(10) A TECHNIQUE FOR EVALUATING SOLID/LIQUID SEPARATION IN SLUDGE AS VIEWED FROM BOTH QUANTITY AND QUALITY OF THE SEPARATED LIQUID

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ABSTRACT; This paper deals with an examination on a technique for evaluating solid/liquid separation effectiveness in sludge without chemical conditioning for a vacuum filter as viewed from both quantity and quality of the separated liquid. It uses a statistical model based on the analysis of the separation curve (i.e., the speed of separation) through a multivariate analysis of variance. Among the three separation factors, suction force is recognized as the main effect. Also, quality of the separated liquid resulting from the filter experiment was examined. Moreover, the analysis was extended to the quality of the separated liquid as related to the speed of separation.

KEY WORDS; Solid/liquid separation, Multivariate analysis of variance, Sludge

1. Introduction

Solid/liquid separation in sludge has been mainly evaluated from the following methods:

1) Measurement of the final moisture content of sludge cake
2) Measurement of the rate of decrease in sludge moisture content
3) Calculation of specific resistance
4) Dynamic analysis

These methods can be classified into two categories; one consists of the first two methods while the other, the second two methods. The basic difference between the two categories is that the first is directly based on data obtained, whereas the second, on theoretical analysis. In practical application, it appears that the first category, and especially the first method, is more suitable for evaluating the effectiveness of solid/liquid separation since it employs the moisture content directly.

Considering a total environmental conservation system, information about the sludge generated from a sewage treatment plant and its dewatering effectiveness must be established. The dewatering should be evaluated not only from the quantity of the liquid separated, but also from the quality of the separated liquid.

In the present paper, as a preliminary work to the solution of the problem mentioned above, a technique for evaluating solid/liquid separation in sludge without chemical conditioning for a vacuum filter is proposed based on the concept of the first category, while a multivariate analysis of factors affecting the separation is employed.

The evaluation of the separation effectiveness is made by comparing the rates of sludge moisture as it decreases within given times or, in other words, to analyze the "separation curve" which describes the quantity of separated liquid as a function of separation time.

The most important parameters of this new technique are $\widehat{\alpha}'$ and $\widehat{\beta}$. The former estimates the volume of the initial quantity of the separated liquid whereas the latter estimates the time-tendency of the increase of volume of separated liquid. From these two values, it is possible to predict the quantity of separated liquid at an arbitrary separation time. The model reveals that when the value of $\widehat{\alpha}'$ is maximum, the value of $\widehat{\beta}$ falls to a minimum. A rapid separation is possible at the initial stage of the separation. First, the maximum value of parameter $\widehat{\alpha}'$ is identified and then the minimum value of parameter $\widehat{\beta}$. If several points are available, the optimum condition is determined by giving priority to the point where $\widehat{\alpha}'$ has its maximum value.

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2. Analysis of separation curve[1)2)]

2.1 Proposal of separation curve model

When putting the sludge in the separation machine, in view of the operational condition, three separation factors[3)~8)] - filter media for filtering, sludge layer thickness, and separation force on the sludge affecting the sludge dewaterability - are selected, and these factors are called separation factors A, B and C, respectively. These factors have three levels each: A_i, B_j, C_k ($i=1\sim l$, $j=1\sim m$, $k=1\sim n$, in the present paper $l=m=n=3$). In each case of the combinations of the factor levels $A_iB_jC_k$, the separation curve as shown in Figure 1, can be obtained. Assuming the quantity of separated liquid, V, to be a function of the separation time t, then from the form of the separation curve, the following model is adopted:

$$V(t) = \alpha t^{\beta} \quad \text{where} \quad \alpha > 0,\ 1 > \beta > 0,\ t > 0 \tag{1}$$

In Section 4.1 the speed of separation at the initial stage shall be examined and the curve retained which has the fastest separation by estimating the parameters, α and β. The procedure is based on the following fact.

Considering two separation curves $V_1(t) = \alpha_1 t^{\beta_1}$ and $V_2(t) = \alpha_2 t^{\beta_2}$ at the initial stage $0 < t < 1$.
The ratio of the two curves is

$$\frac{V_1(t)}{V_2(t)} = \frac{\alpha_1}{\alpha_2} \cdot (t)^{\beta_1-\beta_2}$$

If the parameters such that $\alpha_1 \geqq \alpha_2$ and $\beta_1 \leqq \beta_2$ are taken, then the ratio is always greater than one, and so $V_1(t) \geqq V_2(t)$ for $0 < t \leqq 1$. This means that, when the fastest separation curve at the initial stage ($0 < t \leqq 1$) is selected, α as large as possible and β as small as possible should be chosen.

