Environment Protection Engineering

Vol. 4 1978 No. 2

MAREK SOZAŃSKI*

ON THE APPLICATION OF RHEOLOGICAL METHODS TO THE DETERMINATION OF THE CHARACTERISTICS OF ALUM SLUDGE HYDROTRANSPORT IN CIRCULAR PIPES

Rheological properties of sludges generated during alum coagulation are determined. Methods for calculating the parameters of sludge hydrotransport in circular pipes are reviewed.

NOTATION

A — constant in eq. (16) and (17); equal to 2×10^{-7} m,
a, b, c, d — experimental constants in eqs. (2) and (3),
B, b — constants of the Blasius formula,
c_D — coefficient of resistance (after Fanning),
D_r, R — diameter, radius of the pipe,
d_c — equivalent diameter of the flocs (by volume),
dv/dr — velocity gradient,
g — acceleration of gravity,
He — Hedström's number,
L — length,
Q — flow rate,
Re — Reynolds number,
Re* — generalized Reynolds number,
S_r — surface area per unit volume of real particles,
S_s — surface area per unit volume of a sphere of equivalent dimension equal to $6/d$,
V_d — solids volume concentration in the sludge,
v — average flow velocity,
W — water content,
W_{cr} — critical water content,
Y — yield number
δ — volume of semi-bounded water,
Δ_v/Δ_r — apparent velocity gradient,
Δ_p — head loss,
η — viscosity of a Newtonian fluid,
η_p — plastic viscosity,

---

* Institute of Enivironment Protection Engineering, Wrocław Technical University Wrocław, Poland.

ϱ — sludge density,
τ — tangential stress,
τ_0 — yield stress,
τ_R — tangential stress at the tube wall.

1. INTRODUCTION

Sludges produced in the process of water and wastewater treatment are dispersion systems of a highly complex structure. The properties of this structure are attributable to the particular phenomena that occur during water and wastewater coagulation processes. Hydromechanical effects, occurring during the flow of alum sludges and depending on the geometry of the flocs, and on the magnitude and character of the intermolecular forces, should be considered in terms of general rheological methods. The flow of the sludges should be described on models in which viscosity is represented by rheological parameters. The rheological model of the sludges is selected according to the shape of the experimental flow curves. The integration of the equation for the accepted model, determined by geometry of the circular pipe, allows to obtain the characteristics of the laminar flow. The application of the flow characteristics of the given non-Newtonian fluid to the calculation of sludge hydrotransport parameters is justified by the rheological similarity which permits the determination of the relationships that exist among the geometrical dimensions of the pipes, the flow rates and the rheological parameters for other rheologically similar states.

The paper does not cover the methods of conducting rheological experiments and their interpretation, due to space limitation. References [1–7] cover the subject in depth.

2. RHEOLOGICAL PROPERTIES OF ALUM SLUDGES

Sludges generated during treatment processes behave either as Newtonian fluids or as Bingham plastics. If the water content is markedly high, the rheological properties can be described in terms of Newton's model, and the flow curves produced are straight lines passing through the origin at an angle equal to their viscosity.

The yield stress appears only below a certain moisture level, and then the laminar flow of the sludges is described by two rheological constants, τ_0 and η_p, which characterize Bingham behaviour. The flow curve for a classical Bingham plastic is a straight line with an intercept at τ_0; the slope of the plot indicates the plastic viscosity η_p, the equation being:

$$\tau-\tau_0 = \eta_p \frac{dv}{dr}. \tag{1}$$

The experiments reported in [10] have revealed that the τ_0 and η_p values of alum sludges depend first of all on water content, temperature, specific surface and alum hydroxide content. The rheological parameters of this sludge were plotted as a function of water content (fig. 1 and 2). This relationship was then approximated in terms of the following

