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ENHANCED GRANULATION IN UPFLOW ANAEROBIC SLUDGE BLANKET REACTORS BY USING WATER ABSORBING POLYMER

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The effect of adding water absorbing polymer (WAP) on formation of anaerobic granular sludge was evaluated in lab-scale UASB reactors using glucose or volatile fatty acid (VFA) mixture. The development of granular sludge was significantly enhanced by adding WAP. Granules developed on glucose and VFAs had high methanogenic activities and good settleability. The recommended dosage of WAP was between 750 and 1500 mg/l of reactor volume. SEM observations suggested that rod-type *Methanothrix*-like organisms were prevalent species in the granules developed on the glucose while filamentous *Methanothrix*-like bacteria were predominant in the granules grown on the VFA mixture.

Key Words: *UASB reactor, granular sludge, water absorbing polymer, granulation*

1. INTRODUCTION

Upflow Anaerobic Sludge Blanket (UASB) system, developed by Lettinga and his coworkers in the 1970's[1)], has received widespread acceptance and been successfully used to treat various industrial wastewaters. In a well-operated UASB reactor, the anaerobic sludge is often granular in nature. The granular sludge is self-immobilized bacterial cells and has high metabolic activity and high settleability. An UASB reactor containing granular sludge can achieve a high organic matter removal efficiency at high volumetric organic loading rates. Granulation or cultivation of anaerobic granular sludge is the key to successfully start-up an UASB reactor. Generally, anaerobic digested sludge is an appropriate inoculum source for the start-up of reactor. Accomplishment of granulation in UASB reactor requires 10 to 12 months at ambient temperature, or 3 to 6 months at mesophilic temperature conditions, or 4 or more months at thermophilic temperature conditions, when anaerobic digested sludge is used as inoculum[2)-5)]. The progress of granulation is influenced by many factors including the type of inoculum sludge, wastewater composition, and operational conditions (such as specific organic loading rate, upflow velocity, etc.) [1)-3), 9)-15)]. It is known that granulation does not occur in all cases. Development of a protocol or approach to enhance or stimulate granulation has been important for start-up of an UASB reactor.

One of important factors for development of granules from non-granular sludge is presence of nuclei or biocarrier for microbial attachment growth. Several investigators have studied the effect of inert particles on the granulation[3)-6)]. Hulshoff Pol (1989) reported that when the particles (40 to 100 μm in size) were removed from inoculated sewage sludge, granulation was not observed within the period of time that was usually required for the formation of

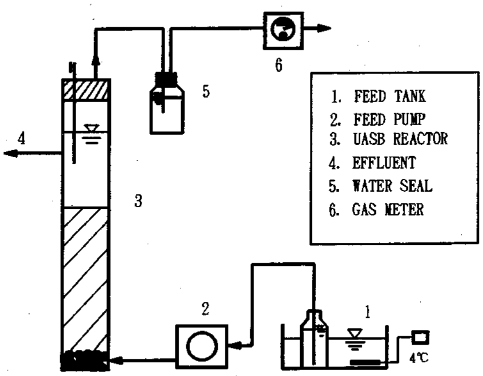

Fig.1 Schematic diagram of lab-scale reactor system.

granules[3]. Addition of the inert particles is likely helpful for the granulation. Adding inert particles (such as zeolite particles with 100 μm size) into inoculated sludge enhanced granulation[6),7)]. However, no difference was also observed in granulation process with and without added sand into digested sludge[4)]. Generally, the specific gravity of the inert particles, especially sand, is greater than biomass. More biomass may accumulate in the upper portion of reactor while the sand particles trend to accumulate in the reactor bottom. Therefore, the chance of contact between the particles and biomass, which is beneficial for microbial attachment growth, may be significantly reduced, resulting in no significant enhancement of granulation.

Recently, we have developed a new approach to enhance granulation by adding water absorbing polymer (WAP) particles into the inoculated digested sludge. This polymer is a pulverulent resin which swells in water and exhibits a complex network structure. Therefore, the polymer can provide more surface for microbial attachment grow than other inert particles. In addition, the contact between particles and biomass can also be improved since the polymer has lower density than sand and other inert materials. In this study, the effect of adding WAP into inoculated sludge on granulation was examined using two typical synthetic wastewaters i.e. a glucose solution and a volatile fatty acid (VFA) mixture solution consisting of acetic, propionic and butyric acids. The effect of dosage of WAP on methanogenic activity and granulation was also evaluated.

Table 1 Experimental conditions

	Series A			Series B		
Reactor	1	2	3	4	5	6
Inoculated sludge (l)	0.6	0.6	0.6	0.6	0.6	0.6
Inoculum conc. (gVSS/l)	13.8	13.8	13.8	13.8	13.8	13.8
Dosage of WAP (mg/l)	0	750	1500	0	750	1500
Substrate	Glucose	Glucose	Glucose	VFA	VFA	VFA

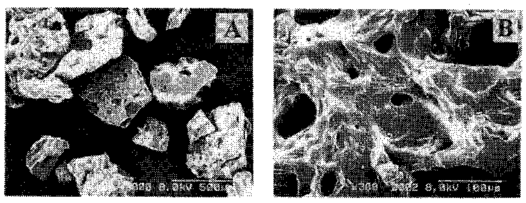

Fig.2 SEM photographs of WAP. A. Outline of WAP particles; B. Surface of WAP.

