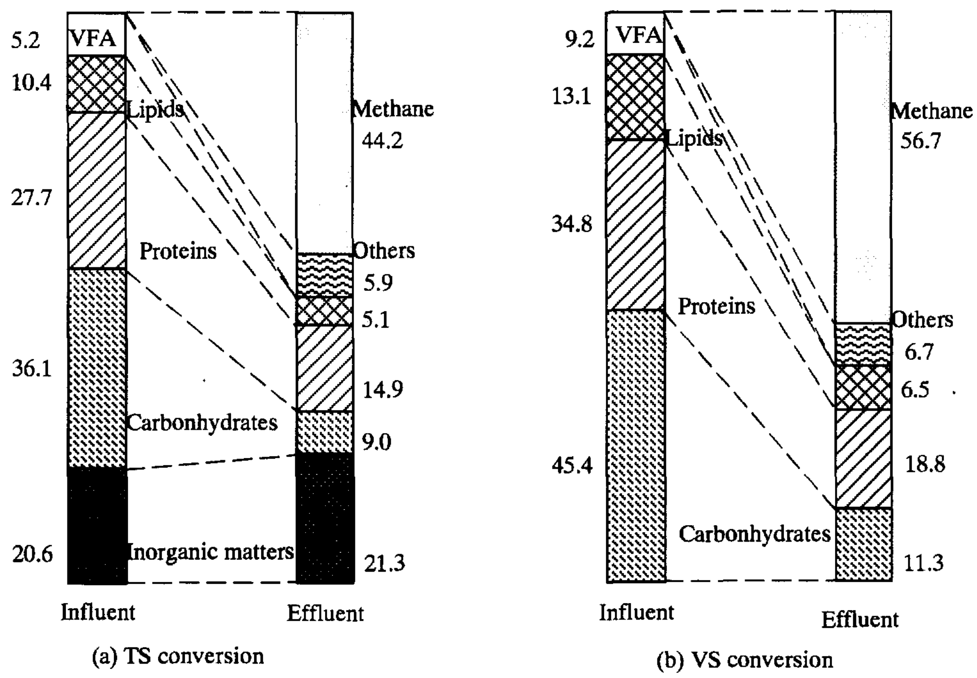

Figure 3. Mass balance of TS and VS conversion in the full-scale digester.

Mass balance in digester

Figure 3 illustrates the mass balance in the digester. The influent TS was composed of 20.6% inorganic matter, 36.1% carbohydrates, 27.7% proteins, 10.4% lipids and 7.3% VFA. In the digester, the influent TS (100%) was converted into various forms, including 44.2% digestion gas, residual TS (21.3%), carbohydrate (9.0%), proteins (14.9%), lipids (5.1%) and others (5.9%). The TS of digested sludge contained 37.9% inorganic matter and 62.1% VS. On the other hand, the influent VS was composed of carbohydrates (45.4%), proteins (34.8%), lipids (13.1%) and VFA (about 9.2%). In the digester, the influent VS (100%) was converted into methane gas (56.7%), residual carbohydrate (11.3%), proteins (18.8%), lipids (6.5%) and others (6.7%). As a result, the total digestion gas yield was 0.422 m^3/kg-TS added or 0.531m^3/kg-VS added, and the methane gas yield was 0.256 m^3-CH4/kg-TS added or 0.324 m^3/kg-VS added. The digestion gas yield was higher than those reported by Ghosh (1990) and Sato(1987).

Table 4. SMA of digester sludge using different substrate

Substrate	MPA of digester sludge (this study)	
	ml-CH4/g-VSS.h	g-COD/g-VSS.d
Formate	0.75	0.051
Acetate	1.31	0.089
Propionate	1.22	0.084
Butyrate	2.51	0.172
Glucose	1.82	0.125
Peptone	2.02	0.139
Lipid	1.69	0.116
Sewage sludge	2.02	0.139

Metabolic activity and population of MPB

Both the SMA and MPN measurments have been used as indicators of bacteria population size of individual trophic groups in complex anaerobic ecosystems (Mackie and Bryant, 1981; Dolfing and Bloemen, 1985; Chartrain and Zeikus, 1986; Li and Noike, 1989). Table 4 summarizes the SMA of the digester sludge measured using the raw sludge and 7 different organic compounds, individually, as substrate. The SMA using raw sludge as substrate was 0.139 g-methane-COD/g-VSS.day, which was highest compared with the SMA using individual organic matter as substrate.

Table 5. Populations of hydrogen- and acetate-consuming methanogens

	Hydrogen-consuming methanogens		Acetate-comsuming methanogens	
	MPN/ml	MPN/g-VSS	MPN/ml	MPN/g-VSS
December	2.0×10^7	1.4×10^9	1.4×10^7	9.9×10^8
February	6.9×10^7	5.1×10^9	4.2×10^7	3.1×10^9
April	9.1×10^7	6.3×10^9	8.5×10^7	5.9×10^9
Average	6.0×10^7	4.3×10^9	4.7×10^7	3.3×10^9

Table 5 summarizes the populations of each trophic groups of methanogenic bacteria measured in December, 1994, February and April, 1995. Hydrogen-consuming methanogens were enumerated on the order of 10^7-10^8 MPN/ml or 10^9-10^{10} MPN/g-VSS, and acetate-consuming methanogens were on the order of 10^7-10^8 MPN/ml or 10^9-10^{10} MPN/g-VSS. It is interesting that the population of hydrogen-consuming methanogens was higher than that of acetate-consuming methanogens. In addition, both populations of hydrogen- and acetate-consuming methanogens in the full-scale egg-shaped digester were comparable to those of bench-scale experiments using primary sludge (Li and Noike, 1990) and using cattle waste (Mackie and Bryant, 1981).

