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THE ANALYSIS OF METHODS FOR MEASUREMENTS OF SLUDGE SPECIFIC RESISTANCE

One of the basic parameters that determine the filtrability of sludge is specific resistance. Specific resistance constitutes an integral part of the equations describing the filtration. The theory of filtration, basically developed by RUTH, CARMAN and GALE [4, 6, 7, 15, 16], involves a number of coefficients and concepts that have been gradually introduced by different authors in their efforts to produce the ideal case.

In order to fit the mathematical model of CARMAN [4] sludge filtration must not be viewed as continuous process. In reality the function $p(t/v) = f(v)$ deviates from the linearity at the beginning and the end of the process. This report presents the results of laboratory test performed in order to compare the values of the sludge specific resistance obtained by different methods of measurement.

The studies have revealed that slight differences in test procedure as well as interpretation of the measurement results yield essential differences in the values of sludge specific resistance. In view of the above it is advisable and necessary that the methods of measurement and calculation of the parameter be unified, i.e. they should be transformed into one method allowing uniform interpretation of the test results.

NOTATIONS

A — filtration area, m^2,
K_e — mass of dry solids per unit mass of wet filter cake, %,
K_0 — mass of dry solids per unit mass of sludge, %,
Δp — applied pressure difference, N/m^2,
R — total resistance to filtration, m^{-1},
R_c — resistance of the filter cake, m^{-1},
R_m — resistance of the filter medium, m/kg,
V_1 — volume of filtrate, m^3,
V_0 — volume disregarded, m^3,
C — mass of dry solids in the cake per unit volume of filtrate, kg/m^3,
C_1 — mass of dry solids on the sludge per unit volume of sludge, kg/m^3,
dt/dv — reciprocal flow rate,
t_0 — filtration time disregarded, s,

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r — specific resistance of filtration, m/kg,
w — mass of dry solids in the settled filter cake per unit filtration area, kg/m^2,
V_i — volume of filtrate per unit filtration area, m^3/m,
ϱ_f — density of the filtrate, kg/m^3,
μ — viscosity of the filtrate, cp,
t — filtration time, s.

Laboratory analyse of sludge, commonly known as sludge tests, are carried out to define the filtration properties of the sludge and to determine the basic parameters of filtration.

Before the sludge is to be analysed two characteristic quantities should be distinguished, i.e. sludge specific resistance and filtration resistance. A similar distinction is known in electrotechnics where specific resistance of the material and that of the wire or element are differentiated. The sludge specific resistance determines filtration properties and allows a comparison of the precipitated sediments under different technological conditions. These factors help to compare the mode of sludge conditioning and initial choice of the dewatering method. Filtration resistance is a parameter used to choose and design the dewatering apparatus. To measure the sludge specific resistance a Büchner funnel is used in order to simulate filtration resistance by means of a measurement system similar to the real filter, e.g. a laboratory filter press or a measurement system with a filter plate. The study of sludge filtration properties is based on the filtration theory developed by RUTH [15, 16], CARMAN [4], and GALE [6, 7].

2. THEORY

In the simplest equation of filtration the following parameters are considered: filtrate flow through the specific filtration surface (as a factor connected with a total pressure difference between the sludge and the filtration medium), viscosity of filtrate passing through the sludge, and total resistance as a sum of the sludge resistance and that of the filtration medium

$$\frac{dv}{dt} = \frac{\Delta p}{\mu} \frac{1}{R_c + R_m}. \tag{1}$$

The resistance of the filtration medium during the filtration can be constant, whereas he sl udge resistance increases with the increase of dry mass in the sludge:

$$R_c = rw, \tag{2}$$

where r is the sludge specific resistance at the unit loading of the filtration surface with sludge dry mass equal to:

$$w = cv, \tag{3}$$

where:

$$c = \frac{K_0 \varrho_f}{\left(1 - \frac{K_0}{K_e}\right) \cdot 100.}. \tag{4}$$

