International Journal of Environmental Science and Development, Vol. 1, No. 2, June 2010
ISSN:2010-0264

Dewatering Waste Activated Sludge Using Greenhouse-Gas Flotation followed by Centrifugation

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***Abstract*—The aim of this study is to develop a simple method for dewatering waste-activated sludge (WAS) for easier reuse and safer disposal of sludge. The paper builds on the success of a new flotation technique developed in previous research by the author utilizing the high water solubility of CO_2 gas along with the model-gas ($80\%N_2+20\%CO_2$). The paper introduces a simple laboratory model for dewatering WAS in two stages, flotation followed by centrifugation. The first stage enables recycling a mixture of greenhouse gases containing 20% of CO_2 and 80% of N_2 gases by volume. The second stage uses a simple centrifuge model for dewatering WAS. Experiments were carried out to reduce the moisture content and volume of WAS. This was executed by generating low pressure using centrifugal force introduced by a simple centrifuge apparatus. Using the experimental dewatering model, promising results were obtained for dewatering WAS. Furthermore, additional data were obtained, such as the effect of temperature on the efficiency of dewater-ability. It is hoped that the results of this study will lead to more study for the efficient reuse of greenhouse gases. This can happen by collecting and recycling industrial emissions of fossil fuels then utilizing them in wastewater and sludge treatment, thereby decreasing the resulting harmful effects of these gases on global warming.**

***Index Terms*—CO_2-gas, centrifugation, flotation, nitrogen, waste-activated sludge.**

I. INTRODUCTION

As a general idea, dewatering sludge is a physical unit operation to reduce its moisture content for reasons such as reuse, disposal, etc. Although there are different conventional methods used for this purpose, current methods still need to be improved or simplified. In this paper, a simple method is developed for dewatering the floated sludge [4].

The method applies the use of low pressure force introduced by centrifugation method in a simple centrifuge model. This method could also be used for the fresh sludge, i.e. without flotation. However, flotation of the sludge using a mixture of ($80\%N_2+20\%CO_2$)-gases, model-gas, improves the dewatering results and is a new technique, as shown in this paper. The target here is to reduce the sludge volume and moisture content of the waste-activated sludge (hereafter WAS) by utilizing a simple method for dewatering. This method should at least result in equal or better results than conventional dewatering methods. Also, recycling a model-gas produced by factory smokestacks and the burning gas of fossil fuels could be possible by collecting the gas emissions using one of the known methods of gas collection, such as the down delivery method, through cooperation between the source producing the gas and the treatment plants [3]. For the flotation stage in conventional methods, air is dissolved in the wastewater under a pressure of several atmospheres, followed by a release to atmospheric level, called the "supersaturate and release" method [1], [2]. Instead of air, in this paper the usefulness of dissolved CO_2 gas flotation, mixed with a model-gas was presented. This unique idea comes from the fact that CO_2 gas has about 20 to 30 times' higher water-solubility than air. This phenomenon depends on the generation of CO_2 micro-bubbles after the pressure release. One should keep in mind that the differences of gas substances give little influence on the bubble flotation results, so that CO_2 gas flotation leads to the decrease of greenhouse effect in addition to the enhancement of micro-bubble flotation efficiency [5]-[9]. For practical uses, the effluent gases from industrial incinerators or factories are not pure CO_2 gas. Methane and nitrogen are produced with CO_2 gas in a mixture. After the previous success of using a model-gas ($80\%N_2+20\%CO_2$) for the flotation of WAS, recycling that mixture of gases could be possible [5]. If we apply a simple centrifugation method using a centrifuge model on the floated sludge, we could reduce the sludge volume and moisture content. Some experimental runs on using micro-bubbles of mixture of ($80\%N_2+20\%CO_2$) gases instead of air were performed.

The optimal results of conditions for CO_2 gas-flotation using the model-gas were concluded in a previous study [5]. After obtaining successful results for flotation of the WAS using the model-gas, experiments were carried out to reduce the moisture content and final volume of the floated sludge using a centrifuge model, Fig. 3. Using the centrifuge model for the floated WAS, the WAS volume could be reduced to a satisfactory amount. No flocculants or chemicals were added during the two stages.

