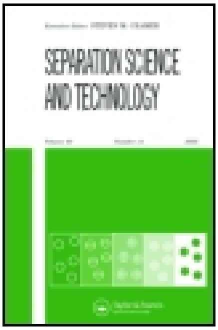

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Effects of Recycling-Sludge Operation on the Structure and Moisture Content of Floc in Water Treatment Plant

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ABSTRACT

Recycling-sludge operation is applied in the Feng-Yuan Water Treatment Facility to treat low turbidity source water. By employing fractal dimension analysis and the dilatometry technique, the effects of recycling-sludge operation on the structure and moisture content of sludge flocs are studied. As the results show, the recycling-sludge operation can decrease the average bound water content by nearly 13–24% and increase the effective floc density, thereby forming a compact structure with a high fractal dimension and low floc porosity. The results also indicate that a significant correlation arises between the fractal dimensions and the bound water content of the sludge flocs.

Key Words. Sludge dewatering; Bound water; Fractal dimension; Effective floc density

INTRODUCTION

Sludge in a water treatment facility is often characterized by a high water content (over 80%) as well as high resistance to either gravity or mechanical dewatering. The problems arising from such occurrences are always associated with handling and ultimate disposal. In light of the more stringent environmental regulations in Taiwan, the moisture content of

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dewatered cake has become a relevant issue for operators in a water treatment facility.

Sludge produced under sweep-floc coagulation often contains greater amounts of water, thereby resulting in more difficulty in dewatering than sludge generated by means of charge-neutralization (1). The recycling of settled alum sludge can contribute toward an improvement in filtration as well as settling characteristics of the sludge in the sedimentation process. It is also known to be helpful in promoting the flocculation of low-turbidity water by increasing the rate of flocculation and to have density of the formed floc (2). Floc with a low density is thought to have a loose structure, high porosity, and high water content.

Tsang and Vesilind (3) classified the water content into four categories: free water, interstitial water, surface water, and bound (internal) water with drying method. They stated that general dewatering procedures fail to remove surface and bound water. Robinson and Knocke (4) indicated that the dilatometric technique is most capable of accurately determining the bound water content among other drying techniques. Regarding the effect of moisture distribution of sludge on the dewatering, free water, a major part of the moisture in sludge, can be easily removed by mechanical dewatering equipment. However, bound water, which occupies less than 10% of the moisture in the sludge, is difficult to remove. What type of moisture exists in sludge and how to improve the efficiency of sludge dewatering (moisture separation) consequently become influential factors in sludge handling, management, and disposal, especially in light of economic considerations. Therefore, a quantitative analysis of variations in floc density, bound water, and physical structure during the flocculation process would facilitate the assessment of moisture change in the sludge.

Excess development in the area of water sources results in rivers, lakes, and reservoirs containing a high concentration of suspended solid. In Taiwan the turbidities of water are quite obviously different between the rainy seasons (primarily in the spring and summer) and the dry season. Moreover, the turbidities may change from 10 to thousands of NTUs in only a few minutes when a heavy rainfall occurs in an upstream watershed area. The Feng-Yuan Water Treatment Facility is a typical example. Normal operations ensue for high and sharp change in turbidity conditions. An alternative sludge-recycle applied for the low turbidity condition has been designed to prevent the floc penetrating through the filter and to reduce the requirement of the coagulant.

In this study an attempt has been made to investigate the effects of recycling-sludge on the floc density, floc structure, and moisture content of sludge.

EXPERIMENTAL SECTION

The Feng-Yuan Water Treatment Facility consists of a rapid mixing tower, four-stage flocculation basin, clarifier, filtration bed, and chlorination basin. Settled sludges in the clarifier and backwash flocs were pumped into a thickening basin. During the low turbidity period of source water, part of the thickened sludge returns at hourly intervals to the rapid-mix tower through the level controller. In this study the sludge samples were taken from the end side of the flocculation basin both during recycling as well as without recycling.

A free settling test has been employed by many investigators (5–7) to measure the wet density of sludge flocs. Based on measurement of the floc terminal settling velocity and floc diameter, the floc density can be calculated with modified Stoke's equations (5). Before the measurement, sludge flocs were carefully collected by a pipette and then slowly released into the quiescent column. Prior to the sample settling, a 2.5-mm ϕ iron line was vertically sunk to the center of the quiescent column and was focused by a video camera to show the scale on the video tape. The settling travel of individual sludge aggregates in a quiescent column was recorded by a video camera equipped with a close-up lens. The floc diameter and settling velocity in the column were determined by replaying the tape.