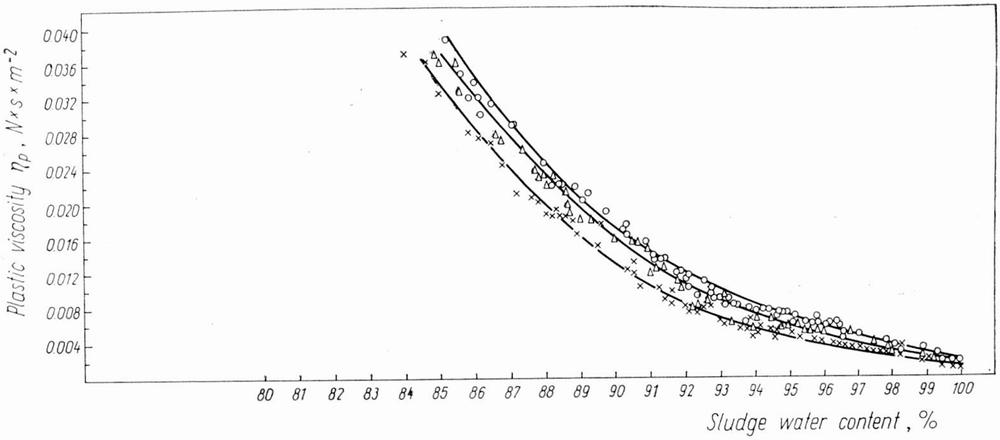

Fig. 1. Plastic viscosity vs. water content for precipitated alum sludge

temperatures; ○ — 273.45 K, △ — 283.15 K, × — 293.15 K

Rys. 1. Wpływ uwodnienia osadu pokoagulacyjnego na wartość lepkości plastycznej

temperatury; ○ — 276,45 K, △ — 283,15, K, × — 293,15 K

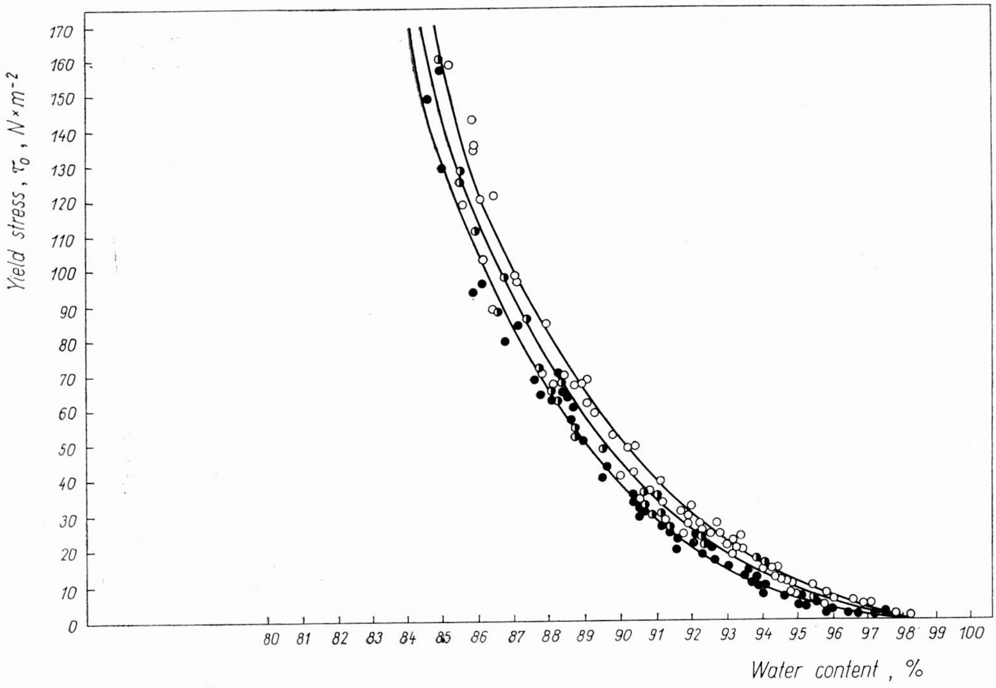

Fig. 2. Yield stress vs. water content for precipitated alum sludge

temperatures; ○ —273.45 K, ◑ — 283.15 K, ● — 293.15 K

Rys. 2. Wpływ uwodnienia osadu pokoagulacyjnego na wartość granicy płynięcia

temperatury; ○ — 273,45 K, ◑ — 273,15, K, ● — 293,15 K

exponential functions

$$\eta_{\text{pl}} = \eta^{a*} \exp[b^*(W_{\text{cr}} - W)], \tag{2}$$

and

$$\tau_0 = d^* \exp[c^*(W_{\text{cr}} - W)]. \tag{3}$$

The correlation coefficients vary from 0.9172 to 0.9981. The effect of temperature (273.45–293.15 K) on the rheological properties of the sludges studied increases with the increasing water content. At increase in the specific surface and alum hydroxide content of the sludges is responsible not only for the increasing values of the rheological parameters (even though water content and temperature remain constant) but also for the decrease of critical water content, at which the yield stress is known to appear.

In the experiments presented in [19] the increase of the specific surface from 22 $m^2 g^{-1}$ to 35 $m^2 g^{-1}$ (due to the variation in the alum hydroxide content) has raised the critical water content of the sludges from 94% to 98%. THOMAS [20] suggests that the rheological properties of sludges containing floc particles be approximated in terms of the relations