CONCLUSIONS

1. The total solids (TS) of the raw sludge contained 20% inorganic matter and 80% volatile solids (VS), which were further composed of carbohydrates (45.4%), proteins (34.8%), lipids (13.1%) and VFA (about 9.2%). At the mesophilic egg-shaped digestion tank, the removal efficiencies of carbohydrates, lipids, proteins and VFA reached 75%, 50.6%, 46% and 100%, respectively, and the reduction efficiencies of TS, VS, SS, VSS were 44.2%, 56.6%, 46.6% and 61.9%, respectively.

2. The result of gas production showed that 1 m3 of influent concentrated sludge (5%) could produce 21 m^3 of digestion gas containing 61% of methane. Of all influent sludge COD, about 57% was converted to methane and as a result, the total digestion gas yield was 0.422 m^3/kg-TS added or 0.531m^3/kg-VS added and the methane gas yield was 0.256 m^3-CH4/kg-TS added or 0.324 m^3/kg-VS added

3. The SMA of digester sludge using formate, acetate, propionate, butyrate, glucose, peptone, lipid and the raw sludge individually as substrate were 0.051, 0.089, 0.084, 0.172, 0.125, 0.139, 0.116, 0.139 g-methane-COD/g-VSS.day, respectively.Both the hydrogen- and the acetate-consuming methanogens were enumerated on the order of 10^7-10^8 MPN/ml or 10^{19}-10^{10} MPN/g-VSS, but the number of hydrogen- consumers was slightly higher than that of acetate-consumers.

REFERENCES

APHA (1992). Standard Methods for the Examination of Water and Wastewater. 18th Ed. Washington, D.C.

Balch, W. E., Fox, G. E., Magrum, L. J. and Wolfe, R. S. (1979). Methanogens: Reevalution of unique biological group. *Microbiol. Rev.* **43**, 260-296.

Chartrain, M. and Zeikus, J. G. (1986). Microbial ecophysiology of whey biomethanation: characterization of bacterial trophic populations and prevalent species in continuous culture. Appl. *Environ. Microbiol.*, **51**, 188-196.

Dolfing, J. and Bloemen, W. G. B. M. (1985). Activity measurements as a tool to characterize the microbial composition of methanogenic environment. *J. Microbio. Methods*, **4**, 1-12.

Eastman, J. A. and Ferguson, J. F. (1981). Solubilization of particulate organic carbon during the acid-phase of anaerobic digestion. *J. Water Pollut. Control Fed.*, **53**, 352-366.

Elefsiniotis, P. and Oldham, W. K. (1994). Anaerobic acidogenesis of primary sludge: the role of solids retention time. *Biotechnology and Bioengineeing*, **44**, 7-13.

Ghosh, S. (1987). Improved sludge gasification by two-phase anaerobic digestion. *J. Environ. Engrg.*, **113**, 1265-1284.

Ghosh, S. (1990). Pilot-scale demonstration of two-phase anaerobic digestion of activated sludge. *Wat. Sci. Tech.*, **23**(7-9), 1179-1188.

Li, Y. Y. (1989). Degradation mechnisms of sewage sludge in anaerobic digestion, Ph.D. thesis of Tohoku University, Japan.

Li, Y. Y. and Noike, T. (1992). Upgrading of anaerobic digestion of waste activated sludge by thermal pretreatment. *Wat. Sci. Tech.*, **26**(3/4), 857-866.

Li, Y. Y. and Noike, T. (1989). Characteristics of bacterial population and organic matter degradation in anaerobic sludge digestion: on methanogenic bacteria and homoacetogenic bacteria. *Japan J. Wat. Pollut. Res.*, **12**, 771-780.

Li, Y. Y. and Noike, T. (1990). Degradation behaviour of organic matters in anaerobic digestion of primary sludge, *Proceedings of the 28th Sewage Works Research Conference* (Japan), 477-479.

Mackie, R. I. and Bryant, M. P. (1981). Metabolic activity of fatty acid oxidizing and the contribution of acetate, propionate, butyrate, and CO2 to methanogenesis in cattle waste at 40 and 60°C. *Appl. Environ. Microbiol.*, **41**, 1363-1373.

Owen, W. F., Stuckey, D. C., Healy, J. B., Young, L. Y. and McCarty, P.L. (1979). Bioassay for monitoring biochemical methane potential and anaerobic toxicity. *Wat. Res.*, **13**, 485-492.

Saito, K. (1985). Performance of sludge digestion process in full-scale. *Journal of Japan Sewage Works Association*, **22**(257), 40-54.

Sato, K. (1987). An investigation on performance improvement of anaerobic sludge digestion process. Ph.D. thesis of Tokyo University, Japan.

Watanabe, H. (1994). The role of anaerobic digestion in sludge centralized treatment system. *Proceedings of the Special Seminar on Anaerobic Treatment Process*, Tohoku University, Sendai, Japan, 35-37.