In this study the dilatometry test was used to analyze the bound water content. This method is based on the theory that bound water remains in liquid form at a temperature below the freezing point temperature (−20°C) of free water (8). If the quantities of total water and free water are known, the difference between them is regarded as the bound water content. A dilatometer with a total volume of 50 mL, similar to that used in Ref. 4, was employed to measure the bound water content of our samples. A 15-g sample was introduced into the dilatometer and followed by filling the dilatometer with an indicator fluid. A mineral oil (Shell Donax TG, USA) was selected as the indicator fluid based on the selection criteria described in Ref. 4. Dry ice in an ethanol bath was used to freeze the sludge and to maintain a constant system temperature. The level changes in the dilatometer during the cooling period (20°C to −20°C) were recorded as a function of temperature. Contraction and expansion curves were developed for the indicator oil and the sludge's supernatant over the temperature range used for all dilatometers. A contraction curve for the indicator oil without any supernatant was also established. By using both the contraction curve for the oil and the expansion curve for the supernatant, the contraction coefficient of the oil and the expansion coefficient of the supernatant were quantified. The total water content of the sludge was determined by drying at 105°C for 24 hours; the free (frozen) water content under −20°C was determined according to Eq. (1). Hence, the amount of bound water was calculated by subtracting the free water content from the total water content.

$$\text{Frozen water content} = (\Delta L + W \times A)/B \tag{1}$$

where ΔL = level difference of 20°C to −20°C
W = weight of oil used
A = oil contraction coefficient for each dilatometer
B = expansion coefficient of sludge filtrate for each dilatometer

Prior to the measurement of bound water, the sludge flocs were allowed to settle for 6 hours after sampling from the flocculation basin.

RESULT AND DISCUSSION

A log-log plot of the effective floc density and diameter in the source water with low turbidity is shown in Fig. 1. It indicates that the effective densities of floc decrease with an increase in floc diameters. This relationship has also been observed by others.

Tambo and Watanabe (5) developed an equation to describe the relationship between the floc diameter and the effective floc density:

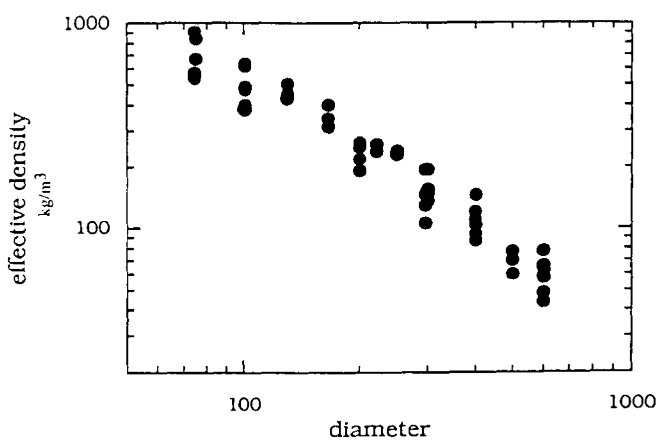

FIG. 1 A typical relationship between effective floc density and diameter.

$$\rho_e = \rho_f - \rho_w = \frac{a}{(d/l)^k} \tag{2}$$

where ρ_e = effective floc density
d/l = dimensionless diameter
ρ_f = floc density
ρ_w = fluid density
d = floc diameter
a, k = constants

The k value can be determined from the slope of the log-log relationship between the diameter and the effective floc density. The values of k and a can be affected by many factors including the chemical and physical properties of the suspension, type of coagulant, coagulant dosage, pH, and agitation time and intensity (5). In this study the influent turbidity varied due to the recycling operation, and other factors including dosage, pH, and mixing intensity were kept constant. Table 1 lists the k value and the effective floc density for the different turbidities of source waters with nonrecycling (normal) or recycling operation. In a previous study it was suggested that the k value is not greatly affected by the pH, agitation intensity, raw water alkalinity, and flocculant aids, but is significantly

TABLE 1
Calculated Results of k Value and Effective Density of Floc (size = 100 μm) in the Recycling-Sludge and Normal Operation Conditions[a]

Operation condition	D/P	k	Effective floc density (log ρ_e)
R	0.1	1.17	2.28
N	4.0	1.81	2.17
R	0.12	1.69	2.55
N	4.1	1.79	2.37
R	0.13	1.22	2.76
N	4.9	1.64	2.52
R	0.08	1.07	2.44
N	5.7	1.45	2.27
R	0.11	1.42	2.39
N	5.2	1.72	2.21