$$\tau_0 = 7.55 \times 10^{-2} \times \delta^4 \times V_d^3, \tag{4}$$

and

$$\eta_p = \eta \exp[(2.5 + \delta) V_d] \tag{5}$$

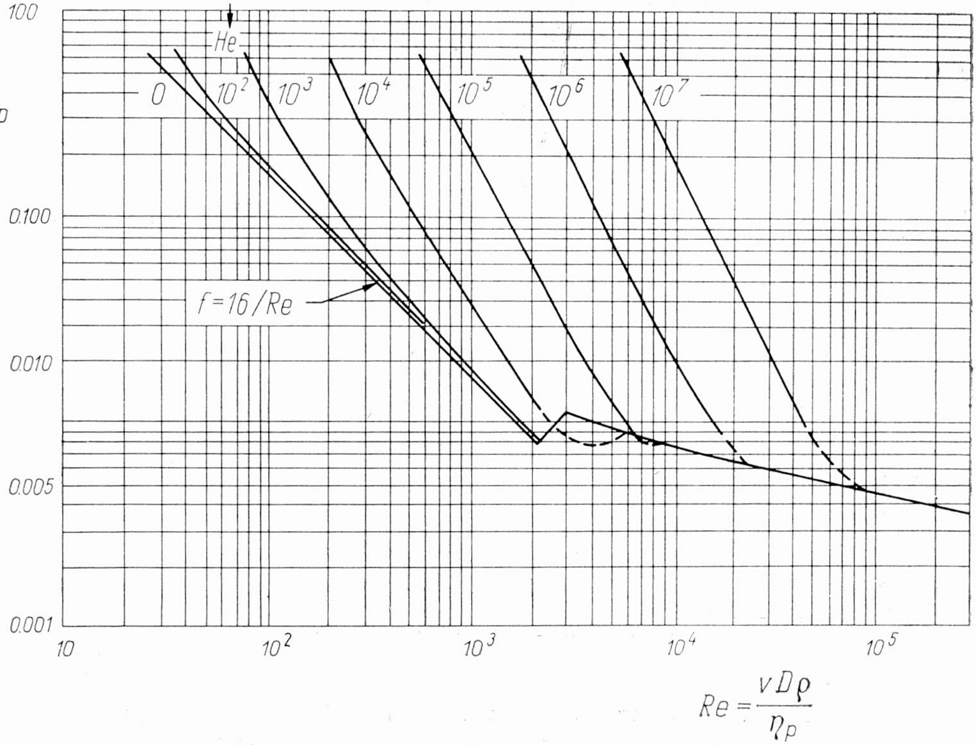

Fig. 3. Coefficient of resistance as a function of Reynolds number and Hedström's number

Rys. 3. Zależność współczynnika oporów od liczby Reynoldsa i liczby Hedströma where δ represents the ratio of the volume of water bounded by the solid phase to the volume of the solid phase.

Both the qualitative and quantitative compositions of the sludges generated undergo constant changes, and the presence of organic matter causes additional variations. These changes are responsible for the significant dispersion of the rheological parameter values, which in turn necessitates statistical interpretation of the experimental results. Examples illustrating such a dispersion are shown in fig. 3 and 4 (after CHOU [4]). As can be seen from these figures, both water content and the anaerobic digestion exert a considerable effect on the rheological parameters of sludges produced in wastewater treatment processes. That is why DICK and EWING [5] have suggested that the effects of anaerobic sludge digestion be evaluated in terms of rheometry. THOMAS [20] has established some interesting relations which describe the rheological properties of sludges containing 0.35–20 μm particles of certain minerals with a 0.02–0.23 volumetric fraction of the solid phase:

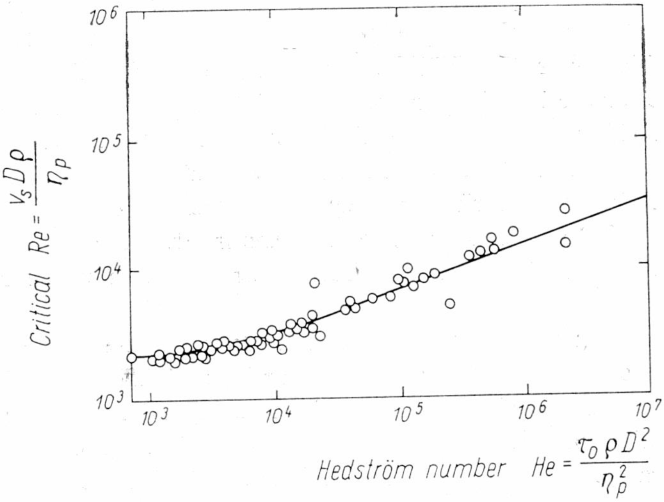

Fig. 4. Critical Reynolds number vs. Hedström's number

Rys. 4. Kryterium ruchu burzliwego określone dla liczb Reynoldsa i Hedströma

$$\tau_0 = \frac{1025}{d_c^2} \exp\left[0.7\left(\frac{S_r}{S_s} - 1\right)\right] V_d^3, \tag{6}$$

and

$$\eta_p = \eta \exp\left[\left(2.5 + \frac{14}{\sqrt{d_c}} \frac{S_r}{S_s}\right) V_d\right] \tag{7}$$

(d_c denotes the particle diameter, in μm; τ_0 is obtained in $\mathrm{KGm^{-2}}$).

Both equations allow to describe the results for kaolin-, totanium dioxide-, boron- and carbon-oxide sludges. Their application to the interpretation of industrial sludges is, however, troublesome, due to the difficulties in the determination of S_s, S_r and d_c. Nevertheless, from the equations it follows that a number of industrial sludges can be considered as having properties of a Bingham plasic.

3. HYDROTRANSPORT OF SLUDGES

The theory of hydrotransport for water-containing dispersion systems is still far from being developed and commonly accepted, even though many theoretical and experimental studies on this subject are reported in the literature. The theories of gravitation and diffusion employed so far are based on hypotheses which have not been verified or justified by experiments. Neither any mathematical formula describing turbulent flow is available.

Therefore some additional assumptions should be made to simplify the mathematical operations rather than to describe precisely the mechanism of the phenomenon. The conventional, simplified approach to these problems involves the hydraulic classification of sludges and determination of the hydrotransport characteristics for the particular types of sludge.

Sludges generated in water- and wastewater-treatment processes are classified among the quasi-homogeneous systems which include particles of different kind and size. Tangential stresses caused by velocity gradients during flow depend not only on the geometrical and hydromechanical factors but also on physical-chemical ones. As yet, an accurate mathematical formula describing tangential stresses to which the sludges are exposed, in terms of the theory of structure (initiated by EINSTEIN [6], BOEDER [3], SIMKA [17] and KUHN [10]) is far from being completed. In this situation, the application of rheological models which provide a macroscopic description of some phenomena, and do not explain the structure of dispersion systems, seems the only way out.