The parameter c is often replaced by c_1

$$c_1 = \frac{K_0 \varrho_f}{100 - K_0}. \tag{5}$$

After introducing (2) and (3) into (1) and integrating, a linear dependency is obtained:

$$\frac{t}{V_i} = \left(\frac{\mu r c}{2 \Delta p}\right) V_i + \frac{\mu R_m}{\Delta p}. \tag{6}$$

Since V is a filtrate volume obtained from the unit surface

$$V_i = \frac{V}{A} \tag{7}$$

the eq. (6) takes the form:

$$\frac{t}{V} = \left(\frac{\mu r c}{2 \Delta p A^2}\right) V + \frac{\mu R_m}{\Delta p}. \tag{8}$$

The eq. (8) is graphically represented by straight line V versus t/V with its tangent equal to:

$$b = \frac{\mu r c}{2 \Delta p A^2} \tag{9}$$

from which the sludge specific resistance is easily found:

$$r = \frac{2 \Delta p A^2 b}{\mu c}. \tag{10}$$

Substitution of the parameter c for c_1 yields the apparent specific resistance which is linked with the real resistance by the equation:

$$r_r = r \frac{100 - K_0}{100 \left(1 - \frac{K_0}{K_e}\right)}. \tag{11}$$

Specific resistance of compressible sludge cannot be measured by a direct method. COACKLEY and JONES [7] have developed an indirect measuring method with the use of Büchner funnel and based on eq. (8) of CARMAN [4]. Numerous modifications of this method are found in literature.

The theory of filtration has been developed for noncompressed sludge, since it better represents the reality. It should be pointed out that the filtration of the sludge does not follow the mathematical model of CARMAN [4] during filtration test. In fact the function $f(V) = t/V$ deviates from linearity at the beginning and the end of the process. This has a crucial effect on the value of the specific resistance. Disturbances occurring at the beginning of the process are caused by the formation of the first layer of the cake on the filtration medium. Consequently, most authors [9, 11, 12, 17, 18, 20, 21] who use the sludge specific resistance measuring method suggest that the first batch of the filtrate should be rejected. Filtration time as well as filtration volume are different at the initial stage, affecting the value of the sludge specific resistance. A time factor is also crucial in the measurement. In the literature different ways for determining the end-point of the measurement are described. COACKLEY [5] suggests to run the process up to the moment the cake breaks, i.e. until the pressure starts dropping. In the case of municipal sludge the time is very long and amounts to several hours. ZINGLER [19] suggests to end the measurement when all solids had formed the cake in the system (coefficients log V, log t), since the measuring points deviate from the straight line. In the method developed by HEIDE [8] the measurement is ended after 75 cm^3 of the filtrate has been obtained. TUROWSKI [18] suggests to carry out the measurement for 20 min. NOTEBAERT et al. [14] consider the moment at which the points of the curve $t/v = f(V)$ deviate from the straight line as the end-point of measurement.

3. EXPERIMENTAL

The investigations were carried out using excess untreated sludge, digested and taken from the Silesian treatment plants and conditioned sludge. The sludge was initially homogenized and its specific resistance was measured using the apparatus constructed by COACKLEY [5] (fig. 1). A Büchner funnel, 9 cm in diameter, was linked with a filtrate measuring cylinder of the capacity of 100 cm^3. The unit was equipped with a pipe to connect a vacuum pump. The volume of the sludge sample was 100 cm^3 and the measurement

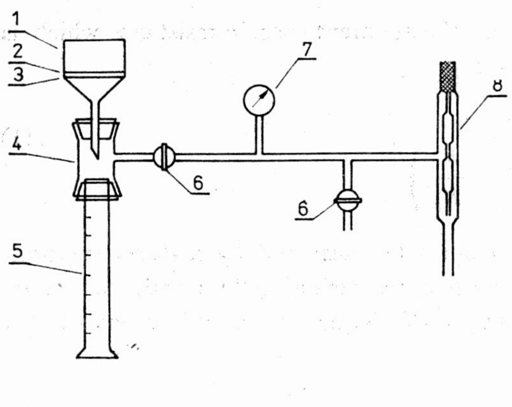

Fig. 1. Apparatus for measurements of sludge specific resistance

1 – Bücher funnel, *2* – filter paper, *3* – metalplastic grid, *4* – vacuum head, *5* – measuring cylinder, *6* – valve, *7* – manometer, *8* – vacuum pump