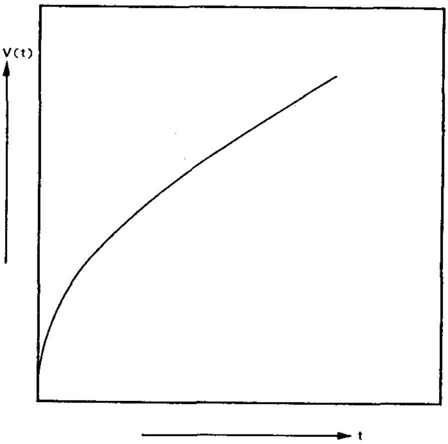

Fig.1 Typical separation curve

On the other hand, the condition with small α and large β means that the speed of separation at the initial stage is very slow.

From the model (1), it is known that the parameter α indicates the quantity of separated liquid when the unit time ($t = 1$) has passed. The parameter β ($0 < \beta < 1$) determines the shape of the separation curves and gives us some information about the relative rate of change to the quantity of the separated liquid $V(t)$, that is, the ratio of the derivative $V'(t)$ to $V(t)$,

$$\frac{V'(t)}{V(t)} = \frac{\beta}{t} .$$

2.2 Logarithmic transformation

In order to estimate parameters α and β in the model (1) through a linear regression analysis, natural logarithms of both sides of Eq.(1) shall be taken. By taking natural logarithms, Eq.(1) becomes a linear equation:

$$\ln V(t) = \alpha' + \beta \ln t \quad \text{where} \quad \alpha' = \ln \alpha \tag{2}$$

By carrying out the regression analysis with respect to Eq.(2), $\widehat{\alpha}'$ and $\widehat{\beta}$ as the estimated values of α' and β are obtained.

The value of $\widehat{\alpha}'$ estimates the volume of the initial quantity of the separated liquid when a unit time passes, and the value of $\widehat{\beta}$ estimates the time-tendency of the increase of volume of the separated liquid. From these two values, it is possible to predict the quantity of the separated liquid at an arbitrary separation time.

2.3 Multivariate analysis of variance

If the fitting of the regression equation is good enough to summarize the data, the analysis can be continued further. There are two estimates $\widehat{\alpha}'$ and $\widehat{\beta}$ for each separation curve of each level $A_iB_jC_k$ ($i=1\sim l,\ j=1\sim m,\ k=1\sim n$). They shall be put together in a vector notation as

$$x_{ijk} = (x^1_{ijk},\ x^2_{ijk})' = (\widehat{\alpha}',\ \widehat{\beta})' \tag{3}$$

for $A_iB_jC_k$. As there is a 2-dimensional observational vector for each separation curve, a multivariate analysis of variance to the data set shall be applied.

$$\{(x^1_{ijk},\ x^2_{ijk})',\ \ i=1\sim l,\ j=1\sim m,\ k=1\sim n\}$$

Multivariate analysis of variance is a technique for testing the main effect and interaction of various kinds of factors taking up the p-variate at the same time. This method corresponds to the direct extension of the analysis of variance with a single variate.

Each mean vector is determined as follows.

$$\bar{\bar{x}}_{\cdots} = \frac{1}{lmn}\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} x_{ijk} \tag{4}$$

$$\bar{\bar{x}}_{i\cdot\cdot} = \frac{1}{mn}\sum_{j=1}^{m}\sum_{k=1}^{n} x_{ijk} \tag{5}$$

$$\bar{\bar{x}}_{\cdot j\cdot} = \frac{1}{ln}\sum_{i=1}^{l}\sum_{k=1}^{n} x_{ijk} \tag{6}$$

$$\bar{\bar{x}}_{\cdot\cdot k} = \frac{1}{lm}\sum_{i=1}^{l}\sum_{j=1}^{m} x_{ijk} \tag{7}$$

$$\bar{x}_{ij\cdot} = \frac{1}{n}\sum_{k=1}^{n} x_{ijk} \tag{8}$$

$$\bar{x}_{i\cdot k} = \frac{1}{m}\sum_{j=1}^{m} x_{ijk} \tag{9}$$

$$\bar{x}_{\cdot jk} = \frac{1}{l}\sum_{i=1}^{l} x_{ijk} \tag{10}$$

Using each mean vector as obtained from the Eq.(11) to (18), each variation is calculated.