3.1. LAMINAR FLOW OF SLUDGES EXHIBITING BINGHAM PLASTIC BEHAVIOUR

Unlike Newtonian fluids (e.g., water) the flow of a Bingham plastic does not develop at arbitrarily low tangential stresses and requires the application of a tangential stress exceeding the yield stress.

The volume of a Bingham plastic transported in circular pipes in a unit of time, is defined by Buckingham's and REINERS [15] formula

$$Q = \frac{\pi R^4 \Delta_p}{8L\eta_p}\left[1 - \frac{4}{3}\left(\frac{\tau_0}{\tau_R}\right) + \frac{1}{3}\left(\frac{\tau_0}{\tau_R}\right)^4\right]. \tag{8}$$

Following REINER [16], the last term on the right-hand side of eq. (8) can be neglected, if $\tau_0/\tau_R < 0.5$. PARZONKA [12] shows that this situation occurs in the majority of cases considered here. Hence eq. (8) becomes

$$\tau_R = \eta_p \frac{8v}{D_r} + \frac{4}{3}\tau_0. \tag{9}$$

Eq. (9) in the $\frac{8v}{D_r}$, τ_R co-ordinates is a straight line for which the plastic viscosity is an angular coefficient, and $\frac{4}{3}\tau_0$ is the initial ordinate of the straight line with the abscissa Δ_v/Δ_r equal to zero. From the eq. (9), the rheological parameters of sludges exhibiting Bingham plastic behaviour (referred to as Bingham sludges) can be calculated basing on the experimental flow curve. The pressure drop in the pipes, caused by the friction resistance of Bingham plastics, takes the form

$$\frac{\Delta_p}{L} = 32\left(\frac{\tau_0}{6D_r} + \frac{v \times \eta_p}{D_r^2}\right) \tag{10}$$

obtained by the substitution of $\tau_R = D_r \Delta_p/4L$ into eq. (9) and its suitable transformation. Eq. (10) is often used in engineering practice. CALDWELL and BABBITT [1] have employed this equation to establish the flow characteristics for wastewater sludges. Using the same equation, KOWAL and SOZAŃSKI [9] have interpreted the investigation results for the hydrotransport of precipitated alum sludge. The Reynolds number modified for the laminar flow of a Bingham plastic in pipes is given by

$$\mathrm{Re}^* = \frac{v \times D_r \times \varrho}{\eta_p + \frac{\tau_0 D_r}{6v}}. \tag{11}$$

Assuming that Re = 2300, and solving the equation for v the following expression is obtained

$$v = 1150\left[\frac{\eta_p + \sqrt{\eta_p^2 \quad \frac{\varrho\tau_0 D_r^2}{3450}}}{\varrho D_r}\right] \tag{12}$$

which defines the average critical value, above which the flow of Bingham sludges is no longer laminar.

Another method aimed to calculate the laminar flow parameters for Bingham sludges is based on the dimensional analysis and has been developed by HEDSTRÖM [8], and GOVIER and WINNIG [7]. HEDSTRÖM has determined the character of relationship existing between the coefficient of hydraulic resistance c_D and the basic parameters of hydrotransport

$$c_D = f\left(\frac{vD_r\varrho}{\eta_p}, \frac{\tau_0 D_r^2 \varrho}{\eta_p^2}\right) \tag{13}$$

(c_D is a function both of the Reynolds number — in which Hedström has replaced the viscosity of a Newtonian liquid with the plastic viscosity of the Bingham plastic — and of the Hedström number). Eq. (13) is a basis for the diagram (fig. 3) developed by Hedström and illustrating the variation of the c_D values under laminar flow. A criterion indicating the development of a turbulent flow has been determined by Hanks and Pratt [8] (fig. 4) on the basis of dimensionless relations proposed by Hedström. Fig. 4 shows that the development of a turbulent flow can be determined from both the Reynolds number (Re) and the Hedström number (He). Govier and Winnig [7] have described the laminar flow of a Bingham plastic as

$$c_D = f\left(\frac{vD_r\varrho}{\eta_p}, \frac{\tau_0 D_r}{v\eta_p}\right) \tag{14}$$

where c_D depends on Re and $Y = \mathrm{He}(\mathrm{Re} = \tau_0 D_r/v\eta_p)$.

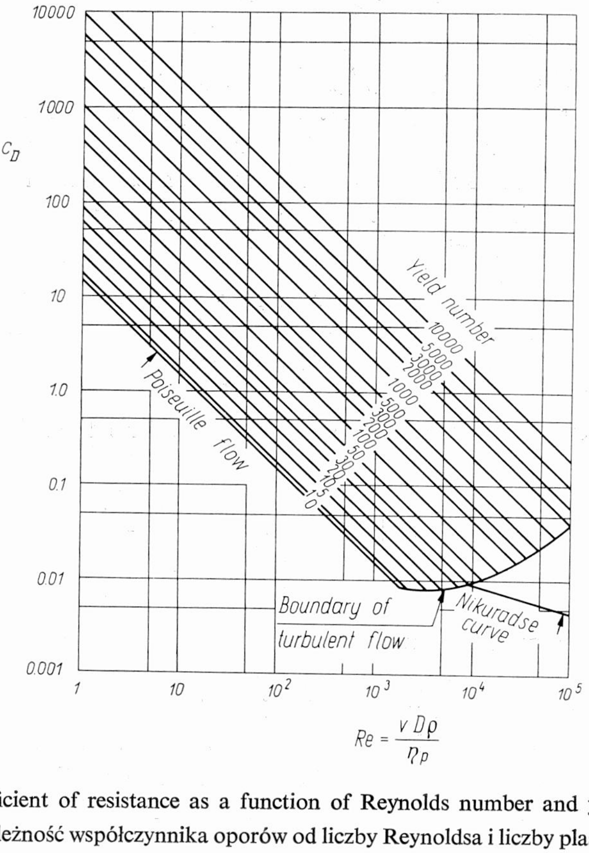

Fig. 5. Coefficient of resistance as a function of Reynolds number and yield number

