# (34) STUDY ON SLUDGE DEWATERING EVALUATION TECHNIQUES USING A STATISTICAL MODEL - IN VIEW OF BOTH QUANTITY OF FILTRATE AND FILTRATE QUALITY

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ABSTRACT; In view of environmental systems, this paper aims at proposing a scientific and positive evaluation technique in sludge dewatering as viewed from both quantity and quality of the filtrate obtained without sludge conditioning. The contents are as follows: (1) Through a multivariate analysis of variance, the optimum condition which produces the maximal quantity of filtrate is determined under the condition of the three dewatering factors, that is, type of filter cloth, sludge thickness, and filtration pressure in both pressure and vacuum filters. (2) In terms of the filtrate quality, both the pressure filter and the vacuum filter are compared. (3) With respect to both the pressure filter and the vacuum filter, the trade-off relationships between the speed of filtration (quantity of filtrate) and filtrate quality are determined. By means of the mean values of the ranking numbers weighted by Japanese effluent standards, the correlation coefficients for the relationships are determined, and these values are compared with those values based on the mean values of non-weighted ranking numbers.

KEY WORDS; sludge dewatering, speed of filtration, filtrate quality, multivariate analysis of variance, environmental systems

## 1. Introduction

With the increase in the percentage of sewered population, the quantity of sewage sludge discharged from wastewater treatment plants has been increasing steadily. Considering a rapid increase in the construction of sewerage which is expected in the future, an effective sewage sludge treatment is a subject of great importance.

At present, in the sludge dewatering process for sludge treatment, sludge conditioning such as adding the coagulant in order to improve the dewatering efficiency is mainly adopted. Therefore, it is very important to consider rationalization of the dewatering process in actual treatment plants, and to determine optimum dewatering operational conditions with sludge conditioning. However, it is first of all necessary to grasp dewatering characteristics without sludge conditioning.

As for the judgement of the sludge dewatering effects in the sludge treatment mentioned above, the following have been used. (1) The technique to measure the final moisture content of the sludge cake after a given time of dewatering. (2) The technique to compare the rates of the decrease in sludge moisture content within a given time. (3) The technique to measure Ruth's specific resistance. (4) The technique by a dynamic analysis[1)2)]. These techniques have been conducted and mainly pay attention to the moisture content of sludge cake.

Based on the idea mentioned above, this paper aims at proposing a scientific and positive evaluation technique for the excess activated sludge in sludge dewatering from the view of both quantity and quality of the filtrate obtained without sludge conditioning.

The construction of this paper is as follows: In section 2, in order to examine the optimum dewatering operational condition without sludge conditioning, the analysis of filtration curve and filtrate quality is shown, respectively. Section 3 describes the experimental apparatus and method with respect to the pressure filter and the vacuum filter which are, in general, used as the mechanical dewatering apparatus in Japan. Moreover, in section 4 are the experimental results and discussion, while in section 5 the conclusion.

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## 2. Analysis of filtration curve[3)~5)]

### 2.1 Proposal of filtration curve model

When putting the sludge in the dewatering machine, in view of the operational condition, three dewatering factors[6)~10)] affecting the sludge dewaterability - filter media for filtering, sludge layer thickness, and filtration pressure on the sludge - are selected, and these factors are called the dewatering factors of A, B, and C, respectively. These factors have three levels each: $A_i$, $B_j$, $C_k$ ($i = 1 \sim \ell$, $j = 1 \sim m$, $k = 1 \sim n$, in the present paper $\ell = m = n = 3$). In each case of the combinations of the factor levels $A_i B_j C_k$, the filtration curve as shown in Fig. 1 can be obtained. Assuming that the quantity of filtrate, V, is the function of filtration time t, the form of the filtration curve is given as in Fig. 1. From the form, the following model is adopted:

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

Fig. 2 shows two filtration curves: $V_1(t) = \alpha_1 t^{\beta}$, in which the speed of filtration is the faster of the two, and $V_2(t) = \alpha_2 t^{\beta}$, in which it is the slower of the two, at the initial stage $0 < t \leqq 1$.

The ratio of the two curves is

$$\frac{V_1(t)}{V_2(t)} = \frac{\alpha_1}{\alpha_2} t^{\beta_1 - \beta_2} \tag{2}$$

If we take the parameters $\alpha_1 \geqq \alpha_2$ and $\beta_1 \leqq \beta_2$, 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 filtration curve at the initial stage ($0 < t \leqq 1$) is selected, the largest possible $\alpha$ and the smallest possible $\beta$ should be chosen.

On the other hand, the condition with small $\alpha$ and large $\beta$ means that the speed of filtration at the initial stage is very slow.

From the model(1), it is known that the parameter $\alpha$ indicates the quantity of filtrate when the unit time ($t = 1$) has passed. The parameter $\beta$ indicates the quantity of filtrate when the unit time ($t = 1$) has passed. The parameter $\beta$ ($0 < \beta < 1$) determines the shape of filtration curves and gives us some information about the relative rate of change to the quantity of filtrate V(t), that is, the ratio of the derivative $\dot{V}(t)$ to $V(t)$,

$$\frac{\dot{V}(t)}{V(t)} = \frac{\beta}{t} \tag{3}$$

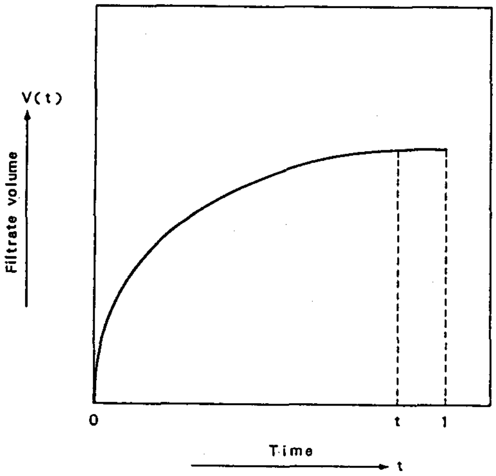


Fig. 1. Typical filtration curve.