$$S_T = \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} (x_{ijk} - \bar{\bar{x}}_{\cdots})(x_{ijk} - \bar{\bar{x}}_{\cdots})' \tag{11}$$

$$S_A = \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} (\bar{\bar{x}}_{i\cdot\cdot} - \bar{\bar{x}}_{\cdots})(\bar{\bar{x}}_{i\cdot\cdot} - \bar{\bar{x}}_{\cdots})' \tag{12}$$

$$S_B = \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} (\bar{\bar{x}}_{\cdot j\cdot} - \bar{\bar{x}}_{\cdots})(\bar{\bar{x}}_{\cdot j\cdot} - \bar{\bar{x}}_{\cdots})' \tag{13}$$

$$S_C = \sum_{i=1}^{m}\sum_{j=1}^{l}\sum_{k=1}^{n} (\bar{\bar{x}}_{\cdot\cdot k} - \bar{\bar{x}}_{\cdots})(\bar{\bar{x}}_{\cdot\cdot k} - \bar{\bar{x}}_{\cdots})' \tag{14}$$

$$S_{A\times B} = \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} (\bar{x}_{ij\cdot} - \bar{\bar{x}}_{i\cdot\cdot} - \bar{\bar{x}}_{\cdot j\cdot} + \bar{\bar{x}}_{\cdots})(\bar{x}_{ij\cdot} - \bar{\bar{x}}_{i\cdot\cdot} - \bar{\bar{x}}_{\cdot j\cdot} + \bar{\bar{x}}_{\cdots})' \tag{15}$$

$$S_{B\times C} = \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} (\bar{x}_{\cdot jk} - \bar{\bar{x}}_{\cdot j\cdot} - \bar{\bar{x}}_{\cdot\cdot k} + \bar{\bar{x}}_{\cdots})(\bar{x}_{\cdot jk} - \bar{\bar{x}}_{\cdot j\cdot} - \bar{\bar{x}}_{\cdot\cdot k} + \bar{\bar{x}}_{\cdots})' \tag{16}$$

$$S_{A\times C}=\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n}(\bar{x}_{i\cdot k}-\bar{\bar{x}}_{i\cdot\cdot}-\bar{\bar{x}}_{\cdot\cdot k}+\bar{\bar{\bar{x}}}_{\cdot\cdot\cdot})(\bar{x}_{i\cdot k}-\bar{\bar{x}}_{i\cdot\cdot}-\bar{\bar{x}}_{\cdot\cdot k}+\bar{\bar{\bar{x}}}_{\cdot\cdot\cdot})' \quad (17)$$

$$S_e=S_T-S_A-S_B-S_C-S_{A\times B}-S_{B\times C}-S_{A\times C} \quad (18)$$

where S_T : grand variation

S_A : variation due to factor A

S_B : variation due to factor B

S_C : variation due to factor C

$S_{A\times B}$: variation due to the interaction between factors A and B

$S_{B\times C}$: variation due to the interaction between factors B and C

$S_{A\times C}$: variation due to the interaction between factors A and C

S_e : variation due to error

Using these values, a multivariate analysis of variance of the three-way layout method (parameter) is conducted in the form as shown in Table 1[9].

3. Experimental apparatus and method

A vacuum filter shown in Figure 2, which is used in a Nutsche test in a bench-scale study, is used as a separation testing apparatus in this study. A Buchner funnel has a diameter of 10 cm and a volume of 450 mℓ.

The sludge used for the apparatus is obtained from a municipal wastewater treatment plant. The sludge properties[10] are given in Table 2. Solid/liquid separation experiments are made without chemical conditioning. Type of filter cloth, sludge layer thickness, and suction force are taken up as the separation factors. The quantity of separated liquid is measured 5 min., 10 min., 15 min., 30 min., 45 min., and 60 min. after the experiment starts.

In the multivariate analysis of variance, to analyze main effects and interactions of the three factors mentioned above, the layout of the factors is determined as L_{27}. The factors and their respective levels in the experiment of solid/liquid separation are shown in Table 3, while Table 4 shows the layout in the experiment. The whole experiment is conducted in a random order.

With respect to the examination of the quality of the separated liquid, SS is measured according to the standard filtration method[11], while TOC and T-N are measured based on the standard sewage examination method[12].