II. METHODS

The sample used is WAS taken from a municipal sewage treatment plant in Kitakyushu City, Japan. Its moisture content ranged between 0.9960 and 0.9985. The pH value ranged between 6.3 and 7.4. The sludge volume index (SVI) was about 200. At first, the flow of the two gases was adjusted to feed the pressurized tank by the required ratio ($80\%N_2+20\%CO_2$) in volume using electronic flow meters,

Manuscript received July 5, 2010.
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shown in Fig. 1.

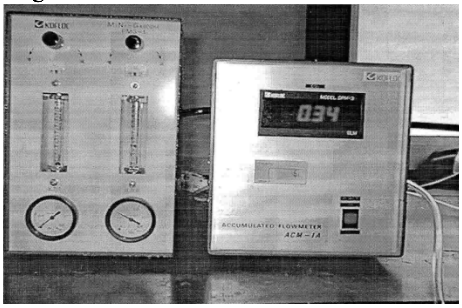

Fig. 1: Flow meters for adjusting the model-gas [5].

In order to generate the micro-bubbles of the gas, the sludge is pressurized in the tank (b) and supersaturated in 6 minutes. That period was previously proven to be enough time for supersaturating the sludge with CO_2 gas [9]. In order to dissolve the model-gas into the WAS, the gas circulation and liquid circulation methods were tested in a pressurized tank. After several trials of flotation using pure carbon dioxide [9], it was found that about 4 to 6 minutes' liquid circulation at the gauge pressure of 40 to 80kpa achieved good flotation results as this value of the saturation pressure equals about 1/10 of the usual dissolved-air flotation pressure. In order to promote the formation of micro-bubbles, the WAS that was supersaturated by the model-gas was injected to the flotation cell (a) at a high speed [6], [9].

As shown in Fig. 2, "Laboratory Flotation Model," the experimental flotation model consisted of two parts. The first part was used to dissolve the model gas into the WAS using the gas and liquid circulation methods [4], [6], [9], and [10]. The inner diameter of the pressurized tank was 10cm and the total height was about 100cm [4], [6], and [10]. The second part, the flotation cell (a), was an enclosed acrylic pipe with an inner diameter of 6.4cm and a height of 100cm. The flotation cell had three openings, each for adding the sludge, exposing to the air pressure, and fixing the gauge pressure. Furthermore, the flotation cell was surrounded by a cylindrical water jacket to control the temperature of the WAS using the circulation method [4], [6], [10]. The typical procedure for each run consisted of using four liters of WAS and a flow rate of model-gas for WAS saturation equaling 2.0 liters/minute.

For generating the fine micro-bubbles of the gas, the WAS underwent bubbling for 6 minutes. In each run, the bubbling pressure was kept constant, as shown in Table I. The bubbled WAS was then transmitted to the flotation cell and exposed to atmospheric pressure using the pressure release method. The mixture underwent thermal treatment using 50°C, 40°C, 30°C, and 20°C. Also, the 60 minute duration of the flotation used was the same as that used in the CO_2 gas flotation [4]-[7].

Before beginning the experiment, pH value and the temperature of the WAS were measured. All samples were exposed to air during the period of experiments to ensure the full aeration of the WAS and to keep its physical characteristics constant.

TABLE I: EXPERIMENTAL DATA AND RESULTS OF STAGE 1, FLOTATION

Run No.	Initial Data							Results		
	H_o	T_{si}	T_{so}	ε_o	B_t	B_p	S_p	H_{f60}/H_o	ε_∞	C_s
	Cm	°C	°C	-	Min	kPa	kPa	%	-	%
1	80	14.5	50	0.997	6	80	60	80.9	0.982	79.4
2	80	16.5	50	0.997	6	60	60	80.4	0.971	78.9
3	80	16	50	0.997	6	40	60	74.5	0.98	73.0
4	80	17	40	0.996	6	80	60	65.3	0.981	62.8
5	80	15.5	40	0.995	6	60	60	63.6	0.982	62.1
6	80	15	40	0.995	6	40	60	62.4	0.983	61.2
7	80	15.5	30	0.997	6	80	60	61.7	0.984	60.5
8	80	16.5	30	0.996	6	60	60	60.6	0.985	59.4
9	80	18	30	0.995	6	40	60	58.4	0.983	57.2

Where the formula

$$C_s\% = 100 \times (1 - \frac{(H^* - H_{f60})}{H_o})$$

represents the volume reduction of WAS after one hour of flotation.