Rys. 5. Zależność współczynnika oporów od liczby Reynoldsa i liczby plastyczności

The c_D values suitable for practical purposes are listed in fig. 5, after Govier and Winnig. The effect of the yield number on the critical Re number is shown in fig. 6 (after Hanks and Pratt [8]).

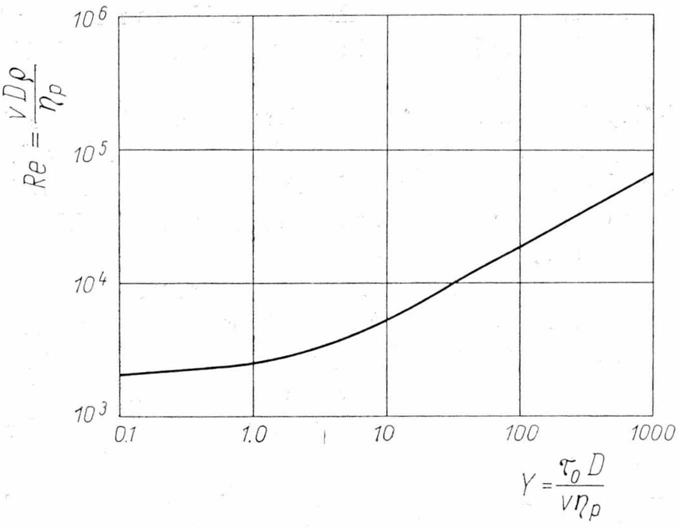

Fig. 6. Critical Reynolds number vs. yield number

Rys. 6. Kryterium ruchu burzliwego określone dla liczby Reynoldsa i liczby plastyczności

3.2. TURBULENT FLOW OF BINGHAM SLUDGES

Owing to the rheological properties of sludges produced in water and wastewater treatment both the flow in pipes and the flow velocity fall either in the range of the laminar flow or in the smooth region of the turbulent flow. Turbulent flow with a developed roughness effect is initiated at a water content exceeding the critical value. When the critical value is exceeded, both sludges and wastewater behave as Newtonian fluids. The turbulent flow of sludges which falls in the region of hydraulic smoothness is also characterized by a marked influence of the rheological parameters on the resistance coefficient. It is advisable to calculate the pipeline for Bingham sludges in terms of the Blasius formula generalized by THOMAS [20]

$$c_D = B\left(\frac{vD_r\varrho}{\eta_p}\right)^{-b}. \tag{15}$$

Basing on experimental results, Thomas has evaluated the B, b constants

$$B = 0.079\left[\left(\frac{\eta}{\eta_p}\right)^{0.48} + \left(\frac{\varrho\tau\ A^2}{\eta^2}\right)^2\right], \tag{16}$$

and

$$b = 0.25\left[\left(\frac{\eta}{\eta_p}\right)^{0.15} + \left(\frac{\varrho\tau_0 A^2}{\eta^2}\right)^2\right]. \tag{17}$$

Some other relationships proposed for the same fluids (as for example the Torrance equation) are mathematically quite sophisticated, therefore, less applicable in engineering practice.

Equations (8)–(17) show that the state of flow is significantly influenced by the rheological and physical properties of the sludge, by the pipe diameter and the flow velocity. The choice of the pipe diameter and flow velocity should be economically justified for any situation and based on the flow characteristics of the sludge which take into account its rheological properties.

As yet, no criteria are available for the optimal design of the hydrotransport of sludges. The formulae discussed here are suitable for the calculations of some conventional operation requirements for a hydrotransport installation, and in the case of a steady flow they take into account the extreme water content values and different types of sludges.

The design methods presented in this paper are fully accurate only for sludges having the properties of an idealized Bingham plastic with constant physical, chemical and biological composition. Since there are not two sludges of identical composition and properties in practice, the sludge samples used for rheometric experiments are likely to differ from the sludge which will be transported in the designed pipeline. Some deviations between real rheological properties and those adopted in the Bingham model for approximation procedures should also be expected.

It is to be noticed here that thixotropy is also likely to occur. The passage through the pumps results in the damage of the thixotropic structure of the sludge transported; nevertheless, an extended stagnation of the sludge in the pipes (e.g., during failure) can cause an overload of the motor when the pump is set in operation. During operation the insides of pipes become covered with growth and crust decreasing the capacity of the system. This decrease is not taken into account here.

The design methods described in this paper should be considered as approximate ones. At the present time our knowledge is insufficient, and we are not able to include in our calculations all the factors that affect the hydrotransport parameters. It is only after a long-term operation of the system, supported additionally with routine testing, that more accurate data will be obtained.

4. EXAMPLE

Let us calculate the characteristics of the hydraulic transport for primary sludges with given water contents, when the flow velocity in a 400 mm diameter pipe is equal to 0.5m^3/s, 1.0 m/s, and 2.0 m/s. The rheological properties accepted for calculations are listed in table 1.