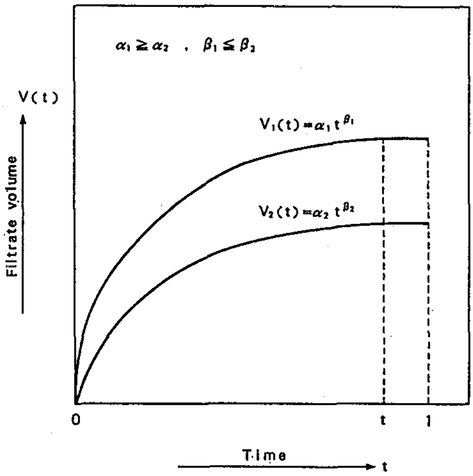


Fig. 2. One formula for faster filtration and the other for slower filtration.

2.2 Conversion of filtration curve into a logarithmic linear model

In order to estimate parameters $\alpha$ and $\beta$ in the model (1) through a linear regression analysis, natural logarithms of both sides of Eq. (1) shall be taken:

$$\ln V(t) = \alpha' + \beta \ln t, \quad \text{where} \quad \alpha' = \ln \alpha \tag{4}$$

The model (1) is defined for comparing the filtration curves, and also designed to describe ln t and ln V(t). Moreover, the model is not introduced with the physical implications other than time. Therefore, based on the model, the differential at t = 0 is not defined, and the model is considered only in t > 0. In case of fitting the statistical model ($V(t) = \alpha t^{\beta}$) to the various kinds of filtration curves, the interpretation of the estimated values ($\hat{\alpha}$, $\hat{\beta}$) of population parameter is the subject. Fortunately, the comparison of filtration curves at the initial stage ($0 < t \leq 1$) gives some light on the interpretation of population parameter ($\alpha$, $\beta$). This is a measure to try the interpretation of population parameter ($\alpha$, $\beta$) including physical information, except for time. At the initial stage ($0 < t \leq 1$), we can arbitrarily set up the unit time (t = 1).

By carrying out the regression analysis with respect to Eq. (4), $\hat{\alpha}'$ and $\hat{\beta}$ as the estimated values of $\alpha'$ and $\beta$ are obtained.

From these two values, it is possible to predict the quantity of filtrate at an arbitrary filtration time. If there are a few points at the initial stage, the maximal condition of quantity of filtrate is determined by giving priority to the point which has the maximum value of $\hat{\alpha}'$, because the filtration curve with respect to the point dominates the remaining portion of the curve as time passes.

2.3 Selection of optimum dewatering operational condition through a 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 $\alpha'$ and $\beta$ for each filtration curve of each level $A_i B_j C_k$ ($i = 1 \sim \ell$, $j = 1 \sim m$, $k = 1 \sim n$). They shall be put together in a vector notation as

$$x_{ijk} = (x_{ijk}^1, x_{ijk}^2)' = (\hat{\alpha}', \hat{\beta})' \tag{5}$$

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

Each mean vector is determined as follows.

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

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

$$\bar{\bar{x}}_{\cdot j\cdot} = \frac{1}{ln} \sum_{i=1}^{l} \sum_{k=1}^{n} x_{ijk} \tag{8}$$

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

$$\bar{x}_{ij\cdot} = \frac{1}{n} \sum_{k=1}^{n} x_{ijk} \tag{10}$$

$$\bar{x}_{i\cdot k} = \frac{1}{m} \sum_{j=1}^{m} x_{ijk} \tag{11}$$

$$\bar{x}_{\cdot jk} = \frac{1}{l} \sum_{i=1}^{l} x_{ijk} \tag{12}$$

By using each mean vector obtained, each variation is calculated and by 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[11]. Based on Table 1, the optimum dewatering operational condition can be determined.

## 3. Experimental apparatus and method

Two kinds of dewatering testing apparatus are used in this research. One is a cylindrical pressure filter simulator, as shown in Fig. 3(a). The pressure tank has a diameter of 10 cm and a volume of 1200 mℓ. The other type is a vacuum filter, which is used in a Nutsche test in a bench-scale study, as shown in Fig. 3(b). A Buchner funnel has a diameter of 10 cm, the same as the pressure tank, and a volume of 450 mℓ.

The sludge used for the apparatus is obtained from a municipal wastewater treatment plant. The sludge properties are given in Table 2. Sludge dewatering experiments are made without sludge conditioning. In the design of the experiment, three types of filter cloths (i.e., $A_1$ = PF-8044, $A_2$ = PF-401, and $A_3$ = P-2088), sludge layer thickness (i.e., $B_1$ = 10 mm, $B_2$ = 20 mm, and $B_3$ = 30 mm), and filtration pressure/suction (i.e., $C_1$ = 0.03 MPa, $C_2$ = 0.06 MPa, and $C_3$ = 0.09 MPa) are used as main dewatering foctors affecting the quantity of filtrate in both experiments. The quantity of filtrate is measured at 5 min., 10 min., 15 min., 30 min., 45 min., and 60 min. after the experiment starts.

The experiment with the vacuum filter is carried out in the same way as that with the pressure filter except for using a suction force instead of feed pressure.