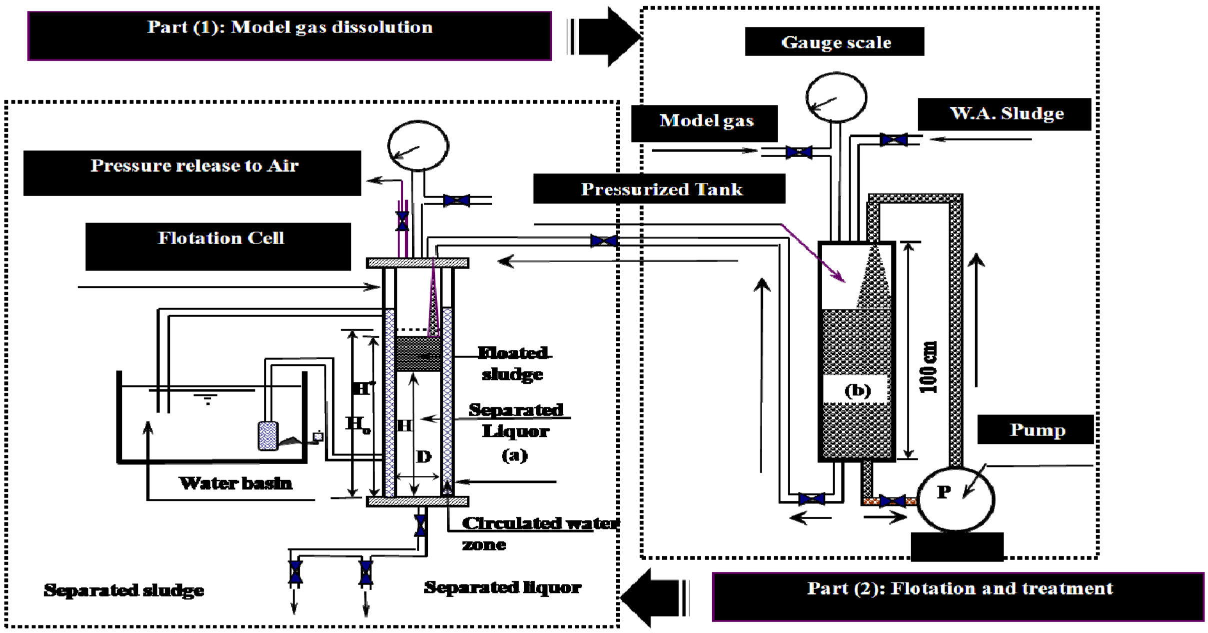

Fig. 2: Experimental Flotation Model [4]

III. Results and Discussion

A. Stage 1: Flotation.

The experimental data and results summarized in Table I were as follows. T_{si} and T_{so} are the WAS temperatures at the start and around the flotation cell during the experiment, respectively. The value T_{so} was adjusted to a constant value during each run using an electronic water heating basin. The symbols B_t and B_p refer to the bubbling time and pressure for gas dissolution, respectively. Also, S_p is the spouting pressure used to inject the sludge from the nozzle at the top of the cell and perpendicular to sludge [6], [9], and [13]. The value of S_p was constant and equals 60kpa because the result of changing the spouting pressure was ineffective [6], [9].

The symbols H_o and H_f refer to the initial height of the sludge and the height of separated liquor at any time during the experiment. In addition, H_{f60} and H^* refer to the height of the separated liquor after one hour of flotation and the total height of sludge, respectively. H^* is higher than H_o due to the space occupied by the bubbles.

The value ε_o refers to the initial moisture content of the WAS. The values ε_o and ε_∞, refer to the initial and final moisture contents of the WAS before and after flotation. The value of pH for the separated liquor after flotation was measured in order to check the amount of gas dissolved in the sludge. The initial height of all flotation specimens was set about 80cm, so the volume of the spouted sludge in the flotation cell of all experiments remained almost constant [6, 13]. The temperature degrees around the flotation cell were controlled using a water jacket, and the experiments were executed using thermal treatments of 30°C, 40°C, and 50°C.