Table 1 Multivariate analysis of variance of the three-way layout method

(1) Design of experiments

Factor A : ℓ level   Factor B : m level   Factor C : n level

Number of repetitions : 1   Data : p-dimensions

(2) Multivariate analysis of variance

Factor	Variation(S_f)	Degrees of freedom(ν_f)	Chi-square	Test standard
A	S_A	$\ell-1$	χ^2_A	$\chi^2_{p(\ell-1)}(\alpha)$
B	S_B	$m-1$	χ^2_B	$\chi^2_{p(m-1)}(\alpha)$
C	S_C	$n-1$	χ^2_C	$\chi^2_{p(n-1)}(\alpha)$
A×B	$S_{A\times B}$	$(\ell-1)(m-1)$	$\chi^2_{A\times B}$	$\chi^2_{p(\ell-1)(m-1)}(\alpha)$
B×C	$S_{B\times C}$	$(m-1)(n-1)$	$\chi^2_{B\times C}$	$\chi^2_{p(m-1)(n-1)}(\alpha)$
A×C	$S_{A\times C}$	$(\ell-1)(n-1)$	$\chi^2_{A\times C}$	$\chi^2_{p(\ell-1)(n-1)}(\alpha)$
E	S_e	$(\ell-1)(m-1)(n-1)$		
T	S_T	$\ell mn-1$		

$$\chi^2_f=-\left[(\ell-1)(m-1)(n-1)-\frac{1}{2}(p-\nu_f+1)\right]\log_e \nu_f$$

$$\nu_f=\frac{|S_e|}{|S_f+S_e|} \qquad (f=A, B, C, A\times B, B\times C, A\times C)$$

4. Results and Discussion

In this section, not only the optimum levels of factors with respect to the separation curve (i.e., the speed of separation) but also the experimental condition which gives the fastest speed of separation are discussed when the filter is used. Also, the quality of

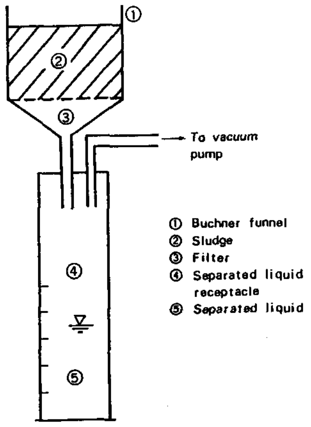

Fig. 2 Schematic view of experimental apparatus

Table 2 Characteristics of sample sludge used

Sample sludge		Activated sludge
Total solids	(%)	3.3
Volatile solids	(%)	79.6
Suspended solids	(%)	3.0
Conductivity	(μs/cm)	2800
Alkalinity	(mg/ℓ)	580
pH		6.0
Temperature	(℃)	30.0
TOC	(mg/ℓ)	4600
T−N	(%)	0.125

Table 3 Level of factor

Factor		Level			Remarks
Type of filter cloth	A	α	β	γ	α: PF−8044 β: PF−401 γ: P−2088
Sludge layer thickness (mm)	B	10	20	30	
Suction force (MPa)	C	0.03	0.06	0.09	

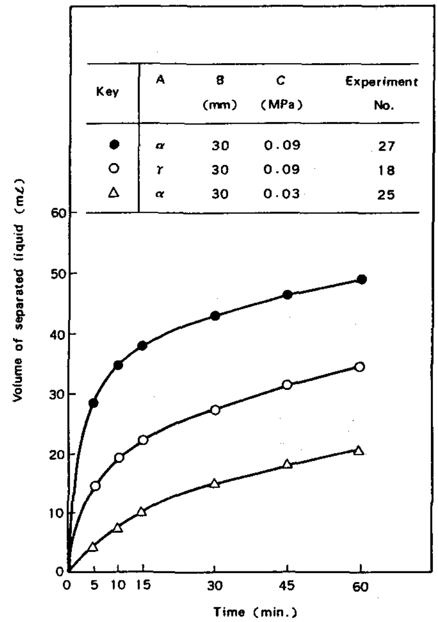

Fig.3 Separation curves measured

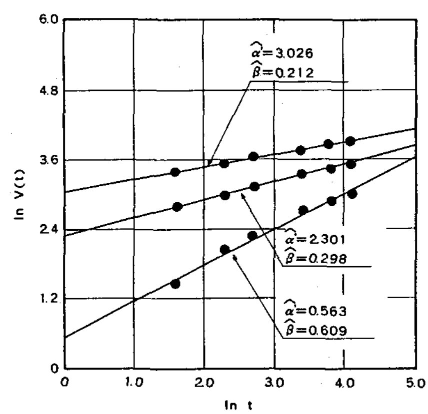

Fig. 4 Regression lines

the separated liquid resulting from the experiment of the filter is analyzed. The experiment is also extended to the examination of the relationship between the speed of separation and the quality of the separated liquid.