In the multivariate analysis of variance, to analyze the main effects and the interactions of the three factors, that is, filtration pressure/suction, sludge layer thickness, and type of filter cloth, the layout of the factors is determined as $L_{27}$. The factors and their levels in both experiments are shown in Table 3. Table 4 shows the layout of both experiments. All the experiments are conducted in a random order.

With respect to the examination of the filtrate quality, SS is measured according to the standard filtration method[12], while TOC and T-N are measured based on the standard sewage examination method[13].

## 4. Results and discussion

### 4.1 Analysis of filtration curve

The contribution of the regression equation with respect to the experimental points for the pressure filter is more than 93.9 %, and for the vacuum filter the contribution is over 98.9 %. These results are given by regression analysis. The values of $\widehat{\alpha}'$ and $\widehat{\beta}$ determined by the regression analysis of the filtration curve in both experiments are shown in Table 4. We may think that the repeatability of the filtration experiment could be possible provided the same sludge is present. In practice, however, there can be a little irregularity in the data obtained, since, in general, sewage sludge dewatering characteristics are very complicated and their structure is liable to be destroyed by the presence of filtration pressure. Therefore, $\widehat{\alpha}'$ may sometimes decrease as the filtration pressure increases like Nos. 1 and 2 of Table 4.

Since the fitting of the regression equation to the data resulting from both experiments is good enough, the analysis can be continued further. The analysis results and discussion are shown in the following subsections.

#### 4.1.1 The maximal condition of the quantity of filtrate as viewed from the speed of filtration

The scatter diagram of $\widehat{\alpha}'$ and $\widehat{\beta}$ mentioned above in both experiments is shown in Figs. 4 and 5.

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

(1) Design of experiments

Factor A : $\ell$ 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($\nu_f$) | Chi-square | Test standard |
|---|---|---|---|---|
| A | $S_A$ | $\ell-1$ | $\chi^2_A$ | $\chi^2_{p(\ell-1)}(\alpha)$ |
| B | $S_B$ | $m-1$ | $\chi^2_B$ | $\chi^2_{p(m-1)}(\alpha)$ |
| C | $S_C$ | $n-1$ | $\chi^2_C$ | $\chi^2_{p(n-1)}(\alpha)$ |
| 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 | $S_T$ | $\ell mn-1$ | | |

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

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

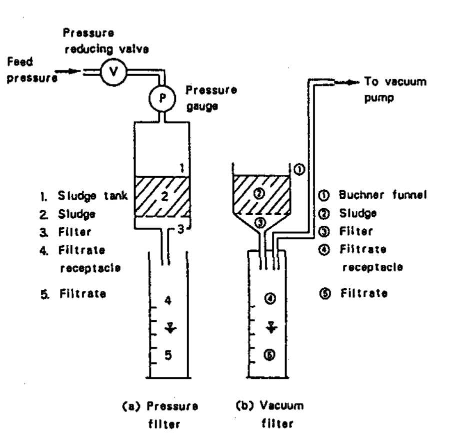


Fig. 3. Schematic diagram of experimental apparatus.

In the case of the pressure filter, it can be seen from Figs. 4 and Table 4 that the maximum value of $\widehat{\alpha}'$ is found in experiment 20, i.e., $A_1B_1C_2$, and the minimum value of $\widehat{\beta}$ is also found in the same experimental condition. The maximal condition for the pressure filter is $A_1B_1C_2$, while in the case of the vacuum filter, it can be seen from Fig. 5 and Table 4 that the maximum value of $\widehat{\alpha}'$ is found in experiment 27, i.e. $A_1B_3C_3$ and the minimum value of $\widehat{\beta}$ is found in experiment 21, i.e. $A_1B_1C_3$. Therefore, it is seen that by taking the value of $\widehat{\alpha}'$, the maximal condition for the vacuum filter is $A_1B_3C_3$.

4.1.2 Selection of optimum dewatering operational condition through a multivariate analysis of variance

Table 5 shows the results of multivariate analysis of variance. In the case of the pressure filter, it has been revealed that none of the dewatering factors have been recognized as the main effect nor has the interaction of all dewatering factors been recognized either. However, Fig. 4 shows that there seems to be two clusters. One cluster corresponds to the level Ⅰ of factor A (PF-8044), and the other cluster corresponds to the levels Ⅱ (PF-401) and Ⅲ (PF-2088). From the viewpoint of the significance level with nearly 10 %, the type of filtrate cloth is recognized as the main effect. Therefore, the type of filter cloth seems to have a moderate effect on the rate of filtration.

On the other hand, in the case of the vacuum filter, it has been revealed that factor C, i.e. the suction force, is recognized as the main factor for dewatering. The relationship between $\widehat{\alpha}'$ and $\widehat{\beta}$ relating to the suction force is shown in Fig. 5. Fig. 5 clearly shows that there are three clusters. Each of them corresponds to each level of suction force (factor C), respectively. The optimum level is $C_3$ (0.09 MPa). The interaction among the three dewatering factors is not recognized. Regarding the speed of filtration, the comparison between the two mean vectors in both cases of pressure and vacuum filters was carried out by using Hotelling's $T^2$ statistics[14]. It has been proved that there is no difference between the two mean vectors as can be expected from Figs. 4 and 5.