Rys. 1. Aparat do pomiaru oporności właściwej

1 – lejek Büchera, *2* – papier filtracyjny, *3* – metalowo-plastikowa siatka, *4* – wysokość podciśnienia, *5* – cylinder pomiarowy, *6* – pojedynczy kurek, *7* – manometr, *8* – pompa próżniowa was made at the pressure of 5×10^4 N/m^2. Whatman No. 1 filtration paper was used as a filtration medium. The measurements began at the moment when the first drop of filtrate fell onto the cylinder bottom and ended at the moment when the pressure decreased.

The results of the studies are presented in tabs. 1 and 2 as well as in figs. 2, 3, 4. At the beginning of the graph the spread of the data was considerable due to the formation of the cake layer on the filtration medium. Since determined value of the specific resistance depends mainly on the tangent of the inclination angle, it has been interpolated among the points that markedly form a straight line.

4. DISCUSSION

These investigations have shown that small differences in the measuring and interpreting test results lead to considerable differences in the observed values of sludge specific resistance. Table 1 shows the values of specific resistance for different types of sludges depending on the volume of the filtrate V_0 that has been disregarded. Calculations were made for the parameter b determined from the measuring points obtained before the cake breakage [19]. The smallest values of specific resistance were obtained in the case when initial filtration volume was taken into account for the interpretation of results. The values of the specific resistance increase with those of V_0 yielding large differences and varying for various types of sludge. The greatest differences in the values of the specific resistance were obtained for sludge that is easily dehydrated. The analysis of the values of the specific resistance determined for various types of sludge indicates that both in case when t_0 was constant (in most methods 60—120 s) and when t_0 and V_0 were the same for different types of sludge the results obtained differ from one case to another. Fig. 2 presents the graph of the function $f(V) = t/V$ for the excessive easily dewaterable sludge from the wastewater treatment plant in Wisła-Jawornik, the initial volume being taken into account (curve *1*). Data for various values of V_0 and t_0 (curve *2—5*) are also given. Fig. 3 presents an analogous graph for a digested sludge from the wastewater treatment plant in Pyskowice, characterized by markedly worse filtration properties. In both cases the slope of a straight line increases with the increase in V_0 (for the second and the third filtration phases), however, in the case of easily dewaterable sludge the increase of the tangent coefficient of the straight line $f(V) = t/V$ is much greater than in the case of hard dewaterable sludge. Because of the high and different effect of V_0 on the determined value of specific resistance, it is advisable to begin the measurements of time and volume at the moment when the first drop of the filtrate falls onto the bottom of the measuring cylinder, not disregarding the first batches of the filtrate. Analysis of the run of the function $f(V) = t/V$ indicates that it is parabolic and can be replaced by the two straight lines [19, 20]. The inclination coefficient of the second line is several times greater than that of the first one. Since the quantities A, Δp, μ, and c from eq. (8) are constant