After one hour of flotation, the flotation was stopped and flotation characteristics were then measured, such as moisture content of the floated sludge zone and suspended solids of the separated liquor [6], [13]. The flotation results are shown in Table I. The values of pH for the separated liquor after flotation ranged between 6 and 6.5. This means the dissolution of the model-gas ($80\%N_2+20\%CO_2$) was executed and the liquor became more acidic. However, the pH value was higher after using dissolution of pure CO_2 gas because the dissolved amount of CO_2 gas in the model-gas is lower. The significant factors used for the flotation process of the sludge are as follows [3], [4]:

(1) final flotation height (H_{f60})
(2) sludge volume reduction (C_s)
(3) settling height of the sludge after one hour
(4) moisture content of the floated sludge which we aim to decrease (ε_∞)
(5) economy and practical use of the flotation process.

B. Stage 2: Centrifugation

Centrifugation is considered a method for separating liquids of different density, thickening slurries, or removing solids. Thus, dewatering WAS can be carried out using centrifugation. An electric centrifuge model was prepared for this objective, as shown in Fig. 3a and 3b.

Fig. 3a: Centrifuge dewatering model [4].

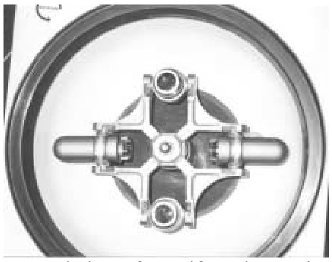

Fig. 3b: Internal view of centrifuge dewatering model [4].

The model is an electric centrifuge by which a maximum revolutions of 5000rpm could be produced. Its commercial name is Himac CT 6D, Hitachi. Dewatering tube dimensions and radius of revolution are shown in Fig. 4. The tube consists of an outer glassy tube, inner PVC tube, filter paper and filter cloth. The glassy tube fits into an external metallic tube. This external tube has an inner diameter of 4.0cm and is attached to the electrical centrifuge driver. The centrifuge apparatus exposes this tube to a definite number of revolutions using electrical power. These revolutions affect the sludge surface by an equivalent pressure. The pressure produced compresses the sludge and separates the solid particles from water through the filter media. Experiments were carried out to reduce the moisture content of WAS using the flotation process and then exposure to centrifugal force.

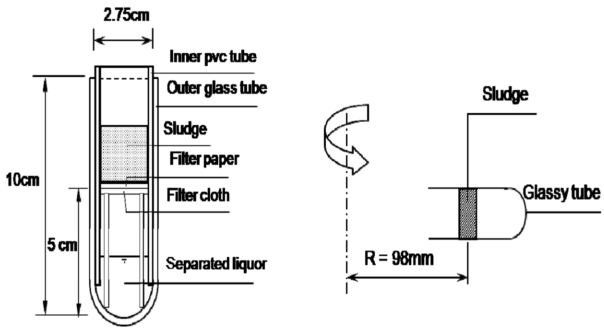

Fig. 4: Geometric dimensions of dewatering tube.

The floated sludge was divided into samples of about 5g each in weight. Each sample was exposed to a centrifugal force for 15, 30, 60, or 90 minutes at four different revolutions, 1600rpm, 2200rpm, 2800rpm, and 4600rpm. These specific revolutions were chosen to obtain a close value of equivalent pressure to the ones used in the previous method, [3] to compare the results. The pressure value was calculated using the centrifugal force formulas. After centrifugation, the weight of the remaining solids and moisture content were measured.

Table II shows the initial conditions before dewatering and the final results. Final moisture content and solid fraction of the sludge and the final volume of separated liquor are presented. The sludge volume is reduced by the amount of separated water, i.e. 3.5 to 1.5ml, or approximately 30% to 75% of the initial volume is reduced.

Using 1600rpm, which produces about 20kPa effective pressure, the solids fraction increased from 1.9% before dewatering to 4.5-7% after centrifugation, an increase of 2.25-3.5 times. This variation depends on the revolution time and the treatment temperature of the floated sludge. In the case of floated sludge treated at 40°C, the final solid fraction is always higher, as shown in Table II. Using 4600rpm, which produces about 110kPa effective pressure, the solids fraction increased from 1.9% before dewatering to 6.5%-11%, an increase of 3.3-5.5 times.