4.1 Analysis of separation curve

Out of a total of 27 separation experiments, the curves for three typical cases of separation with the filter are shown in Figure 3. The details for the three factors are as follow: filter cloths, two types; sludge layer thickness, 30 mm; and suction force, 0.03 and 0.09 MPa. These separation curves are plotted in a log scale, and shown in Figure 4. When fitted with Eq.(2), the contribution of the regression equation with respect to the experimental points is higher than 98.8 %. The results are given in Table 4.

Table 4 Layout

Item / No.	Type of filter cloth	Sludge layer thickness (mm)	Suction force (MPa)	Parameter estimated $\hat{\alpha}'$	Parameter estimated $\hat{\beta}$
1	β	10	0.03	1.173	0.518
2	β	10	0.06	0.991	0.573
3	β	10	0.09	2.615	0.260
4	γ	10	0.03	1.143	0.529
5	γ	10	0.06	1.411	0.471
6	γ	10	0.09	2.893	0.245
7	β	20	0.03	1.242	0.513
8	β	20	0.06	1.426	0.480
9	β	20	0.09	2.000	0.368
10	γ	20	0.03	1.025	0.538
11	γ	20	0.06	1.470	0.474
12	γ	20	0.09	2.329	0.321
13	β	30	0.03	1.103	0.524
14	β	30	0.06	1.870	0.391
15	β	30	0.09	1.543	0.433
16	γ	30	0.03	0.886	0.589
17	γ	30	0.06	1.289	0.513
18	γ	30	0.09	2.301	0.298
19	α	10	0.03	0.809	0.560
20	α	10	0.06	1.667	0.401
21	α	10	0.09	2.826	0.157
22	α	20	0.03	0.800	0.576
23	α	20	0.06	1.807	0.361
24	α	20	0.09	2.540	0.246
25	α	30	0.03	0.563	0.609
26	α	30	0.06	0.945	0.550
27	α	30	0.09	3.026	0.212

4.1.1 The speed of separation

The scatter diagram of $\hat{\alpha}'$ and $\hat{\beta}$ determined by the regression analysis is shown in Figure 5. The value of $\hat{\alpha}'$ estimates the volume of the initial quantity of separated liquid when a unit time passes, and the value of $\hat{\beta}$ estimates the time-tendency of the increase in the volume of separated liquid. The model equation proposed reveals that when the value of $\hat{\alpha}'$ is maximum, the value of $\hat{\beta}$ becomes minimum. A rapid separation is possible at the initial stage of the separation. Therefore, in order to locate the maximum experimental condition which has the fastest speed of separation, the following procedure is needed.

First, the maximum value of $\hat{\alpha}'$ is identified and then the minimum value of $\hat{\beta}$. If there are few points, the maximal condition is determined by giving priority to the point which has the maximum value of $\hat{\alpha}'$, because the separation curve with respect to the point dominates the remaining portion of the curve as the time passes. In the filter, it can be seen from Figure 5 that the maximum value of $\hat{\alpha}'$ is found in experiment 27 (Table 4) and the minimum value of $\hat{\beta}$ is found in experiment 21 (Table 4). Therefore, it is seen that the maximal condition for the filter is in experiment 27.

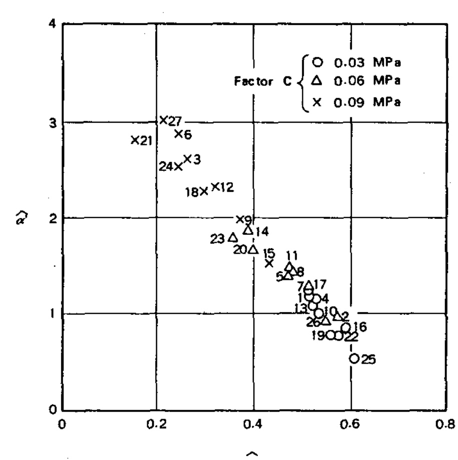

Fig.5 Relation between $\hat{\beta}$ and $\hat{\alpha}'$

4.1.2 Multivariate analysis of variance

Table 5 shows the results of the multivariate analysis of variance. It shows that suction force (Factor C) is recognized as the main effect of the separation factor. Figure 5 clearly shows that there are three clusters. Each of them corresponds to the level of factor C (suction force), respectively. The optimum level is 0.09 MPa of suction force. The interaction among the three separation factors is not recognized.