Table 1

Effect of disregarded initial volume on the value of the specific resistance

Wpływ pominięcia objętości początkowej na wartość oporności właściwej

Type of sludge	Dry mass concentration in the feed %	Meas-uring time s	Dry mass concentration in dehydrated sludge %	Time disre-garded s	Volume disre-garded cm^3	Specific resistance $\times 10^{12}$ m/kg	Increase in the specific resistance %	Coagulant
Excess from the treatment plant in Wisła-Jawornik	4.28	150		—	0.0	0.95	—	coagulant
				5	10.0	1.39	46	Fixer IS
				15	28.0	7.92	733	dose 4.2%
				60	55.0	83.2	7657	
Excess from Strzemieszyce plant	4.92	360	10	0.0	0.0	7.13	—	coagulant
				60.0	24.5	11.7	64.0	Zetag 32
				120.0	22.0	15.9	123.0	dose 1.2%
Mixed digested from Bytom plant	2.46	420	6	0.0	0.0	8.35	—	coagulant
				60.0	31.0	14.82	78.7	Fixer IS
				120.0	40.5	20.25	142.6	dose 8.4%
Mixed digested from Bytom plant	2.46	480	8.5	0.0	0.0	16.05	—	coagulant
				60.0	35.0	18.62	16.0	$FeCl_3$
				120.0	45.0	21.84	36.1	dose 8.4%
Mixed digested from Pyskowice plant	4.75	500	13.5	0.0	0.0	12.2	—	coagulant
				60.0	12.0	13.8	13.1	Fixer IS
				120.0	25.0	15.5	27.0	dose 10.5%
Mixed digested from Pyskowice plant	4.75	1200	9.0	0.0	0.0	32.6	—	without preli-
				60.0	9.0	53.8	65.0	minary pre-
				120.0	14.0	62.56	91.9	paration
Mixed digested from Tychy plant	7.2	1200	14.4	0.0	0.0	24.8	—	without preli-
				60.0	5.0	34.8	40.3	minary pre-
				120.0	8.0	40.9	64.9	paration
Mixed digested from Skoczow plant	6.42	5400	14.5	0.0	0.0	56.7	—	without preli-
				60.0	5.0	58.5	3.2	minary pre-
				120.0	8.0	62.1	9.5	paration
Mixed digested from Pyskowice plant	4.75	10800	9.13	0.0	0.0	171.7	—	coagulant
				60.0	9.0	193.1	12.4	Fixer IS
				120.0	13.0	198.3	15.5	dose 2.65%

Table 2

Effect of disregarded initial volume on the value of the specific resistance

Wpływ pominiętej objętości początkowej na wartość oporności właściwej

Type of sludge	Dry mass concentration %	Duration time of filtration phase II s	Time of measurement s	Dry mass concentration by the end of phase II %	Dry mass concentration in the dehydrated sludge %	Specific resistance of the phase II $\times 10^{12}$ m/kg	Specific resistance of the phase III $\times 10^{12}$ m/kg	Increase in the specific resistance at transition of phase II into III
Excess from the treatment plant in Wisła-Jawornik	4.28	150	300	15.2	36.0	0.95	18.12	1807
Excess from the treatment plant in Strzemieszyce	4.92	360	1080	10.0	14.4	7.13	53.2	646
Mixed digested from Bytom treatment plant	2.46	420	1320	6.0	14.0	8.35	71.9	761
Mixed digested from Bytom plant	2.46	480	1320	8.5	13.8	16.05	70.6	328
Mixed digested from Pyskowice plant	4.75	500	1170	13.5	16.3	12.2	20.25	65.9
Mixed digested from Pyskowice plant	4.75	1200	9600	9.0	17.5	32.6	187.0	473
Mixed digested from Tychy plant	7.2	1200	4800	14.4	30.0	24.8	69.2	179
Excess digested from Skoczow plant	6.42	5400	13200	14.5	21.0	56.7	299.4	428
Mixed digested from Pyskowice plant	4.75	10800	21000	9.13	13.5	171.7	315.8	83