TABLE II: EXPERIMENTAL CONDITIONS AND RESULTS STAGE (2), CENTRIFUGATION

No.	Time	°C	Rpm	Initial M_c	Final M_c	Vol. Filtrate (ml)	Solid Fraction ($1-\varepsilon$)	a	b
1	15 minutes	40	1600	0.982	0.955	0.9546	0.045	0.065	0.208
			2200	0.982	0.948	1.46	0.0521		
			2800	0.983	0.936	2.3299	0.0642		
			4600	0.983	0.933	2.3589	0.0674		
2		30	1600	0.981	0.952	1.9985	0.0478	0.062	0.163
			2200	0.981	0.949	1.7132	0.0513		
			2800	0.981	0.944	2.2079	0.0564		
			4600	0.980	0.934	2.7914	0.0659		
3	30 minutes	40	1600	0.982	0.945	1.882	0.055	0.073	0.178
			2200	0.982	0.943	1.5716	0.057		
			2800	0.983	0.929	2.0152	0.071		
			4600	0.983	0.923	2.4457	0.077		
4		30	1600	0.981	0.950	3.2965	0.05	0.071	0.198
			2200	0.981	0.945	2.1539	0.055		
			2800	0.981	0.939	3.6464	0.061		
			4600	0.980	0.925	3.3199	0.075		
5	60 minutes	40	1600	0.982	0.945	2.4609	0.055	0.08	0.239
			2200	0.982	0.944	2.8301	0.0561		
			2800	0.983	0.929	2.8181	0.0712		
			4600	0.983	0.912	2.404	0.0881		
6		30	1600	0.981	0.942	1.7224	0.0582	0.079	0.192
			2200	0.981	0.939	2.0609	0.0614		
			2800	0.981	0.936	2.0977	0.0635		
			4600	0.980	0.913	1.5778	0.0874		
7	90 minutes	40	1600	0.982	0.930	2.5636	0.0699	0.101	0.222
			2200	0.982	0.924	2.606	0.0763		
			2800	0.983	0.918	2.8606	0.0817		
			4600	0.983	0.891	3.4393	0.1092		
8		30	1600	0.981	0.938	3.3842	0.0617	0.083	0.195
			2200	0.981	0.937	2.4605	0.0633		
			2800	0.981	0.933	2.6322	0.0671		
			4600	0.980	0.907	3.2096	0.0934		

Fig. 5 and 6 show a comparison between final solid fractions of the sludge using different numbers of revolutions when changing revolution period. Moreover, they show the effect of centrifugation on the final moisture content of WAS. It is clear that increasing the number of revolutions decreases the moisture content. This is due to increasing the effective pressure that compresses and separates the water from sludge. The final solid fraction results are nearly similar because after revolution the filter cloth is filled with the particles of sludge. Thus, there is no chance for more separation unless some backwash is used. Using backwash in this case is difficult because the centrifuge is closed. However, centrifugation of WAS after flotation proved to be a very simple and effective method for accomplishing the solids/water separation.

The compressibility of WAS shows the pressure effect on increasing the solid fraction of the sludge. From the best-fit curves we could approximate the relation between concentration of solids and applied pressure, as shown in (1).

Compressibility of the floated sludge using different centrifugation periods and thermal treatment temperatures is shown in Fig. 7 and 8, where the values of "a" and "b" are shown in Table II. Constant "a" ranges between 0.062-0.101, average value is 0.077. The constant "b" ranges between 0.163-0.239, average value is 0.199. Constant "b" indicates the compressibility of the sludge. If "b" is high, the sludge compressibility is high. From the curves, an average approximated formula for this kind of sludge, i.e. waste activated sludge pretreated by flotation, can be written as follows,

$$1-\varepsilon = 0.077 \times P^{0.199} \qquad (1)$$

Equation (1) can be used to estimate roughly the final solid fraction of the sludge using any thermal treatment degree [10]-[13]. However, it cannot be considered as an accurate formula for this target [3], [4].