4.2 Analysis of quality of separated liquid

4.2.1 Optimum levels of the three factors

Table 5 Multivariate analysis of variance

Factor	Chi-square (χ^2_f)	χ^2 test α 0.05	χ^2 test α 0.01
A	6.569	9.49	13.28
B	2.418	9.49	13.28
C	18.690**	9.49	13.28
A×B	5.519	15.51	20.10
B×C	3.524	15.51	20.10
A×C	7.305	15.51	20.10
E	—	—	—
T	—	—	—

Table 6 shows a list of the quality of the separated liquid for the filter. Using the listed values of SS, TOC, and T-N, an analysis of variance of L_{27} is carried out to examine which factor is more effective in improving the quality of separated liquid. In the filter, main effect of the type of filter cloth is significant with significance level of 1 % and main effect of suction force is also significant with significance level of 1 % with respect to the value of SS. With respect to the value of TOC, main effect of the type of filter cloth is significant with significance level of 5 %. As for T-N, main effect of suction force is also significant with significance level of 1 %. The lowest value of SS was found with filter cloth of β type and the suction force at 0.09 MPa. As for TOC, filter cloth of β type gave the lowest value. Finally, for T-N, the suction force was found at 0.06 MPa.

Table 6 List of quality of separated liquid

No.	Experimental condition: Type of filter cloth	Sludge layer thickness (mm)	Suction force (MPa)	Quality of separated liquid: SS (%)	TOC (mg/ℓ)	T-N (%)
1	β	10	0.03	0.076	810	0.067
2	β	10	0.06	0.100	940	0.044
3	β	10	0.09	0.760	1000	0.065
4	γ	10	0.03	0.078	730	0.043
5	γ	10	0.06	0.180	1720	0.076
6	γ	10	0.09	0.930	1450	0.085
7	β	20	0.03	0.066	760	0.061
8	β	20	0.06	0.038	910	0.004
9	β	20	0.09	0.410	1210	0.013
10	γ	20	0.03	0.052	1160	0.026
11	γ	20	0.06	0.280	1080	0.017
12	γ	20	0.09	0.650	360	0.082
13	β	30	0.03	0.078	770	0.033
14	β	30	0.06	0.062	1110	0.019
15	β	30	0.09	0.210	1280	0.047
16	γ	30	0.03	0.066	850	0.049
17	γ	30	0.06	0.210	890	0.047
18	γ	30	0.09	0.570	1250	0.040
19	α	10	0.03	0.310	1470	0.024
20	α	10	0.06	0.420	1330	0.017
21	α	10	0.09	1.200	1920	0.102
22	α	20	0.03	0.032	1000	0.049
23	α	20	0.06	0.450	2220	0.055
24	α	20	0.09	1.100	1510	0.099
25	α	30	0.03	0.140	2290	0.040
26	α	30	0.06	0.140	1400	0.029
27	α	30	0.09	1.300	1580	0.112

4.2.2 Discussion

When estimating the effectiveness of solid/liquid separation, paying attention only to the values of $\hat{\alpha}'$ and $\hat{\beta}$ without considering the quality of the separated liquid in the experiment, it can be seen from Figure 5 that the maximal condition is determined by giving priority to the point which has maximum value of $\hat{\alpha}'$. However, all the quality of the separated liquid in the maximal condition mentioned above is worse than that of the other conditions. That is, regarding the two items, viz., SS and T-N, the quality of the separated liquid is respectively the worst of all, and with regard to TOC, the quality is the worst but two experimental conditions.

Therefore, it is understood that in searching for the optimum separation condition in the experiment, it is necessary to estimate the effectiveness of solid/liquid separation totally from the viewpoints of $\hat{\alpha}'$, $\hat{\beta}$ and the quality of the separated liquid.

4.3 Relationship between the speed of separation and quality of the separated liquid

In order to check whether there is any relationship between the speed of separation as represented by the data ($\widehat{\alpha}'$, $\widehat{\beta}$) and the three measurements SS, TOC, and T-N for the quality of the separated liquid, all observations of each data set are arranged in order in the appropriate sense so as to obtain their ranking numbers. By using these numbers instead of their real values, scatter diagrams between the speed of separation and the quality of the separated liquid are examined.

4.3.1 Ordering and ranking numbers

First, the ranking of the speed of separation is conducted with respect to the results from Nos. 1 to 27 in the filter. From Figure 5 all the speeds of the separation data ($\widehat{\alpha}'$, $\widehat{\beta}$) may be arranged in the order which follows. The fastest is No. 27, the second is No. 6 and so on. The ordering is 27>6>21>3>24>12>18>9>14>23>20>15>11>8>5>17>7>1>4>13>10>2>26>16>19>22>25. The top is given to the fastest separation and the last to the slowest one. Second, the ranking of the values of SS, TOC, and T-N is also conducted with respect to the result from Nos. 1 to 27. The top is given to the lowest value for the quality parameters and the last to the highest. When the same values come out, the mean value of the ranking numbers is taken.