Table 2. Characteristics of sludge used in the experiment.

| Sample sludge | | Excess activated sludge |
|---|---|---|
| Total solids | (%) | 3.3 |
| Volatile solids* | (%) | 79.6 |
| SS | (%) | 3.0 |
| Conductivity | (μs/cm) | 2800 |
| Alkalinity | (mg/ℓ) | 580 |
| pH | | 6.0 |
| Temperature | (°C) | 30.0 |
| TOC | (mg/ℓ) | 4600 |
| T-N | (%) | 0.125 |

* Based on total solids.

Table 3. Levels for each of the three dewatering factors.

| Factor | Levels | | | Remarks |
|---|---|---|---|---|
| Type of filter cloth (A) | Ⅰ | Ⅱ | Ⅲ | Ⅰ : PF-8044*<br>Ⅱ : PF-401*<br>Ⅲ : P-2088* |
| Sludge layer thickness (B) (mm) | 10 | 20 | 30 | |
| Filtration pressure (C) (MPa) | 0.03 | 0.06 | 0.09 | |

* Filter cloth specification.

Table 4. Layout and the parameters estimated.

| No. | Type of filter cloth | | Sludge layer thickness (mm) | | Filtration pressure (MPa) | | Parameter estimated | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PF | VF | PF | VF | PF | VF | PF | | VF | |
| | | | | | | | $\widehat{\alpha}'$ | $\widehat{\beta}$ | $\widehat{\alpha}'$ | $\widehat{\beta}$ |
| 1 | Ⅱ | | 10 | | 0.03 | | 1.394 | 0.446 | 1.173 | 0.518 |
| 2 | Ⅱ | | 10 | | 0.06 | | 0.682 | 0.594 | 0.991 | 0.573 |
| 3 | Ⅱ | | 10 | | 0.09 | | 1.748 | 0.411 | 2.615 | 0.260 |
| 4 | Ⅲ | | 10 | | 0.03 | | 1.380 | 0.443 | 1.143 | 0.529 |
| 5 | Ⅲ | | 10 | | 0.06 | | 1.484 | 0.444 | 1.411 | 0.471 |
| 6 | Ⅲ | | 10 | | 0.09 | | 1.861 | 0.359 | 2.893 | 0.245 |
| 7 | Ⅱ | | 20 | | 0.03 | | 0.825 | 0.539 | 1.242 | 0.513 |
| 8 | Ⅱ | | 20 | | 0.06 | | 1.970 | 0.429 | 1.426 | 0.480 |
| 9 | Ⅱ | | 20 | | 0.09 | | 2.266 | 0.321 | 2.000 | 0.368 |
| 10 | Ⅲ | | 20 | | 0.03 | | 1.111 | 0.474 | 1.025 | 0.538 |
| 11 | Ⅲ | | 20 | | 0.06 | | 1.931 | 0.381 | 1.470 | 0.474 |
| 12 | Ⅲ | | 20 | | 0.09 | | 2.284 | 0.301 | 2.329 | 0.321 |
| 13 | Ⅱ | | 30 | | 0.03 | | 1.529 | 0.372 | 1.103 | 0.524 |
| 14 | Ⅱ | | 30 | | 0.06 | | 1.420 | 0.436 | 1.870 | 0.391 |
| 15 | Ⅱ | | 30 | | 0.09 | | 2.867 | 0.237 | 1.543 | 0.433 |
| 16 | Ⅲ | | 30 | | 0.03 | | 1.432 | 0.436 | 0.886 | 0.589 |
| 17 | Ⅲ | | 30 | | 0.06 | | 1.378 | 0.476 | 1.289 | 0.513 |
| 18 | Ⅲ | | 30 | | 0.09 | | 2.258 | 0.321 | 2.301 | 0.298 |
| 19 | Ⅰ | | 10 | | 0.03 | | 2.467 | 0.307 | 0.809 | 0.560 |
| 20 | Ⅰ | | 10 | | 0.06 | | 3.574 | 0.088 | 1.667 | 0.401 |
| 21 | Ⅰ | | 10 | | 0.09 | | 2.970 | 0.224 | 2.826 | 0.157 |
| 22 | Ⅰ | | 20 | | 0.03 | | 2.074 | 0.408 | 0.800 | 0.576 |
| 23 | Ⅰ | | 20 | | 0.06 | | 2.517 | 0.353 | 1.807 | 0.361 |
| 24 | Ⅰ | | 20 | | 0.09 | | 3.199 | 0.222 | 2.540 | 0.246 |
| 25 | Ⅰ | | 30 | | 0.03 | | 2.311 | 0.285 | 0.563 | 0.609 |
| 26 | Ⅰ | | 30 | | 0.06 | | 2.531 | 0.285 | 0.945 | 0.550 |
| 27 | Ⅰ | | 30 | | 0.09 | | 3.374 | 0.211 | 3.026 | 0.212 |

PF : Pressur filter
VF : Vacuum filter

Table 5. Results of multivariate analysis of variance.

| Factor | Pressure filter | | | | Vacuum filter | | | |
|---|---|---|---|---|---|---|---|---|
| | Chi-square($\chi_1^2$) | $\chi^2$ test | | | Chi-square($\chi_1^2$) | $\chi^2$ test | | |
| | | $\alpha$ | | | | $\alpha$ | | |
| | | 0.10 | 0.05 | 0.01 | | 0.10 | 0.05 | 0.01 |
| A | 7.453 | 7.78 | 9.49 | 13.28 | 6.569 | 7.78 | 9.49 | 13.28 |
| B | 0.291 | 7.78 | 9.49 | 13.28 | 2.418 | 7.78 | 9.49 | 13.28 |
| C | 4.871 | 7.78 | 9.49 | 13.28 | 18.690** | 7.78 | 9.49 | 13.28 |
| A × B | 2.368 | 13.36 | 15.51 | 20.10 | 5.519 | 13.36 | 15.51 | 20.10 |
| B × C | 1.662 | 13.36 | 15.51 | 20.10 | 3.524 | 13.36 | 15.51 | 20.10 |
| A × C | 1.005 | 13.36 | 15.51 | 20.10 | 7.305 | 13.36 | 15.51 | 20.10 |

** : Significance level 1 %

4.2 Analysis of filtrate quality

In order to examine the filtrate quality (SS, TOC, T-N), analysis of variance ($L_{27}$) relating to the quality of filtrates is carried out. The analysis result and the discussion are shown in the following.