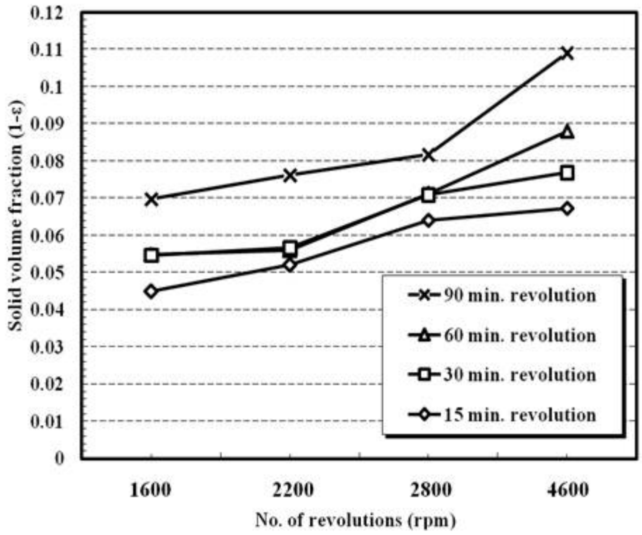

Fig. 5: Solid fraction of WAS after centrifugation (floated WAS at 40°C).

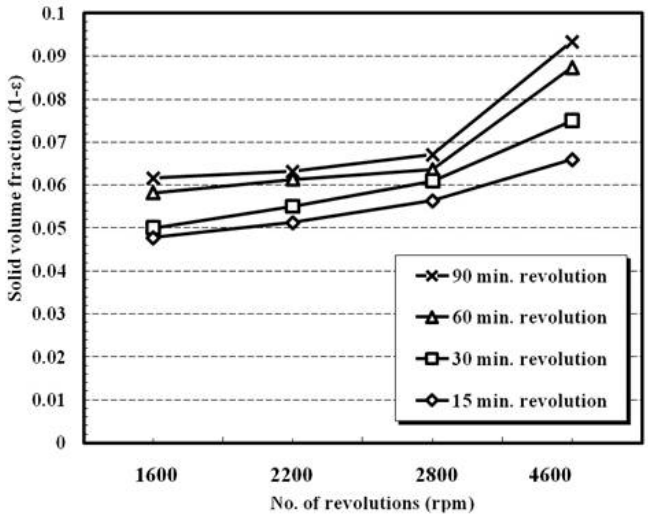

Fig. 6: Solid fraction of WAS after centrifugation (floated WAS at 30oC).

Using 1600, 2200 and 2800rpm gave almost the same final solid fraction using 15, 30 or 60 minutes of revolution. This was reached using 30°C or 40°C floated sludge. Using 4600rpm resulted in higher values of solid fraction, especially with 90 minutes of revolution. In general, using 90 minutes of revolution resulted in higher solid fraction for the floated WAS.

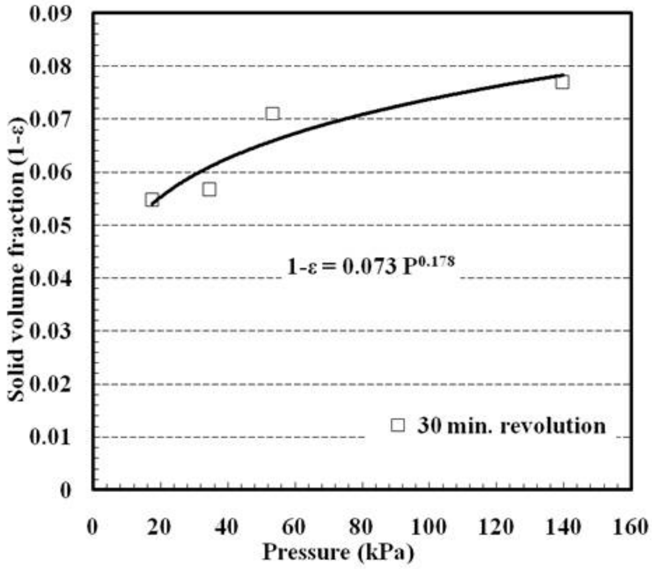

Fig. 7 Compressibility of WAS using centrifugation (floated WAS at 40°C).