By using this ordering all observations of the speed of separation data and quality of the separated liquid data can be transformed to their ranking numbers.

4.3.2 Correlation analysis

By using ranking numbers with the speed of separation data ($\widehat{\alpha}'$, $\widehat{\beta}$) and the quality of the separated liquid data (SS, TOC, T-N), scatter diagrams for the experiment of the filter are drawn. Figure 6 shows the scatter diagram of the speed of separation vs. SS, whereas Figure 7, the speed of separation vs. TOC, and Figure 8, the speed of separation vs. T-N.

Correlation coefficients of these scatter diagrams are given in Table 7. It can be seen from the table that in the filter, the correlation coefficient between the speed of separation and SS is highly significant with a significance level of 1 %, whereas the correlation coefficient between the speed of separation and TOC is not recognized with a significance level of 5 %. The correlation coefficient between the speed of separation and T-N is also significant with a significance level of 5 %. As shown in Figures 6 to 8 and Table 7, the existence of large negative values suggests that there is a trade-off relationship where the optimum level for the speed of separation and quality of the separated liquid cannot be located at the same time.

Therefore, it is necessary to examine the optimum factors on solid/liquid separation in sludge as viewed from both quantity and quality of the separated liquid. That is, a trade-off adjustment is needed. One trade-off adjustment is proposed. Figure 9 shows the relation among the ranking of the speed of separation, ranking of SS (as an example), and number of the experimental condition. First, a scatter diagram is drawn with respect to the two rankings. Second, one standard in relation to the separated liquid such as an environmental standard is positively introduced, and

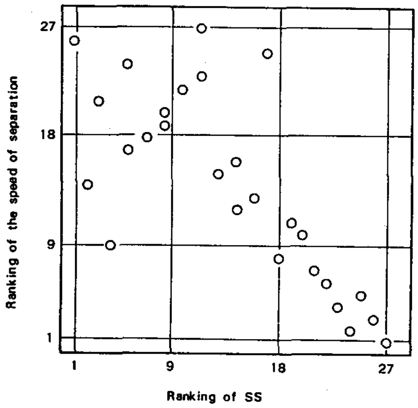

Fig.6 Relation between the ranking of the speed of separation and the ranking of SS

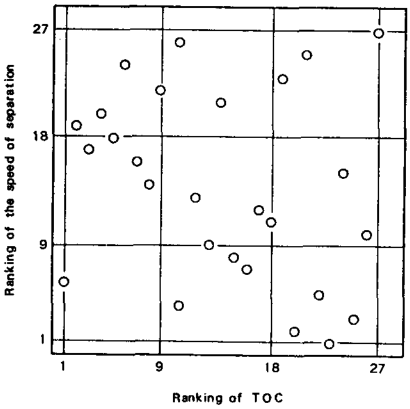

Fig.7 Relation between the ranking of the speed of separation and the ranking of TOC

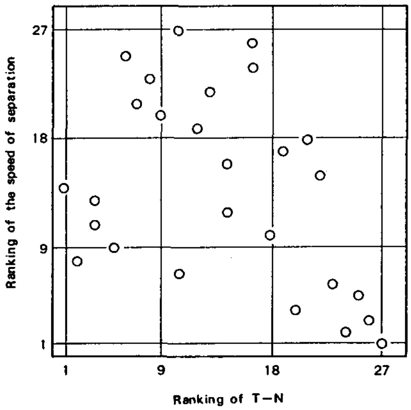

Fig.8 Relation between the ranking of the speed of separation and the ranking of T-N

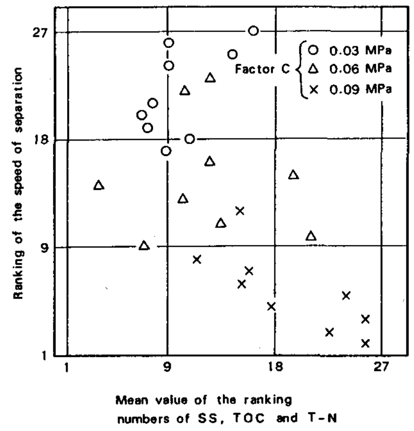

Fig. 10 Relation between the ranking of the speed of separation and the mean value of the ranking numbers of SS, TOC and T-N