2. MATERIALS AND METHODS

(1) Laboratory reactor system

Experiments for development of anaerobic granular sludge was performed in laboratory-scale UASB reactors with 1.3 liters volume (**Fig.1**) at 35±1℃. Each reactor system was equipped with a wet gas meter (model W-NK-1B, Shinagawa Seiki Co., Japan). Six reactors were used in this study and divided into two groups. The reactors, operated at a pH range of 6.5 to 7.5, in Group A were fed with the glucose solution while those in Group B were fed with the VFA mixture. The test conditions including the amount of inoculated sludge, WAP added and substrates used are summarized in **Table 1**.

(2) Water absorbing polymer (WAP)

WAP (ST-500D), was obtained from Sanyo Kasei Co. (Japan). The major composition of the WAP is acrylic compound. The diameter of WAP particles ranged between 100 and 200μm (**Fig.2A**). The polymer had a wet density of 1.0 g/ml. Scanning electron microscopic observation indicated this polymer had a complex network structure (**Fig.2B**) and, therefore, high specific surface for microbial attachment growth.

Table 2 Composition of Synthetic Wastewaters

Components	Concentration (mg/l)	
	Group A	Group B
Glucose	8000	—
Acetic acid	—	3000
Propionic acid	—	1000
Butyric acid	—	1000
$NaHCO_3$	4000	4000
NH_4HCO_3	400	400
$(NH_4)_2SO_4$	200	200
K_2HPO_4	200	200
$CaCl_2$	200	200
Yeast	100	100

Note: Both synthetic wastewaters (per liter) contain 1 ml of trace metal solution

Table 3 Composition of trace metal solution

Components	Concentration (mg/l)
$MgCl_2 \cdot 6H_2O$	4
$FeCl_3 \cdot 6H_2O$	5
$MnCl_2 \cdot 4H_2O$	2
$Al_2(SO_4)_3 \cdot 14\text{~}16H_2O$	4
$Ca(OH)_2$	3
$CoCl_2 \cdot 6H_2O$	0.4
$ZnCl_2$	0.2
$NiCl_2$	0.4
$CuCl_2 \cdot 2H_2O$	0.25

(3) Synthetic wastewater

Two typical synthetic wastewaters were used in this study. Wastewater A contained glucose as carbon source while Wastewater B was a VFA mixture. The composition of the wastewaters and trace metal solution are presented in **Table 2** and **Table 3**, respectively.

(4) Inoculum sludge source

All reactors were inoculated with an anaerobic digested sludge obtained from the municipal wastewater treatment plant in Ube city, Yamaguchi, Japan. The volatile fraction of sludge was 0.61 (w/vol). The specific methanogenic activity of the sludge was determined to be approximately 0.2 $kgCOD \cdot kgVSS^{-1} \cdot d^{-1}$, using a batch test method described later.

(5) Analytic method

Total organic carbon (TOC) concentration in liquid samples was determined with a Shimadzu model 500 TOC analyzer. Biogas composition was analyzed by using a Hitachi 663-30 gas chromatography equipped with a thermal conductivity detector at 150 ℃. VFAs were determined with a Shimadzu GC-14 gas chromatography equipped with a flame ionization detector at 250℃. Prior to determination, liquid samples were acidified by using a 0.2 M formic acid solution (1:1, vol sample/vol formic acid). The determination of suspended solid (SS) and volatile suspended solid (VSS) was performed in accordance with standard methods[18].

(6) Methanogenic activity assays

The specific methanogenic activity (SMA) of sludge was determined in anaerobic serum vials at 35℃ using a modified method according to that proposed by Dolfing and Bloemen[8]. The chemical composition of anaerobic medium was same as that reported by Dolfing and Bloemen[8]. The headspace of 70 ml-serum vials, which contained 25 ml medium, was made anaerobic by flashing with oxygen-free nitrogen gas. Sludge sample (approximately 50 to 100 mg VSS) was added into each vial under the nitrogen atmosphere. Respective substrate solution (glucose, acetic, propionic or butyric acid) was added into the vials to obtain a desired concentration (approximately 1000 mg COD/l) and pH was kept at approximately 7.0. These vials were then sealed with butyl rubber stoppers and aluminum caps, and incubated in a 35℃ shaking water bath incubator (model BT-47, Yamato Co., Japan) at 100 rpm. Gas samples were withdrawn from the vials periodically to determine methane concentration. SMA was calculated based on methane production rate and VSS content in each vial and expressed as $kgCOD \cdot kgVSS^{-1} \cdot d^{-1}$. A factor of 350 ml $CH_4 \cdot gCOD^{-1}$ under standard temperature (273°K) and pressure (1 atm) condition was used for this calculation.