4.2.1 Optimum levels of the three dewatering factors as viewed from filtrate quality

Table 6 shows a list of filtrate quality for both the pressure filter and vacuum filter. By using the listed values of SS, TOC, and T-N, an analysis of variance of $L_{27}$ is carried out. The results of the analysis of variance relating to filtrate quality are shown in Table 7. In the case of the pressure filter, the main effect of the type of filter cloth is significant with a significance level of 1 % and the main effect of the filtration pressure is significant with a significance level of 5 % with respect to the values of SS and TOC.

The interaction among the three dewatering factors is not recognized. With respect to T-N, each factor is not recognized as both the main effect and the interaction. Next, out of all the items of the filtrate quality having a significance, the optimum levels (lowest values) for SS and TOC were found with a filter cloth of type I (PF-8044) and the filtration pressure at 0.03 MPa.

In the case of the vacuum filter, the main effect of the type of filter cloth is significant with a significance level of 1 % and main effect of the suction force is also

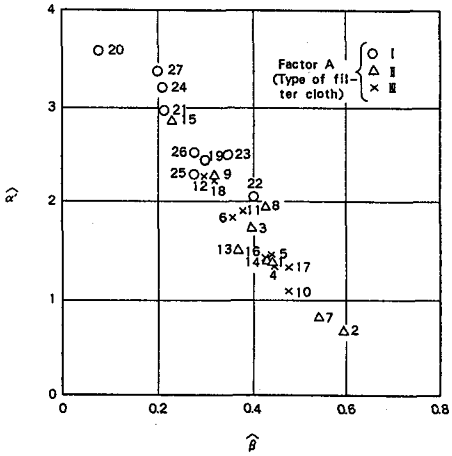


Fig. 4. Relation between $\hat{\beta}$ and $\hat{\alpha}$ for pressure filter.

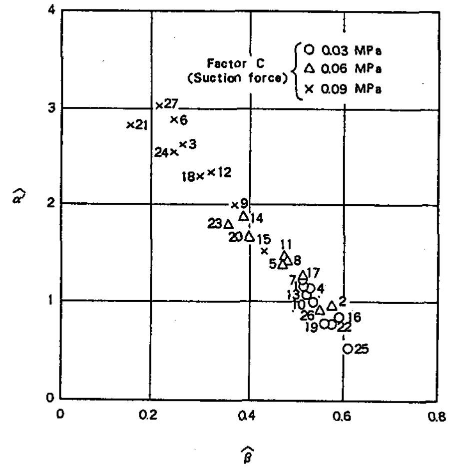


Fig. 5. Relation between $\hat{\beta}$ and $\hat{\alpha}$ for vacuum filter.

significant with a significance level of 1 % with respect to the value of SS. With respect to the value of TOC, the main effect of the type of filter cloth is significant with a significance level of 5 %. Moreover, as for T-N, the main effect of the suction force is also significant with significance level of 1 %. Furthermore, the interaction among the three dewatering factors is not recognized. Next, out of all the items of the filtrate quality having a significance, the optimum level (lowest value) of SS was found with a filter cloth of type Ⅱ (PF-401) and the suction force at 0.03 MPa and, as for TOC, the filter cloth of type Ⅱ gave the optimum level (lowest value). Finally, regarding the optimum level (lowest value) for T-N, the suction force was found at 0.06 MPa.

4.2.2 Comparison of filtrate quality between the pressure filter and vacuum filter

From Table 6, the filtrate quality of the vacuum filter was found better than that of the pressure filter with regard to SS in 26 out of the 27 experiments. Moreover, with respect to TOC, the value of TOC in the vacuum filter is approximately equal to or less than that of the pressure filter in two thirds of all the experiments, viz., 18 out of 27 experiments. Furthermore, with respect to T-N, the value of T-N in the vacuum filter is also nearly equal to or less than that of the pressure filter in about three fifths of all the experiments, viz., 16 out of 27 experiments.

Therefore, first, regarding the filtrate quality (SS, TOC, T-N), in order to examine the difference of the variance based on both apparatus, an analysis of variance of the two-way layout method in which both apparatus are taken as parameters is carried out. The results are shown in Table 8. As a result of an F-test, it was found that the difference of variance regarding the filtrate quality in both apparatus is recognized. In regards to the filtrate quality (SS, TOC, T-N), in order to examine whether there is a difference or not, the two-sided paired t-test with the difference of two population means is carried out by using the filtrate quality (SS, TOC, T-N) resulting from both experiments. The results are shown in Table 9. The result of the two-sided paired t-test as regards to SS is recognized with a significance level of 1 %. As regards to TOC, the result given above is

Table 6. List of filtrate quality.