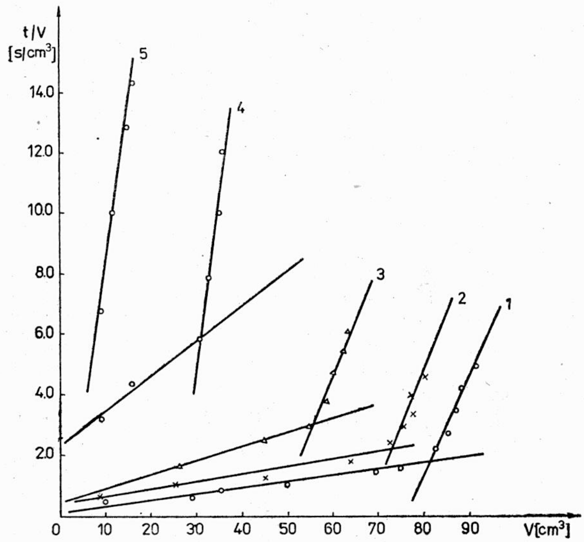

Fig. 2. Function $f(v) = t/v$ for the activated sludge from the Wisła-Jawornik wastewater treatment plant

1 — $v_0 = 0$ cm³, $t_0 = 0$ s; *2* — $v_0 = 10$ cm³, $t_0 = 5$ s; *3* — $v_0 = 28$ cm³, $t_0 = 15$ s; *4* — $v_0 = 55$ cm³, $t_0 = 60$ s; *5* — $v_0 = 74$ cm³, $t_0 = 120$ s

Rys. 2. Wykres funkcji $f(v) = t/v$ dla osadu czynnego z oczyszczalni ścieków Wisła-Jawornik

1 — $v_0 = 0$ cm³, $t_0 = 0$ s; *2* — $v_0 = 10$ cm³, $t_0 = 5$ s; *3* — $v_0 = 28$ cm³, $t_0 = 15$ s; *4* — $v_0 = 55$ cm³, $t_0 = 60$ s; *5* — $v_0 = 74$ cm³, $t_0 = 120$ s

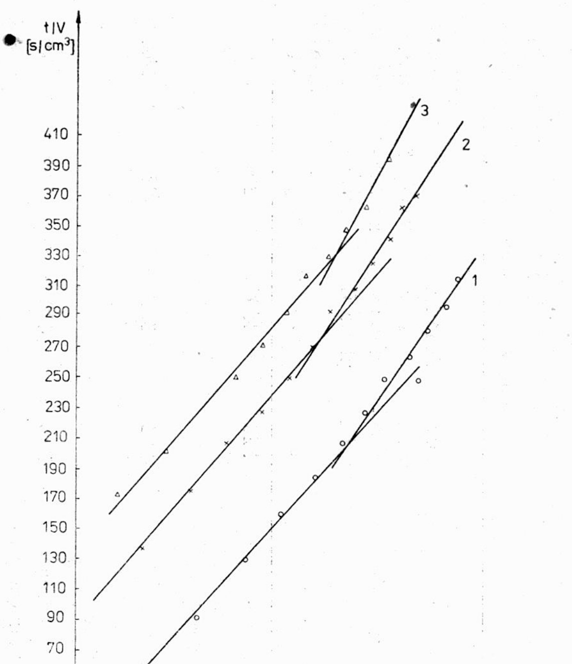

Fig. 3. Function $f(v) = t/v$ for the activated sludge from the Pyskowice wastewater treatment plant

1 — $v_0 = 0$ cm³, $t_0 = 0$ s; *2* — $v_0 = 9$ cm³, $t_0 = 80$ s; *3* — $v_0 = 13$ cm³, $t_0 = 120$ s

Rys. 3. Wykres funkcji $f(v) = t/v$ dla osadu czynnego z oczyszczalni ścieków w Pyskowicach

1 — $v_0 = 0$ cm³, $t_0 = 0$ s; *2* — $v_0 = 9$ cm³, $t_0 = 80$ s; *3* — $v_0 = 13$ cm³, $t_0 = 120$ s during the measurements, the change in the inclination coefficient of the straight line due to the change in the value of the specific resistance being determined. The first part of the graph $f(V) = t/V$ represents filtration with increasing cake layer of the second filtration phase during which there occurs filtration of free interparticle water [10]. At the moment when all sludge particles form a cake, capillary water suction increases coefficient of porosity, the sludge structure breaks and the specific resistance increases (the third phase of filtration). The processes occurring in this phase of filtration are very complex. Apart from the changes in the structure during the sludge flow through the filtrate layer, the sorption and electrokinetic phenomena additionally influence the process. In tab. 2 the values of the specific resistance, duration time and concentration of the dry mass in the cake at the second and third phases of filtration are given for different types of sludge. The value of specific resistance at the transition of the second phase into the third one increases markedly and depends on the character of the sludge. In the case of the easily dewaterable sludges, the increase in the specific resistance is much higher than in those hard dewaterable.