(7) Scanning electron microscopic and microscopic examination

The samples of granular sludge for scanning electron microscopy (SEM) were fixed in 0.1M phosphate buffer (pH7.0) containing 2.5% glutaraldehyde overnight, and dehydrated with a graded series of ethanol solutions. Then ethanol was

Table 4 Operational conditions of reactors in Groups A and B

Period		1	2	3	4	5
Average Influent TOC (mg/l)	A	720	2350	2350	2350	2350
	B	565	2163	2163	2163	2163
Average OLR (Kg TOC•m^{-3}•d^{-1})	A	0.36	1.1	1.5	2.4	3.8
	B	0.3	1.0	1.5	2.2	3.5
HRT (d)		2	2	1.5	1	.67
Operational date (d)		1-20	21-57	58-78	79-113	114-135

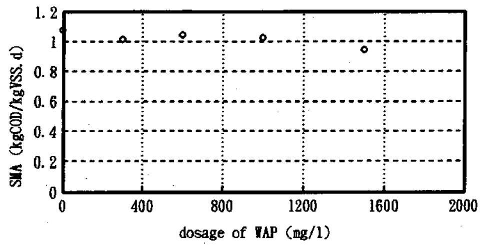

Fig.3 The effect of WAP dosage on SMA activity of anaerobic sludge. Glucose was used as substrate.

replaced with a 2-methyl-2-propanol solution. The samples were subsequently dried by JFD-300 freeze dryer (JEOL Co., Japan) and sputter-coated with gold. SEM microphotographs were taken with a Hitachi S-2300 scanning electron microscope.

Microscopic photographs of granular sludge were taken with a Olympus SZ-PT stereo-microscope (Olympus Co., Japan).

3. RESULTS AND DISCUSSIONS

(1) Effect of WAP dosage on methanogenic activity

Before start-up of reactor testes, the effect of WAP dosage on the specific methanogenic activity (SMA) was examined in order to understand whether WAP caused inhibition of methane production or not. The sludge samples used for this test were withdrawn from a 12 liter UASB reactor that had been fed with a glucose solution for two months. Glucose was used as substrate. The results indicated that no significant inhibition of methane production from glucose was observed even at WAP dosage up to 1500 mg/l (**Fig.3**). Therefore, we decided to use 600 and 1500 mg WAP/l for further reactor tests.

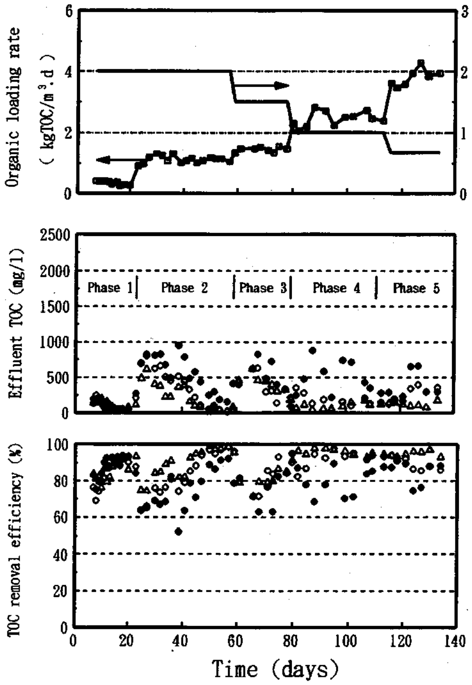

Fig.4 Time course of the OLR, HRT, effluent TOC and TOC removal efficiencies in reactors fed with glucose. ●) reactor 1, ○) reactor 2, △) reactor 3

(2) Granulation with glucose as substrate

Development of anaerobic granular sludge from non-granular anaerobic digested sludge in Group A reactors were achieved with a glucose solution as substrate. WAP was added to Reactors No. 2 and 3 while no WAP was added in Reactor No.1 (**Table 1**).

a) Reactor start-up and TOC removal

After start-up, the reactors in Group A were operated in parallel at a range of organic loading rates (OLR) from 0.36 to 3.8 kg TOC•m^{-3}•d^{-1} (i.e. 1.0 to 10.2 kg COD$_{cr}$•m^{-3}•d^{-1}) over a 135 day period. The reactor operational parameters are summarized in **Table 4**. The operational period is divided into five different periods based on the OLR applied.

The organic loading rates applied to the reactors in Group A, effluent TOC concentrations and TOC removal efficiencies are illustrated in **Fig.4**. During operational Period 1, a high average TOC removal (>90%) was observed in all reactors at a low TOC loading rate. When OLR was increased at the beginning of Periods 2 and 3 , the TOC removal efficiencies in Reactors No.2 and 3 were reduced from 93% to about 75% within one week, and then