The calculations depend on the character of the flow and involve either the simplified Bingham model or Blasius formula generalized by Thomas.

4.1. First of all the critical values of flow velocity, above which the sludge begins to move under turbulent flow, are calculated. The calculations are carried out according to eq. (12) for three water content values; the results are presented in table 2.

Table 1

Water content %	Density kg/m^3	Yield stress Nm^{-2}	Plastic viscosity Nsm^{-2}
98.2	1004	0.955	0.0037
96.0	1020	2.389	0.0148
93.3	1035	4.300	0.0282

Table 2

$\frac{\eta_p}{D_r}$ Nsm^{-3}	$\frac{\varrho\tau_0}{3450}$ N^{2}s^{2}m^{-6}	$\sqrt{\frac{\eta_p}{D_r}+\frac{\varrho\tau_0}{3450}}$ Nsm^{-3}	$\frac{1150}{\varrho}$ m^3 kg^{-1}	v ms^{-1}
0.0092	0.2779	0.5273	1.1454	0.6145
0.0370	0.7063	0.8414	1.1274	0.9903
0.0705	1.2900	1.1380	1.111	1.3427

As can be seen in this table, the development of a turbulent flow from the laminar regime, in a 400 mm diameter pipe, depends on the water content of the sludge and takes place at a flow velocity ranging from 0.61 to 1.34 m/s. For water flowing in a 400 mm diameter pipe, at 293 K, the critical flow velocity is equal to only 5.0×10^{-3} m/s. The values obtained for wastewater sludges fall in the same flow velocity range as that characteristic of wastewater treatment plants. Hence, it follows that sludges in a wastewater treatment plant behave either as laminar or as turbulent flows, depending on the moisture content. Energy losses should, therefore, be calculated for both types of flow.

4.2. Head loss due to the laminar flow of sludges in 400 mm diameter pipes is calculated using eq. (10). The results are shown in table 3

Table 3

$\frac{\tau_0}{6D_r}$ Nm^{-3}	$\frac{v\eta_p}{D_r^2}$, Nm^{-3}			$\frac{\Delta_p}{L}$, Nm^{-3}		
	$v = 0.5$	$v = 1.0$	$v = 2.0$	$v = 0.5$	$v = 1.0$	$v = 2.0$
0.3979	0.0115	turbulent flow		13.103	turbulent flow	
0.9955	0.0462	turbulent flow		33.333	turbulent flow	
1.7917	0.0881	0,1762	turbulent flow	60.154	62.973	turbulent flow

The values presented range from 13.103 to 62.973 Nm^{-3}. It is first of all the yield stress which contributes to the head loss which is evident from the inequality $\tau_0/6D_r > v\eta_p/D_r^2$.

4.3. The determination of head loss under turbulent flow requires that B, b, Re, and c_D be established in terms of eq. (16), (17), (11) and (15), respectively. The results are presented in tables 4 and 5.

For water, b and B are equal to 0.25 and 0.3164, respectively. In the sludges investigated B is markedly lower and falls in the range $(0.420–0.161) \times 10^{-1}$.

The calculated c_D values are below the Blasius curve which is valid for water. This may be explained by the laminarizing effect of the sludge structure.

4.4. Head loss under turbulent flow in 400 mm diameter pipes are listed in table 6.

Table 4

$\frac{\eta}{\eta_p}$	$\left(\frac{\eta}{\eta_p}\right)^{0.15}$	$\left(\frac{\eta}{\eta_p}\right)^{0.48}$	$\left(\frac{\varrho\tau_0 A^2}{\eta^2}\right)^2$	b	B
0.2780	0.8253	0.5409	8.4×10^{-6}	0.2063	0.0420
0.0695	0.6703	0.2781	54.6×10^{-6}	0.1675	0.0219
0.0365	0.6086	0.2041	182.2×10^{-6}	0.1522	0.0161

Table 5

Re $= \frac{vD_r\varrho}{p}$			$4c_D$		
$v = 0.5$	$v = 1.0$ m/s	$v = 2.0$	$v = 0.5$	$v = 1.0$	$v = 2.0$
Laminar flow	108540	217080	laminar flow	0.01536	0.01332
Laminar flow	27567	55132	laminar flow	0.01580	0.01408
Laminar flow		30592	laminar flow		0.01345

Table 6

$\frac{4c_D}{D_r}$, m^{-1}			$\frac{\varrho v^2}{2}$, kg m^{-1}s^{-2}			$\frac{\Delta p}{L}$, Nm^{-3}		
$v = 0.5$	$v = 1.0$	$v = 2.0$	$v = 0.5$	$v = 1.0$ m/s	$v = 1.0$	$v = 0.5$	$v = 1.0$	$v = 2.0$
Laminar flow	0.0384	0.0330	laminar flow	502.0	2008.0	laminar flow	19.277	66.264
Laminar flow	0.0395	0.0352	laminar flow	507.0	2030.0	laminar flow	20.046	71.456
Laminar flow		0.0336	laminar flow		2070.0	laminar flow		69.552

Head loss in 400 mm diameter pipes at a flow velocity between 0.5 and 2.0 m/s varies from about 8.0 N/m³ to about 120 N/m³.