| No. | Experimental conditions | | | | | | Filtrate quality | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Type of filter cloth | | Sludge layer thickness(mm) | | Filtration pressure(MPa) | | SS (%) | | TOC (mg/ℓ) | | T-N (%) | |
| | PF | VF | PF | VF | PF | VF | PF | VF | PF | VF | PF | VF |
| 1 | Ⅱ | | 10 | | 0.03 | | 0.73 | 0.076 | 850 | 810 | 0.063 | 0.067 |
| 2 | Ⅱ | | 10 | | 0.06 | | 0.34 | 0.100 | 980 | 940 | 0.034 | 0.044 |
| 3 | Ⅱ | | 10 | | 0.09 | | 0.78 | 0.760 | 1030 | 1000 | 0.060 | 0.065 |
| 4 | Ⅲ | | 10 | | 0.03 | | 0.54 | 0.078 | 840 | 730 | 0.050 | 0.043 |
| 5 | Ⅲ | | 10 | | 0.06 | | 0.53 | 0.180 | 960 | 1720 | 0.060 | 0.076 |
| 6 | Ⅲ | | 10 | | 0.09 | | 0.58 | 0.930 | 1350 | 1450 | 0.068 | 0.085 |
| 7 | Ⅱ | | 20 | | 0.03 | | 0.38 | 0.066 | 850 | 760 | 0.057 | 0.061 |
| 8 | Ⅱ | | 20 | | 0.06 | | 1.20 | 0.038 | 1430 | 910 | 0.091 | 0.004 |
| 9 | Ⅱ | | 20 | | 0.09 | | 0.96 | 0.410 | 1370 | 1210 | 0.092 | 0.013 |
| 10 | Ⅲ | | 20 | | 0.03 | | 0.52 | 0.052 | 930 | 1160 | 0.065 | 0.026 |
| 11 | Ⅲ | | 20 | | 0.06 | | 0.95 | 0.280 | 1740 | 1080 | 0.095 | 0.017 |
| 12 | Ⅲ | | 20 | | 0.09 | | 1.10 | 0.650 | 1320 | 360 | 0.091 | 0.082 |
| 13 | Ⅱ | | 30 | | 0.03 | | 0.71 | 0.078 | 940 | 770 | 0.085 | 0.033 |
| 14 | Ⅱ | | 30 | | 0.06 | | 0.78 | 0.062 | 970 | 1110 | 0.087 | 0.019 |
| 15 | Ⅱ | | 30 | | 0.09 | | 1.60 | 0.210 | 1470 | 1280 | 0.056 | 0.047 |
| 16 | Ⅲ | | 30 | | 0.03 | | 0.76 | 0.066 | 960 | 850 | 0.060 | 0.049 |
| 17 | Ⅲ | | 30 | | 0.06 | | 0.62 | 0.210 | 780 | 890 | 0.041 | 0.047 |
| 18 | Ⅲ | | 30 | | 0.09 | | 1.70 | 0.570 | 1280 | 1250 | 0.059 | 0.040 |
| 19 | Ⅰ | | 10 | | 0.03 | | 1.40 | 0.310 | 1870 | 1470 | 0.073 | 0.024 |
| 20 | Ⅰ | | 10 | | 0.06 | | 2.00 | 0.420 | 2410 | 1330 | 0.059 | 0.017 |
| 21 | Ⅰ | | 10 | | 0.09 | | 1.50 | 1.200 | 1830 | 1920 | 0.075 | 0.102 |
| 22 | Ⅰ | | 20 | | 0.03 | | 1.50 | 0.032 | 1590 | 1000 | 0.086 | 0.049 |
| 23 | Ⅰ | | 20 | | 0.06 | | 1.70 | 0.450 | 2020 | 2220 | 0.053 | 0.055 |
| 24 | Ⅰ | | 20 | | 0.09 | | 1.90 | 1.100 | 2660 | 1510 | 0.065 | 0.099 |
| 25 | Ⅰ | | 30 | | 0.03 | | 1.10 | 0.140 | 1930 | 2290 | 0.070 | 0.040 |
| 26 | Ⅰ | | 30 | | 0.06 | | 1.00 | 0.140 | 1950 | 1400 | 0.074 | 0.029 |
| 27 | Ⅰ | | 30 | | 0.09 | | 2.00 | 1.300 | 3450 | 1580 | 0.100 | 0.112 |

PF : Pressure filter
VF : Vacuum filter

Table 7. Results of analysis of variance for each of the filtrate quality parameters based on dewatering factors.

| Factor \ Fo values | Pressure filter | | | Vacuum filter | | | F-test | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | α | |
| | SS | TOC | T-N | SS | TOC | T-N | 0.05 | 0.01 |
| A | 17.517** | 32.523** | 0.721 | 10.485** | 7.849* | 2.093 | 4.46 | 8.65 |
| B | 0.077 | 0.440 | 0.136 | 0.988 | 0.562 | 0.920 | 4.46 | 8.65 |
| C | 5.423* | 6.474* | 0.581 | 47.968** | 0.753 | 9.146** | 4.46 | 8.65 |
| A × B | 0.877 | 1.085 | 2.708 | 1.219 | 0.365 | 2.063 | 3.84 | 7.01 |
| A × C | 0.871 | 0.524 | 0.646 | 3.625 | 0.315 | 2.904 | 3.84 | 7.01 |
| B × C | 0.804 | 1.945 | 0.747 | 0.167 | 1.755 | 1.294 | 3.84 | 7.01 |

* : Significance level 5 %
** : Significance level 1 %

Table 8. Results of analysis of variance for each of the filtrate quality parameters based on methods of filtration.

| Factor | $F_0$ values | | | F-test | |
|---|---|---|---|---|---|
| | | | | α | |
| | SS | TOC | T-N | 0.05 | 0.01 |
| PF | 65.50** | 5.71** | 8.671** | 4.23 | 7.72 |
| VF | 3.03** | 3.21** | 0.900 | 1.94 | 2.57 |

PF : Pressure filter
VF : Vacuum filter
** : Significance level 1 %

Table 9. Test results of a comparison for each of the filtrate quality parameters.

| $t_0$ values | | | t-test | |
|---|---|---|---|---|
| | | | α | |
| SS | TOC | T-N | 0.05 | 0.01 |
| 6.165** | 2.138* | 3.117** | 2.008 | 2.682 |

* : Significance level 5 %
** : Significance level 1 %

recognized with a significance level of 5 %. Furthermore, with respect to T-N, the result given above is also recognized with a significance level of 1 %.