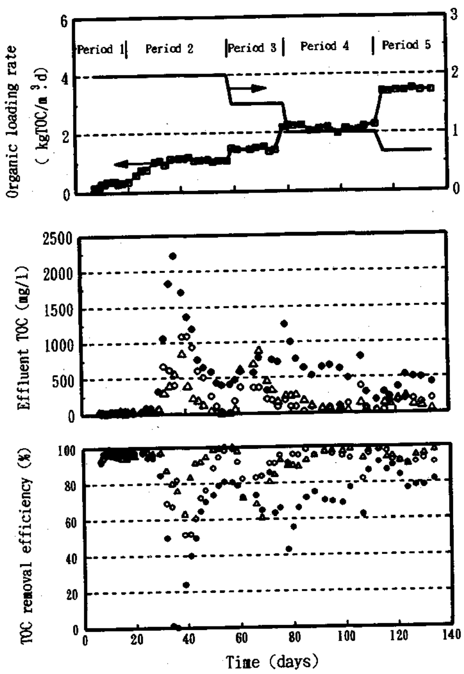

Fig.5 Time course of the OLR, HRT, effluent TOC and TOC removal efficiencies in reactors fed with VFAs.
●) reactor 4, ○) reactor 5, △) reactor 6

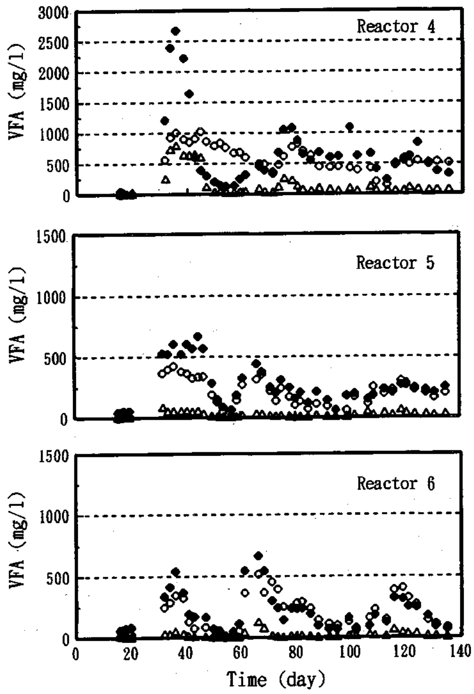

Fig.6 Effluent VFA concentrations of reactors fed with VFAs (Group B).
●) acetic acid, ○) propionic acid, △) butyric acid

were recovered at the level of 85% or more. During the same period, TOC removal efficiency in Reactor No.1 declined from 93% to 65% or less, and then was resumed at the levels of 90 and 85%, in Periods 2 and 3, respectively. This less reduction in TOC removal efficiency implied that more biomass or higher activity was retained in Reactors No.2 and 3 than Reactor No.1 during the start-up of operation.

At the end of Periods 4 and 5, TOC removal efficiencies of 95% and 90% were achieved in Reactors No. 2 and 3, when OLRs were increased up to 2.4 and 3.8 kg TOC•m^{-3}•d^{-1}, respectively. According to the microscopic examination, during this period the granulation was accomplished in these two reactors. On the other hand, higher TOC in effluent (**Fig.4**) and, therefore, lower TOC removal efficiency was observed in Reactor No.1 when OLR was increased. Higher TOC removal efficiency in Reactors No.2 and 3 was due to higher activity or more granules accumulated in these reactors than Reactor No.1.

b) Granule development on glucose

As reported in literature, the progress of granular sludge from non-granular inoculum can be distinguished into at least three phases based on sludge concentration profiles and sludge nature in reactor (Hulshoff Pol et al. 1983; Wu et al. 1985; Hickey et al. 1991). In Phase 1, the sludge bed expanded and sludge concentration in sludge blanket increased. In Phase 2, sludge concentration in the blanket continued to increase and wash-out of flocculent sludge began; consequently the total amount of the sludge in the reactor dropped to a minimum level. At same time , granules began to occur at reactor bottom and gradually grow. In Phase 3, granules were developed to form a granule bed and the volume of granule bed increased.

In this study, these three phases were observed in the reactors. Anaerobic granules with 0.5 to 1.5 mm diameter occurred in the sludge bed of Reactors No.2 and 3 after 40 days of operation (Period 2 in **Table 4**), and according to the microscopic examination, all sludge in these reactors became granular form after additional one month operation. During this period (day 40 to day 70), decomposition of the WAP added was observed by using stereo-microscope and SEM. This caused the granules developed on WAP as nuclei to split into several small fragments. **Fig.8G** and **Fig.8H** showed the SEM photographs of surviving WAP piece in granule in period 3 (Reactor No.3). These fragments, then grew up again to form more mature granules. Eventually, all WAP particles were digested and the granules formed did not contain visible WAP particles.

On the other hand, the results of microscopic examination and effluent SS showed that more flocculent sludge was formed in Reactor No.1 and more biomass was wash-out than Reactors No.2 and 3. Granules were observed in Reactor No.1 after about 60 days of operation and granulation was accomplished after 90 days of operation. This indicated that WAP particles might serve as a biocarrier to allow more biomass attach on them, and therefore, enhanced the formation of granules.

The granules formed in Reactors No.2 and 3 are shown in **Fig.7A** and **Fig.7B**. Compared with the granules developed in the three reactors, we did not find any difference in their shape and size distribution.