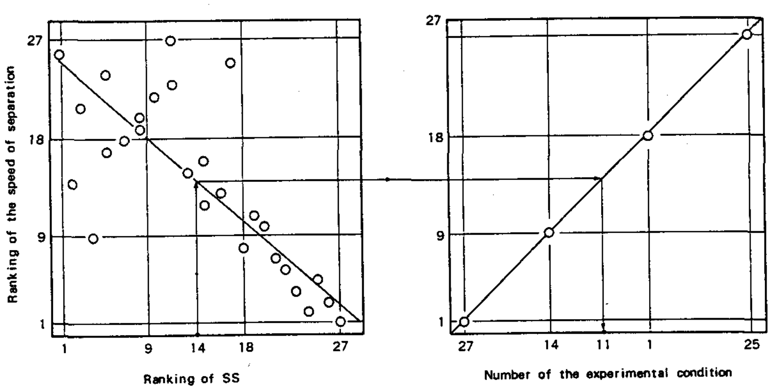

Fig.9 Relation among the ranking of the speed of separation, ranking of SS, and number of the experimental condition

Table 7 Correlation coefficient

Correlation coefficient	SS	TOC	T-N
Speed of separation	−0.748	−0.236	−0.405

from this the experimental condition which can be satisfied in terms of both quantity and quality of the separated liquid at the same time can be obtained. Finally, from the experimental condition obtained, the optimum factors on solid/liquid separation can be determined.

Furthermore, a total evaluation is also done using the three ranking numbers of SS, TOC, and T-N. The mean value of the ranking numbers with respect to the values of SS, TOC and T-N is calculated in experiment Nos. 1 - 27 for the filter, and the scatter diagram is drawn. It can be seen from Figure 10 that, in the filter, the relationship between the two shows a negative correlation with a correlation coefficient r = - 0.610. From the results of Sections 4.1.2 and 4.2.1, the levels of factor C (suction force) on Figure 10 have also been superimposed. In the filter, factor C seems to be the main trade-off factor.

In addition, total evaluation from the viewpoint of both quantity and quality of the separated liquid is also roughly possible. Figure 10 shows the relation between the ranking of speed of separation and the mean value of the ranking numbers of SS, TOC, and T-N. In this case, the optimum condition can be also determined in the same way as is seen in Figure 9, mentioned above.

5. Conclusions

For the estimation of solid/liquid separation effectiveness in sludge, traditionally attention has been paid mainly to the cake moisture content. In the present paper, an emphasis has been put on the quantity and quality of the separated liquid obtained. Considering the problem caused by the separation factors and the optimum combination among them, an examination on a technique for evaluating solid/liquid separation effectiveness in sludge without chemical conditioning for a vacuum filter is done using a statistical model. Quality of the separated liquid for the filter is also analyzed. The research is further extended to the examination of the relationship between the speed of separation and the quality of separated liquid. The results are as follow:

With consideration of the three separation factors, i.e., the filter cloth type (factor A), sludge layer thickness (factor B), and suction force (factor C) and with the laying out of three levels for each factor, it has come to be clear that suction force (factor C) is recognized as the main effect, and no interaction of any two of the separation factors is recognized. It is clear from the result of multivariate analysis of variance that the optimum condition is $A_1B_3C_3$, when estimating the effectiveness of solid/liquid separation paying attention only to the values of $\hat{\alpha}'$ and $\hat{\beta}$.

Viewed from quantity ($\hat{\alpha}'$, $\hat{\beta}$) and quality (SS) of the separated liquid, it is possible to estimate the optimum experimental condition on solid/liquid separation. Based on the condition, the optimum factors can be determined.

The existence of a negative correlation between the speed of separation and the quality of separated liquid suggests that there is a trade-off relationship. Moreover, suction force is a factor which has a significant influence upon the trade-off relationship between the speed of separation and the quality of separated liquid. As for a total evaluation of the solid/liquid separation effectiveness, it is also possible to roughly estimate the optimum condition.

The fitting of the model (2) (i.e., model (1)) is very good and highly significant in the filter experiment. After fitting the model (2), the following two facts are noted. First, from Figure 5, there appears a linear relationship existing between the two parameters, $\alpha'(= \ln \alpha)$ and β. The linear relationship enables us to interpret the model (1) through only one parameter, β or α. Second, by checking residuals in each regression analysis it is known that some nonlinearity still remains after fitting the model (2). This suggests that there is a possibility of the existence of a more sophisticated statistical model, which may need further knowledge of the physical meanings in the experiment.

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