From comparison of the results obtained it follows that the duration of the second phase and the concentration of the dry mass in the cake depend on the physical properties of the sludge analysed. The measurements of the specific resistance of the cake versus filtration time must not be disturbed or made dependent on the capacity of the

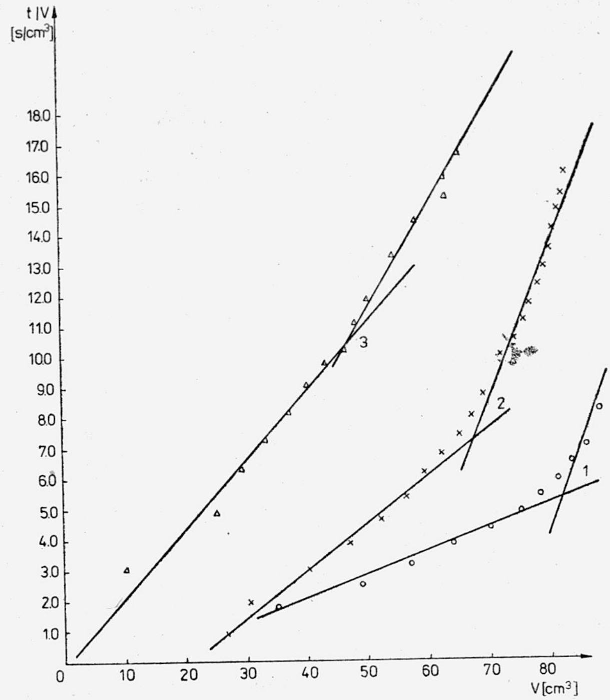

Fig. 4. Function $f(v) = t/v$ for $v_0 = 0$ cm³ and $t_0 = 0$ s

1 — activated sludge from the Bytom wastewater treatment plant, coagulant Fixer IS; *2* — activated sludge from the Bytom wastewater treatment plant, coagulant $FeCl_3$; *3* — activated sludge from the Pyskowice wastewater treatment plant, coagulant Fixer IS

Rys. 4. Wykres funkcji $f(v) = t/v$ dla $v_0 = 0$ cm³ i $t_0 = 0$ s

1 — osad czynny z bytomskiej oczyszczalni, koagulant Fixer IS; *2* — osad czynny z bytomskiej oczyszczalni, koagulant $FeCl_3$; *3* — osad czynny z oczyszczalni w Pyskowicach, koagulant Fixer IS filtrate obtained. Ending of the measurement at a moment not connected with the filtration curve and interpolation of the straight line in the system (V, t/V) for all measuring points lead to a great divergence of the results obtained and cause difficulties in determining the filtration properties of the sludge. The ending of measurements according to the ZINGLER's [19, 20] or NOTEBAERT's [14] methods does not allow to determine fully and appropriately the filtration properties of the sludge (specific resistance in the second phase of the filtration being determined). Consequently, the measuring methods for specific resistance should be unified in order to characterize correctly filtrability of the sludge. For this purpose specific resistance of the sludge and concentration of the dry mass in the second phase and specific resistance in the third phase should be determined. It seems that the above described reasons may cause some difficulties in inplementation of laboratory results in the industrial practice.