(3) Granulation with VFA mixture as substrate

For the reactors of Group B, a VFA mixture was used as substrate. WAP was added to Reactors No.5 and 6 while no WAP was added in Reactor No.4 **(Table 1)**.

a) Reactor start-up and TOC removal

The reactors were started-up side by side with the reactors of Group A. The reactors in Group B were operated at OLRs from 0.3 to 3.5 kg TOC•m^{-3}•d^{-1} (i.e. 0.9 to 10.5 COD_{cr}•m^{-3}•d^{-1}) over a 135 day period. The reactor operation period is also divided into five different periods based on the OLR applied.

The organic loading rates applied, reactor effluent TOC concentrations, and TOC removal efficiencies are illustrated in **Fig.5**. The effluent VFA concentrations of Reactors No.4, 5 and 6 are presented in **Fig.6**. Low effluent TOC and VFA concentrations **(Fig.5** and **Fig.6)** were detected and, therefore, high TOC removal efficiency was achieved in all reactors at the beginning of reactor operation (Period 1 in **Table 4)**. Similar to that observed in the reactors of Group A, higher effluent TOC concentrations were observed, indicating decline of TOC removal efficiency when a higher OLR was applied at the beginning of Periods 2 and 3 **(Fig.5)**. Afterwards, effluent TOC concentrations were decreased and TOC removal efficiencies were increased due to the growth of biomass or activity. Relatively high VFA (acetate, propionate and butyrate) concentrations were observed when the OLRs were increased in these three reactors **(Fig.6)**. In Reactors No. 5 and 6, TOC removal efficiencies were reduced from 96% to 60% at the beginning of Periods 2 and 3 but recovered to 95% at the end of these two periods. However, the TOC removal in Reactor 4 dropped from 96% to less than 20 at the beginning of Period 2 and recovered to only 70% after 37 day operation. This was similar to the observation during the start-up of reactors of Group A, and implied that more biomass or higher activity was retained in reactors when WAP was added into the reactors.

During Periods 4 and 5, effluent TOC concentrations were lower than 200 mg/l **(Fig.5)**, and more than 95% TOC removal was achieved in Reactors No.5 and 6 at organic loading rates of 2.2 and 3.5 kg TOC•m^{-3}•d^{-1}, respectively. During this period, granules occurred in these reactors. At the same time, effluent TOC concentration of Reactor No.4, generally, was greater than 500 mg/l and TOC removal efficiency ranged from 72% to 82% **(Fig.5)**. Overall, higher effluent VFA concentration were detected in the effluent of Reactor No.4 than Reactors No.5 and 6 **(Fig.6)**. This also indicated that better TOC (or VFA) removal was achieved in the presence of added WAP when VFA was used as substrate to develop granules.

b) Granule development on VFAs

The progress of development of granular sludge on VFA mixture was slower than that of in reactors fed with glucose (Group A). Granular sludge occurred in Reactors No.5 and 6 after 70 days of operation. At that time, from the microscopic examination these granules appeared loose and did not show good settleability (average SVI=55.0 ml/g). The development of granules continued. Eventually, granules having good settling properties (average SVI=20.8 ml/g) were formed in Reactors No.5 and 6 after more than four months of operation (**Fig.7C**

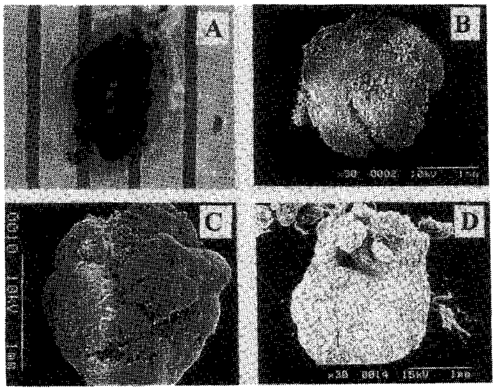

Fig.7 SEM and stereo-microscopic photographs of granules. **A-B**. Granules formed in reactors No.2 and 3. **C-D**. Granules formed in reactors No.5 and 6.

and **Fig.7D**). In addition, no WAP was observed inside the granules, suggesting that WAP added was decomposed by anaerobic bacteria. The mechanism relating decomposition of WAP remains to be studied further.

In contrast, according to the microscopic examination sludge in Reactor No.4 was still in flocculent form even after operation for 135 days. This indicated that the addition of WAP stimulated development of granules from inoculated sludge on the VFA mixture.

(4) Biogas production

The volumes of biogas produced in the reactors of Group A and B were directly proportional to the organic loading rates applied. Initially, lower average biogas yield i.e. 1.3 and 0.9 L biogas/g TOC removed were obtained in the reactors of Group A and B, respectively. These values were less than theoretical methane yield from glucose (1.9 L biogas/g TOC) and VFAs (1.5 L biogas/g TOC).

After 80 days of start-up, the biogas yields were stabilized at a level of 1.9 and 1.4 L biogas/g TOC removed for Group A and B, respectively. The average methane content in gas was 55% and 70% for Group A and B, respectively. Based on these values, the average methane yields in all reactors were closed to the theoretical values of methane yields.