Therefore, in both apparatus, the significant difference is recognized regarding the filtrate quality (SS, TOC, T-N). That is, regarding the filtrate quality, it can be seen that the vacuum filter gives better results than that of the pressure filter.

When we estimate the dewatering effect paying attention to the values of $\widehat{\alpha}'$ and $\widehat{\beta}$ without considering the filtrate quality in both experiments, it can be seen from Figs. 4 and 5 that the three conditions of No. 20 ($A_1B_1C_2$), No. 27 ($A_1B_3C_3$), and No. 24 ($A_1B_2C_3$) in the case of the pressure filter mentioned above are more effective than any one of the experimental conditions for the vacuum filter. However, except for T-N, the filtrate quality in these three experiments for the pressure filter mentioned above is worse than that of experiment No. 27 ($A_1B_3C_3$) which gave the best filtrate quality for the vacuum filter.

Consequently, it is understood that in searching for the optimum dewatering condition in both experiments, it is necessary to estimate the dewatering effect totally from the viewpoint of $\widehat{\alpha}'$, $\widehat{\beta}$, and the filtrate quality.

4.3 Relationship between the speed of filtration and filtrate quality

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

4.3.1 Ordering and ranking numbers relating to the quantity and quality of the filtrate

First, the ranking of the speed of filtration is conducted with respect to the result from Nos. 1 to 27 in the case of the pressure filter. From Fig. 4 all data for the speed of filtration ($\widehat{\alpha}'$, $\widehat{\beta}$) may be arranged in order as follows. The fastest is No. 20 ($A_1B_1C_2$), the second is No. 27

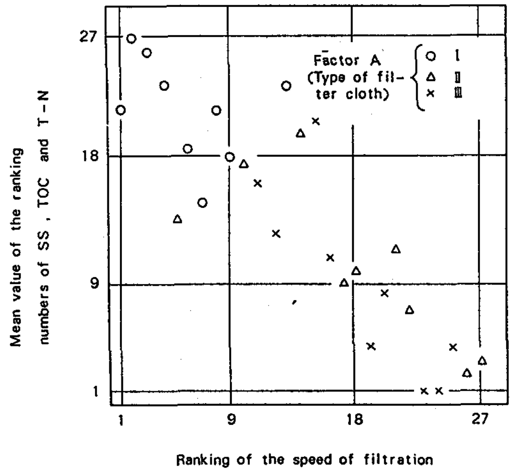


Fig.6. Relation between the ranking of the speed of filtration and the mean value of the ranking numbers of SS, TOC and T—N in pressure filter.

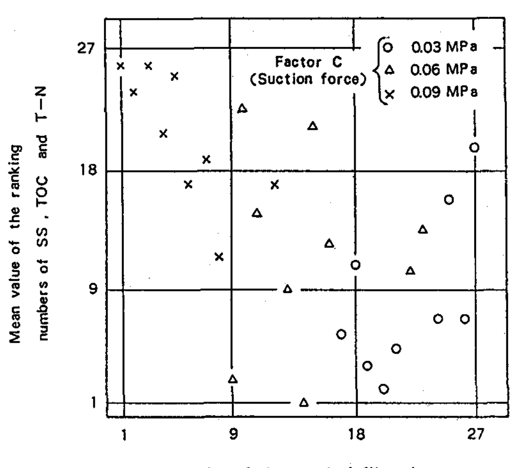


Fig.7. Relation between the ranking of the speed of filtration and the mean value of the ranking numbers of SS, TOC and T—N in vacuum filter.

$(A_1B_3C_3)$ and the slowest is No. 2 $(A_2B_1C_2)$. The ordering is 20>27>24>21>15>26>23>19>25>9>12>18>22>8>11>6>3>13>5>16>14>1>4>17>10>7>2. The top is given to the fastest filtration 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 results from Nos. 1 to 27. The top is given to the lowest value for the filtrate quality parameters and the last to the highest. When the same values come out, the mean value of the ranking numbers is taken.

Similarly, the ranking of the speed of filtration and filtrate quality are conducted with respect to the results from Nos. 1 to 27 in the case of the vacuum filter. The ordering of all data for the speed of filtration $(\widehat{\alpha'}, \widehat{\beta})$ is as follows: 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 ranking of the values of SS, TOC, and T-N is also conducted in the same way as in the pressure filter. By using this ordering, all observations of data for the speed of filtration and filtrate quality can be transformed to their ranking numbers.

Table 10. Correlation coefficients for the ranking numbers.

| Correlation coefficient | | SS | TOC | T-N | Total |
|---|---|---|---|---|---|
| Speed of filtration | Pressure filter | -0.908 | -0.905 | -0.341 | -0.867 (-0.916) |
| | Vacuum filter | -0.748 | -0.236 | -0.405 | -0.559 (-0.699) |

( ): Reference value (Based on the ranking number of mean value of SS, TOC, and T-N weighted by Japanese effluent standards. The standard of TOC is based on that of BOD).