[a] R = recycling-sludge operation. N = normal operation. D/P = ratio of coagulant dose to particles concentration (PAC, ppm/SS, ppm).

influenced by the ratio of coagulant dose to particles concentration (*D/P* ratio); the *k* value increases as the *D/P* ratio increases (5). The results (Table 1) indicates that *k* for the sludge-recycling operation is lower than for normal operation. The *D/P* ratio for the recycling condition is lower than for the normal condition because the particle concentration increases for the sludge-recycling operation. Figure 2 presents a typical comparison of the two operation conditions in log(effective density) vs log(diameter). This figure indicates that the recycling operation in a water treatment facility can be enhanced by dense floc formation, thereby resulting in an increase of the floc's effective density and a decrease of *k* values. This improvement can be attributed to the recycling sludge. When recycling sludge is added to the rapid mixing tower and the flocculation basin, it can be regarded as a coagulant aid which increases the particle concentration and decreases the *D/P* ratio. As a result, the dominant mechanism of flocculation changes from sweep-floc coagulation to charge-neutralization coagulation. It is well known that the sweep-floc mechanism may result in a lightweight, fragile, and slow-settling floc (17). Furthermore, the residual coagulant in recycling sludge also increased the ionic strength of water and enhanced double-layer compression during flocculation. Under such circumstances the degree of coalescence among the particles in the sludge floc would be raised. A more dense floc and a lower *k* value would therefore be produced. This result was also referred to by Glenn et al. (2). They claimed that recycling of alum sludge can contribute toward im-

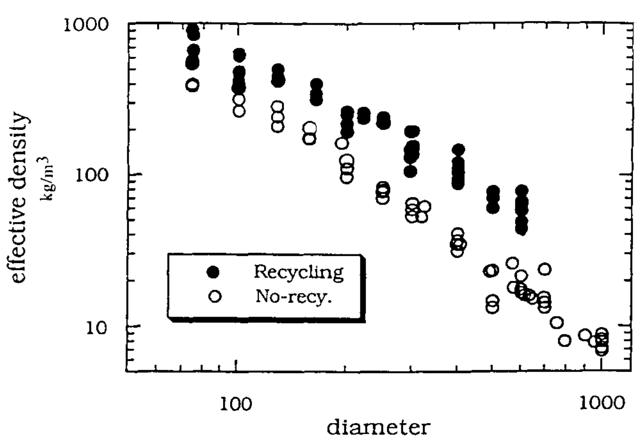

FIG. 2 The effect of recycling-sludge operation on the effective floc density.

provement in promoting the flocculation of low-turbidity water by increasing the flocculation rate and the floc density formed.

The geometric characteristics of particle aggregates generated in water treatment processes are difficult to describe owing to their highly irregular and disordered nature (9). Fractal theory, a mathematical description having no definite form or irregularity, was applied to the description of sludge floc by Mandelbrot (10). Thereafter, fractal theory has been applied to characterize the structure of aggregates, sludge flocs, and filter cakes by many investigators (7, 9, 11, 12, 16). An effective fractal density ($\rho_f - \rho_l$) can be expressed as in Eq. (3) which is related to a radius function for a fractal of radius R formed by n primary particles of radius R_0, a proportionality (C), and a primary particle density (ρ_p) (7).

$$\rho_f - \rho_l = c\left(\frac{R}{R_0}\right)^{D-3} (\rho_p - \rho_l) \tag{3}$$

The fractal dimension (D) can be determined from the slope of the log-log relationship between diameter and effective floc density as listed in Table 2. This table indicates that D values range from 1.19 to 1.93, and the D values of floc formed in recycling operations are higher than normal operations for the low turbidity of the source water. The theoretical values of fractal dimension vary from 1 to 3 and provide a useful index of floc compactness (7, 13). Thus, the flocs produced from the recycling opera-

TABLE 2
Experimental Results for Sludge Flocs

Operation condition[a]	Fractal dimension	Sludge solid content (%)	Bound water content (g-water/g-dry mass)	Bound water reduction (%)
R	1.83	2.05	3.9	17
N	1.19	1.93	4.7	
R	1.31	2.21	4.1	18
N	1.21	2.15	5.0	
R	1.78	1.99	3.5	24
N	1.36	1.98	4.6	
R	1.93	1.86	3.5	20
N	1.54	2.10	4.4	
R	1.58	2.05	3.9	13
N	1.28	1.98	4.5	

[a] R = recycling-sludge operation. N = normal operation.

tion in this field investigation exhibit a more compact structure. This evidence conforms to both the result of density variation as shown in Fig. 2 and to Tambo's work (5). That is, an increase in the ratio of coagulant dose to particle concentration (*D*/*P* ratio in this study) considerably increases the slope (*k* value) of the log(effective density) vs log(diameter) plot. A lower *D*/*P* ratio value for the recycling operation reveals more particles in a rapid-mixing tower. Furthermore, the conditions needed for this lower ratio value which promotes adsorption-charge neutralization tend to form smaller and denser flocs than the conditions promoting sweep-coagulation (1).