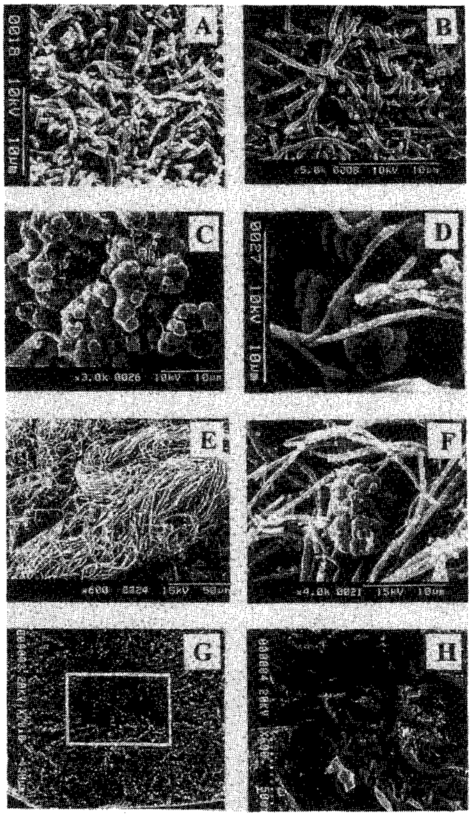

Fig.8 SEM microscopic photographs of sludges. Rod-type *Methanothrix*-like bacteria were observed on the granules developed on glucose (**A-B**). *Methanosarcina*-like cells were predominant on the surface of early developed granules on VFAs (**C-D**). Filament type *Methanothrix*-like bacteria became predominant species in the mature granules developed on VFAs (**E-F**). The surviving WAP piece in granule (**G-H**).

(5) Characterization of granular sludge

a) SEM observation

Based on SEM observations, no significant difference in bacterial morphotypes was observed on the surface of granular sludges withdrawn from the three reactors of Group A at the end of operation. *Methanothrix*-like rods with 2 to 10 cells were prevalent bacteria of granular sludges grown on glucose (**Fig.8A** and **Fig.8B**). For VFA-fed reactors (Reactors No.5 and 6), *Methanosarcina*-like cells were observed as predominant species on the surface of the loose granule withdrawn at the end of operational Period 2 (**Fig.8C** and **Fig.8D**). However, *Methanothrix*-like long filaments became predominant when the reactors operated for another 60 days (**Fig.8E** and **Fig.8F**). At that time, only a few *Methanosarcina*-like cells were observed.

It was not clear why the predominant *Methanothrix*-like species in the granules developed on glucose is rod-type while those in the granules developed on the VFAs mixture was filamentous type because the same inoculum was used for both groups of reactors. The great number of *Methanosarcina* -like cells on the surface of initially appearing granules in Reactors No.5 and 6 may be associated to relatively high acetate concentrations (500 mg/l or more), which is favorable for the growth of *Methanosarcina* species[16),17)], during the first 70 day operation (**Fig.6**). As acetate concentrations became lower (250 mg/l or less), acetate level became more favorable for the growth of *Methanothrix* species. Therefore, *Methanothrix* sp. became predominant.

b) Mean granule size

No significant difference in average granule size was observed among the reactors fed glucose or VFAs at the end of reactor operation. Addition WAP also did not influence the average granule size. The mean diameter of the granules in Reactors No.1, 2 and 3 was 1.8±0.7, 1.9±0.6 and 1.8±0.4 mm in diameter, respectively. The mean diameter of the granules in Reactors No.5 and 6 was 2.1±0.5 and 2.3±0.5 mm in diameter, respectively. The ash content in the granules from Reactors No.1, 2 and 3 was 14～15%, being slight lower than that (17～18%) found in the granules from Reactors No.5 and 6.

c) Specific methanogenic activity

The specific methanogenic activity (SMA) of the granules withdrawn from the reactors in Period 5 were determined in comparison of those with inoculum sludge (**Fig.9A** and **Fig.9B**). The granules from all reactors had much higher SMAs than the inoculum sludge. The granules developed on the VFA mixture had higher SMA from acetate (2.02～2.58 gCOD/gVSS per day) than granules developed on glucose (0.72～1.00 gCOD/gVSS per day). This is consistent with the results reported in literature

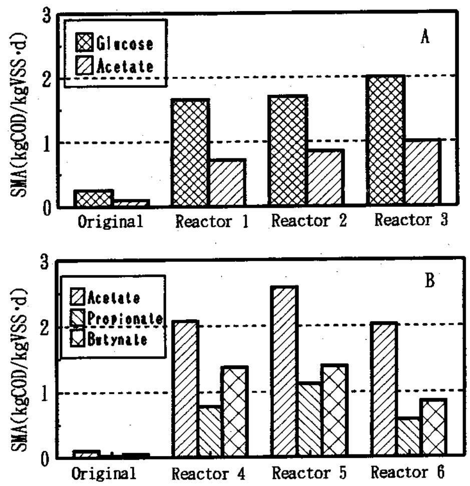

Fig.9 Specific methanogenic activities of granules and sludges.