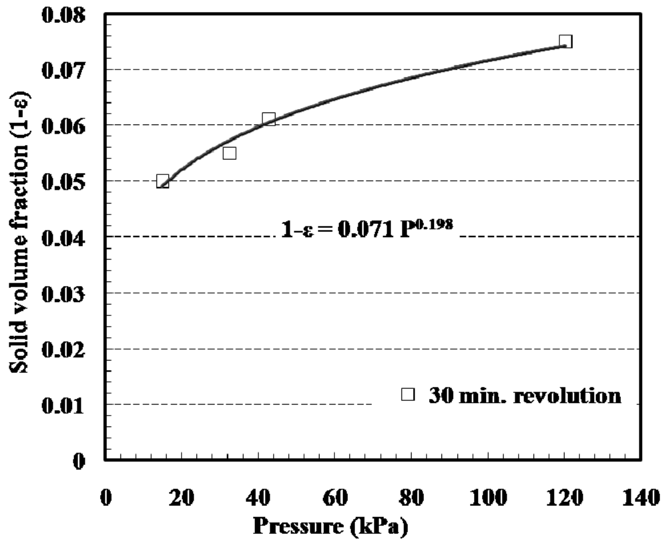

Fig. 8 Compressibility of WAS using centrifugation (floated WAS at 30°C).

The best results were obtained using 40°C floated sludge, 90 minutes of revolutions and 4600rpm. However, using 30°C floated sludge, 60 or 90 minutes of revolutions and 4600rpm achieved exceptionally good results. Constant "a" is almost about 90% of its value using the compression tester, but Constant "b" is almost same value using the compression tester [3], [4]. The main reason is that the pressure is produced directly in the compression tester, whereas it is indirectly produced here. As shown in Table III, the sludge solid fraction increased using the pressure filtration tester to 8-21%, depending on the applied pressure [3]. On the other hand, the sludge solid fraction increased to 5-11% using the centrifuge model, depending on the number of revolutions used.

A comparison between the conventional methods and the laboratory methods is presented in Table III. Referring to this comparison, it can be stated that the objective of the study was achieved and a simple dewatering method was developed.

TABLE III: CAKE SOLIDS OF CONVENTIONAL AND LABORATORY DEWATERING METHOD

No.	Dewatering method		% Cake solids
1	Vacuum filters		13-20[c]
2	Centrifugation	Solid bowl	5-15[c]
		Imperforate basket	8-14[c]
3	Belt filter press		12-20[c]
4	Pressure filtration tester (compression cell)[a]		8-21[b]
5	Centrifuge model [a]		5-11[d]

a. Laboratory model.
b. Using pressure ranges between 0.6-1.2 kgf/cm^2 [3].
c. Values of cake solids for the different conventional methods [4].
d. Using centrifugal force by revolution between 1600-4600rpm.

IV. CONCLUSION

A study of the pressurized-gas flotation of waste activated sludge was conducted in which a model-gas, (80%N_2+20%CO_2) in volume was used in place of air. The aim of this paper was to develop a utilization method of the model-gas, which would be collected from the burning gas of fossil fuels. In addition, a scaled down model of a flotation plant using high solubility of CO_2 in a diluted mixture was intended as well.

Key results obtained were as follows:

a. The solid concentration of floated sludge was about 2–3%, thus the sludge was concentrated 4-5 times higher than using conventional dewatering methods.

b. The turbidity of the separated liquor was so small that it couldn't be measured.

c. The solubility of the CO_2 gas in the model-gas was 10–25% depending on the temperature degree and the bubbling pressure values.

d. The pH value of separated liquor ranged between 6 and 6.5.

Most of the experimental results were relatively equal to or better than those obtained using conventional methods. Therefore, the effectiveness of dissolved model-gas, (80%N_2+20%CO_2), flotation was confirmed. Furthermore, without adding any chemicals, the WAS solid fraction was increased from 5-10% using small and simple centrifuge with maximum revolutions of 5000rpm, after 60-90 minutes of revolution. It can be stated that the laboratory models were highly effective and provide an exceptional basis for the development of full-scale water treatment plants for dewatering aspects. The best results were obtained using 40°C floated sludge, 90 minutes of revolutions and 4600rpm. However, using 30°C floated sludge, 60 or 90 minutes of revolutions at 4600rpm achieved accepted and recommended results.

ACKNOWLEDGMENT

This work shows a great cooperative scientific effort between Japan and Egypt. The author wishes to express his sincerest appreciation to Professor Kazuhiro Fujisaki for his fruitful contact. Great thanks to all the staff members of the water and wastewater laboratory, Kyushu Institute of Technology, Kitakyushu, Japan, for offering the required facilities for the experimental data and analysis.

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