CONCLUSIONS

1. The description of hydromechanical properties of sludges generated in water and wastewater treatment processes cannot involve the Newton model, because viscosity is an empirical and not a physical parameter.

2. Sludges produced during water and wastewater treatment are quasi-homogeneous mixtures of mineral and organic particles and colloids as well as macromolecules and micro-organisms — with water. The phase conditions of sludges have a considerable influence on the behaviour of the flowing sludge, which can be described by a suitable rheological model, provided that the regime is laminar.

3. The rheological properties of sludges are determined experimentally in viscometers (whose geometry is adjusted to the range and accuracy of measurements, as well as to the shape and size of the particles) with the use of models which ensures an optimum approximation of the experimental results. Satisfactory results obtained with a co-axial cylinder viscometer have been interpreted in terms the Bingham's model.

4. At a water content below the critical value the sludges exhibit the properties of a non-Newtonian fluid owing to the structure generated by the flocs compaction.

5. The rheological characteristic of the sludges allows to determine dynamic similarity for the laminar flow in circular pipes by means of generalized $c_D = f(\mathrm{Re})$ criterion. The conventional form of the Reynolds number, involving plastic viscosity instead of Newtonian viscosity, is insufficient and cannot be regarded as a similarity criterion until being supplemented either the Hedström number with yield number.

6. The experiments confirm the usability of the similarity criteria for sludge transport in pipes and enable the application of the Buckingham and Blasius equations to the calculation of the hydrotransport characteristics.

REFERENCES

[1] BABBITT H. E., CALDWELL D. E., *The flow of muds, sludges and suspensions in circular pipe*, Trans. Am. Inst. Chem. Eng. **37**, 1941.

[2] BINGHAM E. C., *Fluidity and plasticity*, McGraw Hill Book Co., New York-Toronto-London 1922.

[3] BOEDER P., *Über Strömungsdoppelbrechung*, Z. Phys. **75**, 258, 1932.

[4] CHOU T. L., *Resistance of sewage sludge to flow in pipes*, Journal Sanitary Engineering Division **9**, 1958.

[5] DICK R. J., EWING B. B., *The rheology of activated sludges*, Water Poll. Control Fed. Meeting, Kansas City, Mo., 1966.

[6] EINSTEIN A., *Eine neue Bestimmung der Moleküldimensionen*, Ann. Phys. **19**, 289, 1906.

[7] GROVIER G. W., AZIZ K., *The flow of complex mixtures in pipes*, Van Nostrand Reinhold, New York.

[8] HEDSTRÖM B. O. A., *Flow of plastics materials in pipes*, Ind. a. Eng. Chem. (Washinpton) **44**, 1952.

[9] KOWAL A. L., SOZAŃSKI M.M., *Studies of chemical sludge removal from the Tomaszów Mazowiecki Waterworks*, Wrocław Technical University, Wrocław 1967 (unpublished, In Polish)

[10] KUHN W., KUHN H., *Trage nach der Aufrollung von Fadenmolekeln in strömenden Lösungen*, Helv. chim. Acta **26**, 1394, 1943.

[11] PARZONKA W., *Rheological properties of uniform soil-water mixtures*, Academy of Agriculture, Wrocław 1966 (unpublished, In Polish).

[12] Parzonka W., *Theory of viscometers for uniform soil-water mixtures* (In Polish), Rozprawy Inżynierskie **1**, 16, 1968.

[13] Rabinovitch B., Über die viscosität und elastisität von solen, Z. phys. Chem. **A145**, 1, 1929.

[14] Reiner M., Rivlin R., *Über die Strömung einer elastischen Flüssigkeit in Couette Apparat*, Kolloid-Ztg. **1**, 43, 1927.

[15] Reiner M., *Deformation strain and flow. An elementary introduction to rheology*, London 1960.

[16] Reiner M., *Über die Strömung einer elastischen Flüssigkeit durch eine Kapillare*, Kolloid-Ztg. **1**, 39, 1926.

[17] Simka R., *The influence of Brownian movement on the viscosity of solutions*, J. phys. Chem. Ithaca **44**, 1940.

[18] Sozański M. M. *The influence of selected physical and chemical properties of chemical sludges on their rheological parameters*, Wrocław Technical University, Wrocław 1975. (unpublished, In Polish)

[19] Sozański M. M. *Introduction to studies of water and wastewater sludges rheology*, Sanitary Engineering Papers (In Polish), No. 15, Wrocław Technical University, Wrocław 1972.

[20] Thomas D. G., *Transport characteristics of suspensions*. Part VII: *Relation of hindered-settling floc characteristics to rheological parameters*, Am. Inst. Chem. Eng. **9**, 310, 1963.