4.3.2 Correlation analysis relating to the ranking of the speed of filtration and filtrate quality

By using ranking numbers with data for the speed of filtration $(\widehat{\alpha'}, \widehat{\beta})$ and the filtrate quality data (SS, TOC, T-N), scatter diagrams for both experiments of the pressure filter and vacuum filter are drawn.

Correlation coefficients of these scatter diagrams are given in Table 10. It can be seen from the table that, in the case of the pressure filter, the correlation coefficient between the speed of filtration and SS, and that between the speed of filtration and TOC are both highly significant, with a significance level of 1 %, whereas the correlation coefficient between the speed of filtration and T-N is not recognized.

Similarly, in the case of the vacuum filter, the correlation coefficient between the speed of filtration and SS is highly significant with a significance level of 1 %, whereas the correlation coefficient between the speed of filtration and TOC is not recognized. The correlation coefficient between the speed of filtration and T-N is also significant with a significance level of 5 %. As shown in Table 10, the existence of large negative values suggests that there is a relationship of trade-off, and the optimum level for the speed of filtration and filtrate quality cannot be located at the same time.

Furthermore, a total evaluation is also done by using the mean value of 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 both kinds of filter and the scatter diagram is drawn. It can be seen from Fig. 6 that, in the case of the pressure filter, the relationship between the two ranking numbers is a negative correlation, with a coient $r = -0.867$.

On the other hand, it can be seen from Fig. 7 that, in the case of the vacuum filter, the relationship between the two also shows a negative correlation with a correlation coefficient $r = -0.559$. It can be seen from these coefficients that the trade-off relationship between the speed of filtration (quantity of filtrate) and filtrate quality in the pressure filter is stronger than that in the vacuum filter. From the results of Sections 4.1.2 and 4.2.1, the levels of the type of filter cloth (factor A) in Fig. 6 and the levels of the suction force (factor C) in Fig. 7 have also been superimposed. In the pressure filter, the type of filter cloth (factor A) is the main trade-off factor, while in the vacuum filter the suction force (factor C) is the main trade-off factor. Moreover, through the use of the mean values of the ranking numbers weighted by Japanese effluent standards in both experiments, the correlation coefficients for the relationships were determined, and these values were compared with those values based on the mean values of non-weighted ranking numbers. Those values mentioned above are shown in Table 10.

5. Conclusion

While the conventional study based on an elemental argument seems to be still of some importance, the comprehensive study with a bird's-eye view of the whole elements, that is, the study with a balance in view, is also needed at the same time.

Moreover, the latest pollution problems in the urban environment have also changed from the pollution problem based on conventional point sources to that of non-point sources. Therefore, while conventional individual processes are important, handling the problem from the broader viewpoint of environmental systems is also necessary at the same time. Consequently, sewage treatment and sludge treatment should also be considered as not only an individual system but as the total environmental system.

In the sewage treatment system, as grasped above, this paper aims at proposing a scientific and positive evaluation technique for excess activated sludge in sludge dewatering as viewed from quantity and quality of the filtrate obtained without sludge conditioning.

(1) With consideration of the three dewatering factors, i.e., filter cloth type, sludge layer thickness, and filtration pressure/suction and laying out (three levels for each factor), it has come to be clear in the case of the pressure filter that none of the dewatering factors is recognized as the main effect, and that no interaction of any two of the dewatering factors is recognized either. However, in Fig. 4, the filter cloth type (factor A) shows a moderate effect in the plot. Therefore, it seems that the examination of the filter cloth type is an important subject. It is clear from the result of multivariate analysis of variance that the optimum condition maximizing the quantity of filtrate in the case of the pressure filter is as follows: PF-8044 type of filter cloth, sludge layer thickness of 10 mm, and filtration pressure of 0.06 MPa. In the case of the vacuum filter, the suction force is recognized as the main effect, and no interaction of any two of the dewatering factors is recognized. It is clear from the result of multivariate analysis of variance that the optimum condition for the vacuum filter is as follows: PF-8044 type of filter cloth, sludge layer thickness of 30 mm, and suction force of 0.09 MPa.

The fitting of the model (4) (i.e., model (1)) is very good and highly significant in both experiments of pressure and vacuum filters. After fitting the model (4), the following two facts are noted. First, from Figs. 4 and 5 there appears a linear relationship existing between the two parameters, $\alpha'$ (= ln $\alpha$) and $\beta$. The linear relationship enables us to interpret model (1) through only one parameter, $\alpha$ or $\beta$. Secondly, by checking residuals in each regression analysis it is known that some nonlinearity still remains after fitting the model (4). This suggests that there is a possibility of the existence of a more sophisticated statistical model, which may need further knowledge of physical meanings in those experiments.

(2) From the result of comparing the items of filtrate quality, it is clear that the filtrate quality in terms of SS, TOC, and T-N is better in the vacuum filter compared with the pressure filter.

(3) The existence of a negative correlation between the speed of filtration and the filtrate quality in the two kinds of filters suggests that there is relationship of trade-off. Moreover, in either kind of filter there is a factor which has a significant influence upon the trade-off relationship between the speed of filtration (quantity of filtrate) and the filtrate quality: the type of filter cloth in the pressure filter while the suction force in the vacuum filter. Moreover, through the use of the mean values of the ranking numbers weighted by Japanese effluent standards, the correlation coefficients for the relationships were determined, and these values were compared with those values based on the mean values of non-weighted ranking numbers.

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