(Hickey et al. 1991).The SMA of the granules from Reactor No.3, which was fed with glucose and added with 1500 mg/l of WAP, had a relatively high SMA from glucose and acetate. On the other hand, the granules grown on VFAs from Reactor No.5, which was added with 750 mg/l of WAP, exhibited higher SMA from acetate, propionate and butyrate.

(6) The effect of added WAP on granulation

The results obtained from reactor experiments demonstrated positive effect of addition of WAP on granulation. As mentioned above, in reactors of Group A, granulation was accomplished earlier in the presence of added WAP than in the absence of WAP. In reactors of Group B, granulation was observed only in the presence of added WAP after operation of 135 days. Generally, granulation on a wastewater containing carbohydrates (such as glucose) is more rapid than that containing only VFAs (Hickey et al. 1991). This may also explain why approximately 70 days and four months were required for accomplishment of granulation on glucose and VFAs, respectively.

Our observation indicated that the granulation progress in the reactors with added WAP was similar to that reported in literature, which can be divided into three distinguished phases (Hulshoff Pol., 1983; Wu et al., 1985; Hickey et al., 1991).

The role of WAP, we assume, during these three phases are:

① In Phase I, anaerobic sludge (or biomass) was rapidly absorbed or attached to WAP particles and, hence, the amount of biomass to be wash-out was significantly reduced.

② During Phase II, microorganisms attached on WAP particles grew rapidly to form initial granules. WAP particles served as a nuclei or biocarrier.

③ In Phase III, granule bed developed rapidly. Decomposition of WAP also occurred. As a results, the initial granules were split into several fragments and these fragments, eventually, developed as mature granules.

4. CONCLUSIONS

This study indicated that the formation of granular in UASB reactors can be enhanced by addition of WAP as a biocarrier into inoculum sludges. The results of reactor tests using both glucose and VFA mixture supported this idea. Granulation can be accomplished within 70 days when glucose was fed as substrate and WAP was added, being much rapid than no WAP was supplied. A full granule bed were developed in the reactors fed with VFAs in four months when WAP was added but granulation was not observed in absence of added WAP. After granules formed, the WAP added was slowly decomposed. The recommended dosage of WAP for the enhancement of granulation was between 750 and 1500 mg/l of reactor volume.

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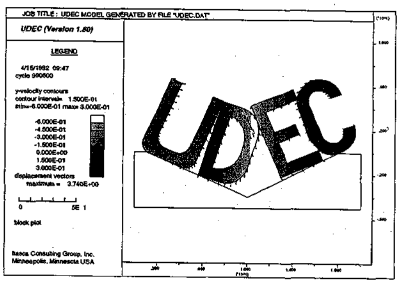
吸水性ポリマーを用いた上向流嫌気性スラッジブランケット(UASB)における グラニュール化の促進に関する研究

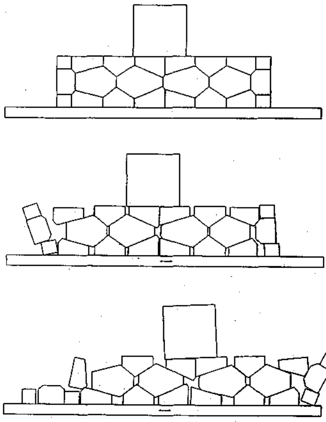
劉　軍・浮田正夫・呉　唯民・今井　剛・中西　弘・深川勝之

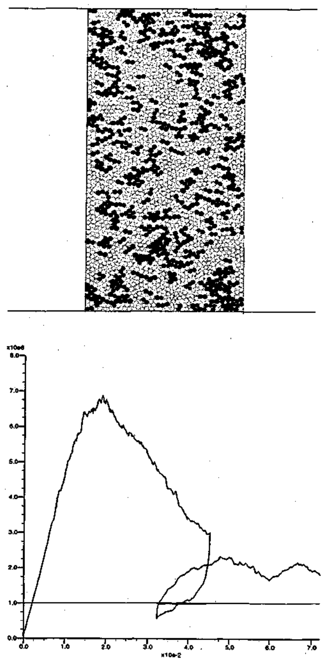
本研究では，グルコースおよび揮発性脂肪酸(VFA)を基質とした実験室スケール UASB における嫌気性菌について，吸水性ポリマー(WAP)を添加することによってグラニュール形成に関する影響を評価した．その結果，WAP を添加することによってグラニュール化が促進されることが実験的に確認された．また，WAP を添加した系の方が無添加系に比較してメタン生成活性が高く，グラニュールの沈降性も良好であった．実験結果から WAP の最適添加量は 750～1500 mg/l 程度であった．電子顕微鏡による観察から，グルコースを基質としたグラニュールでは *Methanothrix* とみられる桿状菌が優占種となっており，一方 VFA を基質とした場合には *Methanothrix* とみられる繊維状菌が優占種となっているのが確認された．