ZASTOSOWANIE METOD REOLOGICZNYCH DO CHARAKTERYSTYKI HYDROTRANSPORTU OSADÓW POKOAGULACYJNYCH W RUROCIĄGACH

Praca jest poświęcona eksperymentalnej ocenie wpływu podstawowych parametrów fizycznych i reologicznych osadów z procesów oczyszczania wód i ścieków na ich hydraulikę w rurociągach. Właściwości reologiczne tych osadów można opisać modelem Binghama, charakteryzującym się dwiema stałymi: granicą płynięcia i lepkością plastyczną, a parametry fizyczne pozwalają zakwalifikować je do układów dyspersyjnych quasi-jednorodnych. Podano reologiczne kryteria podobieństwa zjawiska ruchu osadów ściekowych, takich jak ciecze binghameoskie, w rurociągach. Wyszczególniono uogólnioną liczbę Reynoldsa, liczbę Hedströma i liczbę plastyczności. Przedstawiono prawidłowość rządzącą przepływem uwodnionych osadów w rurociągach, którą następnie zastosowano do określenia i analizy parametrów ruchu laminarnego i burzliwego w konkretnym przykładzie obliczeniowym. Podano sposób wykorzystania ogólnych zależności hydrotransportu cieczy jednorodnych podanych przez Buchinghama, Reinera, Hedströma, Groviera, Winninga, Parzonkę i innych, do analizy zjawisk ruchu osadów ściekowych. Przytoczono wyniki badań własnych określających wpływ uwodnienia osadów pokoagulacyjnych i temperatury na ich właściwości reologiczne. Przedstawione zależności umożliwiają zarówno interpretację wyników badań hydrotransportu osadów oraz obliczenie rurociągów różnych osadów ściekowych pod warunkiem, że ich właściwości reologiczne można aproksymować modelem Binghama. Wyszczególniono również wyniki prac eksperymentalnych, w których wykazane zostały binghamowskie właściwości osadów ściekowych pokoagulacyjnych.

ANWENDUNG RHEOLOGISCHER METHODEN ZUR CHARAKTERISIERUNG VON KOAGULATIONSSCHLÄMMEN BEIM HYDRAULISCHEN TRANSPORT IN ROHRLEITUNGEN

Der Bericht ist der experimentellen Bewertung des Einflusses grundlegender physikalischer und rheologischer Parameter von Schlämmen die aus Wasseraufbereitungs- und Abwasserreinigungsanlagen stammten, auf deren Fließverhalten in Rohrleitungen gewidmet. Die rheologischen Eigenschaften dieser Schlämme sind mit dem Bingham' schen Modell beschreibbar; sie zeichnen sich durch zwei Konstanten aus: durch die Fließgrenze und durch die plastische Viskosität. Die Werte der physikalischen Parameter lassen die Schlämme in quasi-homogene Dispersoide einzureihen.

Rheologische Ähnlichkeitskriterien des Bewegungsvorganges von Klärschlämmen wie von Bingham'schen Flüssigkeiten in Rohrleitungen werden aufgeführt. Man spezifizierte die verallgemeinerten Reynolds-, Hedström- und Plastizitätszahlen. Dargestellt ist die Regelmäßigkeit die beim Fliessen der wasserhaltigen Schlämme in Rohrleitungen herrscht; dies wird nachher zur Bestimmung und zur Analyse von Parametern der laminaren und der turbulenten Strömung am praktischen Rechnungsbeispiel ausgenutzt.

Ein Verfahren wird genannt, in dem allgemeine Formeln des hydraulischen Transportes von homogenen Flüssigkeiten nach Buckingham, Reiner, Hedström, Grovier, Winning, Parzonka u.a. zur Analyse der Strömung von Klärschlämmen angewandt werden. Wiedergegeben werden Ergebnisse eigener Versuche, in denen der Einfluß des Wassergehaltes und der Temperatur von Koagulationsschlämmen auf deren rheologische Eigenschaften getestet wurde.

Die dargelegten Abhängigkeiten ermöglichen sowohl eine Interpretation der Ergebnisse des Hydrotransportes von Schlämmen, wie die Berechnung von Rohrleitungen für verschiedene Schlämme unter der Bedingung, daß deren rheologische Eigenschaften sich nach dem Bingham-Modell approximieren lassen.

Ergebnisse von Untersuchungen an Koagulationsschlämmen, bei denen man die Bingham'schen Eigenschaften nachweisen konnte, werden dargestellt.

ПРИМЕНЕНИЕ РЕОЛОГИЧЕСКИХ МЕТОДОВ ДЛЯ ХАРАКТЕРИСТИКИ ГИДРОТРАНСПОРТА ОСАДКА ОТ КОАГУЛЯЦИИ В ТРУБОПРОВОДАХ

Работа посвящена экспериментальной оценке влияния основных физических и реологических параметров осадков от очистки воды и сточных вод на гидравлику их текучести в трубопроводах. Реологические свойства этих осадков могут быть описаны моделью Бинхэма, характеризующейся двумя постоянными — пределом текучести и пластической вязкостью, а физические параметры позволяюто тнести их к квазиоднородным дисперсионным системам. Приведены реологические критерии подобия явлений движения водосточных осадков в трубопроводах. Представлены обобщенное число Рейнольдса, число Гедстрёма и число пластичности. Описана закономерность, управляющая течением гидратированного осадка в трубопроводах, которые затем применялись для определения и анализа параметров ламинарного и турбулентного течений на конкретном расчетном примере. Изложен способ использования общих зависимостей гидротранспорта однородной жидкости, приводимых Бучинхемом, Гедстрёмом, Гроувьером, Виннингом, Пажонкой и другими, для анализа явлений движения сточного осадка. Представлены результаты собственных исследований автора, определяющих влияние гидратации осадка от коагуляции и температуры на их реологические свойства. Изложенные зависимости позволяют интерпретировать результаты исследований гидротранспорта осадка и производить расчет трубопроводов для разных сточных осадков при условии, что их реологические свойства могут быть приближены моделью Бинхэма. Приведены также результаты опытных работ, в которых были доказаны ,,бинхэмские" свойства сточных осадков от коагуляции.