The diversity of floc structure for sludge may be characterized through an analysis of floc porosity. The floc porosity, ε, can be expressed by (14)

$$\frac{(\rho_f - \rho_l)}{(\rho_p - \rho_l)} = 1 - \epsilon \tag{4}$$

The typical diversity of floc porosity with a variation of floc size for recycling and nonrecycling sludges is shown in Fig. 3. The observed relationship between the floc sizes and their porosity indicates that the floc porosity of the recycling sludge is lower than the nonrecycling sludge when the floc size is smaller than 600 μm. This diversity in floc structure may supply an explanation for the variations in *D* values and, therefore, for the bound water contents, as discussed below.

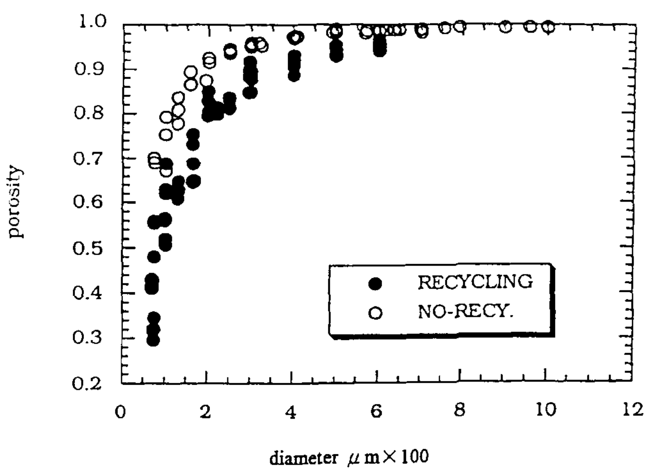

FIG. 3 The effect of recycling-sludge operation on the floc porosity.

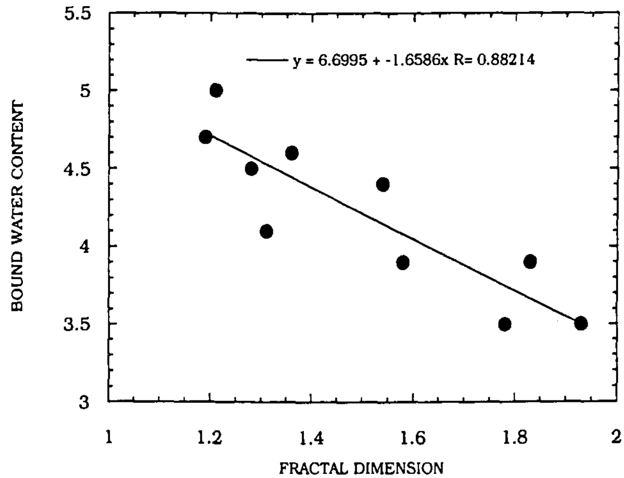

FIG. 4 The relationship of fractal dimension values and bound water content of sludge flocs.

The effects of recycling sludge on the moisture contained in flocs are summarized in Table 2. The data indicate that the recycling-sludge operation can decrease the average bound water content by nearly 13–24%. With the participation of recycling sludge, the flocculation of raw particles tends to form a close configuration and a less interstitial space. These flocs, consequently, have lower porosity and bound water content. Knocke and Kelley (15) indicated that flocs with a high density can result in a better dewatering rate and a higher cake solids concentration. Furthermore, the bound water content notably decreases as the fractal dimension value increases. The relationship between the fractal dimension value and the bound water, as Fig. 4 shows, is a significant linear correlation. A similar result was found in previous work (13). It is suggested that the compactness of sludge flocs shows a close relationship with the bound water content. As a result, we recommend the recycling-sludge operation is an effective strategy to produce more compact aggregates in floc-forming processes for improving the dewatering characteristics of alum sludge.

SUMMARY

The recycling operation in a water treatment facility can enhance the formation of floc, thereby resulting in an increase of the floc's effective

density. The flocs produced from the recycling operation exhibit larger fractal dimension values, more compact structures, and lower bound water contents. In addition, there is a significant correlation between the fractal dimensions and the bound water content of the sludge flocs.

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