個別要素法プログラムシリーズ

■開発元　Dr.Cundall（ITASCA社）







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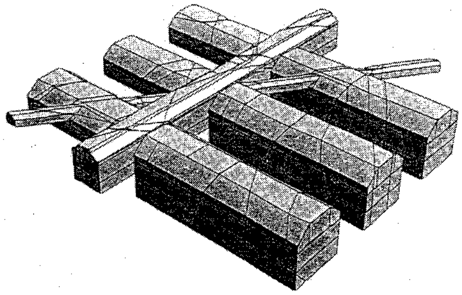
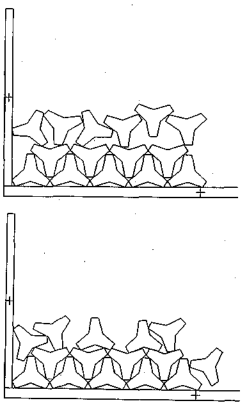
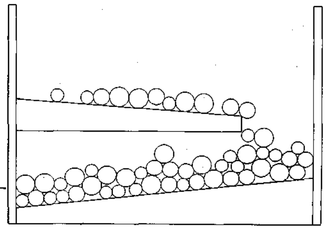


3DEC



BFLOW



BALL-Poly

■価　格

●ロード・モジュール

・UDEC	SUN/IBM-PC（標準バージョン）	110万円
	（Barton-Bandis Optionを含む場合）	160万円
・3DEC	SUN/IBM-PC	550万円
・PFC-2D	SUN/IBM-PC	70万円

●ソース・コード

・UDEC	SUN/IBM-PC（標準バージョン）	190万円
	（Barton-Bandis Optionを含む場合）	240万円
・BFLOW	SUN	190万円

プログラムはいずれも最新バージョンを提供いたします。また、問題に応じたプログラムの開発も行っています。

＊当社は1988年7月からITASCA社の販売代理店をしています。

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㈱システムネットワーク内

地盤の非線形解析プログラム

■開発元　Dr.Cundall（ITASCA社）

FLAC-2D/3D (Fast Lagrangian Analysis of Continua)

1950年代に有限要素法が出現し、コンピュータの発展と共に進歩をとげていったのと並行して、衝撃分野での解析を目的に始まった差分法に基づく、“Hydrocodes”もすくなからぬ成功をおさめていました。応力波伝播を基本とする弾塑性固体の大変形、スライド・ライン手法による滑り・剥離挙動の解析には目覚ましいものがありました。しかし、これらを取り扱うプログラムの多くは公的機関での開発のため公開されたものは余りありませんでした。FLACはこの流れをくむ地盤非線形解析プログラムです。

プログラムの特徴

- 幾何学的大変形及び材料非線形を取り扱うことができます。陽解法のため歪み軟化解析が容易です。
- 複雑な３次元地盤をモデル化するため、優れたジェネレーター機能をそなえています。
- 機能追加のための開発ツールFISHプログラミング言語を備えていますので、機能追加が容易です。

要素ライブラリー

- ２次元平面歪／応力要素（2D）
- ソリッド要素（3D）
- ビーム要素（2D）
- ロックボルト要素（2D, 3D）

適用分野

- 斜面・盛土の設計及び安定解析
- アースダム及びコンクリートダム解析
- トンネル、鉱山掘削解析
- 地下水、圧密、液状化解析（2D）

構成則

- 等方性、非等方性弾性
- 弾塑性（Mohr−Coulomb, Drucker−Prager）
- 偏在ジョイント・モデル（Ubiquitous joint）
- 歪ー硬化／軟化　● ヌル要素
- 液状化FINNモデル（2D）等

その他の構成則の機能追加も可能です。

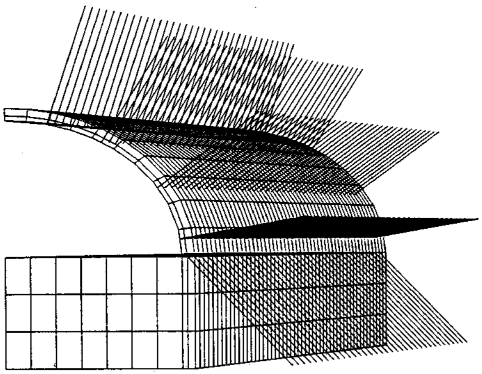
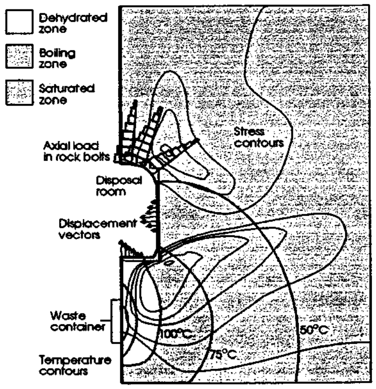


Figure 5 Steel bolt pattern for Method 2



Thermomechanical conditions five years after nuclear waste emplacement.

■価　格（ロード・モジュール）

- FLAC-2D　SUN/IBM-PC（標準バージョン）……………………………80万円
  （Dynamic, Creep, Thermal Optionを含む場合）……110万円
- FLAC-3D　SUN/IBM-PC（Creep Optionを含む）…………………190万円

プログラムはいずれも最新バージョンを提供いたします。また、問題に応じた地盤非線形プログラムの開発も行っています。

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