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ANALIZA METOD POMIARU OPORNOŚCI WŁAŚCIWEJ OSADU CZYNNEGO

Jednym z podstawowych parametrów określających zdolność filtracyjną osadu czynnego jest oporność właściwa, stanowiąca integralną część równania filtracji. Teoria filtracji, gruntownie rozwinięta przez RUTHA, CARMANA i GALE [4, 6, 7, 15, 16], obejmuje liczne współczynniki i pojęcia, wprowadzone stopniowo przez różnych autorów usiłujących skonstruować jakiś idealny przypadek. Nie wolno rozpatrywać filtracji osadu czynnego jako procesu ciągłego, jeśli ma ona pasować do matematycznego modelu Carmana [4]. Funkcja $p(t/v) = f(v)$ odbiega w rzeczywistości od prostej na początku i na końcu procesu. Praca niniejsza prezentuje wyniki badań laboratoryjnych, których celem było porównanie wartości oporności właściwej osadu czynnego otrzymanych przy różnych metodach pomiaru.

Badania wykazały, że zarówno niewielkie różnice w prowadzeniu doświadczeń, jak i interpretacja wyników, są powodem znacznych różnic w wartości współczynnika oporności właściwej. W świetle tego ujednolicenie metod pomiaru i obliczania współczynnika oporności właściwej osadu czynnego jest słuszne i celowe, tzn. powinno się je przekształcić w jedną metodę pozwalającą na jednolitą interpretację wyników doświadczenia.

ANALYSE DER MESSMETHODEN ZUR BESTIMMUNG DES SPEZIFISCHEN FILTERWIDERSTANDES

Grundlegend für die Bewertung der Entwässerungsfähigkeit von Abwasserschlämmen ist der Wert des spezifischen Filterwiderstandes, der auch in der Filtrationsformel enthalten ist. Die Filtrationstheorie, die von RUTH, CARMAN und GALE [4, 6, 7, 15, 16] entwickelt wurde, enthält mehrere Koeffiziente, die zu einer Idealisierung des Prozesses führen. Die Entwässerung des Belebtschlammes darf nicht als kontinuierlich gelten, wenn sie mit der Carman'schen Formel beschrieben wird [4]. Die Funktion $p(t/v) = f(v)$ verläuft sowohl am Anfang wie am Ende des Prozesses nicht linear.

Der vorliegende Bericht gibt die Ergebnisse von Laboruntersuchungen wieder; sie sollten zum Vergleich von Werten des spezifischen Filterwiderstandes, die während verschiedener Meßverfahren erhalten wurden, dienen.

Daraus folgt, daß noch so kleine Abänderungen im Meßverfahren, zu größeren Differenzen des r-Wertes führen. Man sollte daher ein Einheitsverfahren ausarbeiten, welches eine exakte Interpretation der Ergebnisse ermöglichen wird.

АНАЛИЗ МЕТОДОВ ИЗМЕРЕНИЯ УДЕЛЬНОЙ СТОЙКОСТИ АКТИВНОГО ИЛА

Одним из основных параметров, определяющих фильтровальную способность активного ила является удельная стойкость, представляющая собой интегральную часть уравнения фильтрации. Теория фильтрации, основательно развитая авторами RUTH, CARMAN и GALE [4, 6, 7, 15, 16], охватывает многие коэффициенты и понятия, постепенно введённые различными авторами, стремящимися сконструировать какой-либо идеальный случай. Нельзя рассматривать фильтрацию активного ила как непрерывный процесс, если она должна соответствовать математической модели Кармана [4]. Функция $p(t/v) = f(v)$ в действительности отклоняется от прямой в начале и в конце процесса. Настоящая работа представляет результаты лабораторных исследований, целью которых было сравнение значений удельной стойкости активного ила, полученных при различных измерительных методах.

Исследования показали, что незначительные различия в проведении опытов, а также интерпретация результатов являются причиной значительных различий в значениях коэффициента удельной стойкости. В свете этого унифицирование методов измерения и расчета коэффициента удельной стойкости активного ила является правильным и целесообразным, т. е. отмеченные методы должны быть преобразованы в один метод, дающий возможность единой интерпретации результатов испытания.