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SEWAGE SLUDGE RHEOLOGICAL PROPERTIES VARIABILITY IN DEPENDENCE OF DRAWING SLUDGE SAMPLES AT DIFFERENT TIMES

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COMMUNICATION

Keywords: Sludge, rheology, flow curve, rheological model, rheological parameters, non-Newtonian fluid.

Abstract: Sewage sludge is a two-phase mixture, generated during the treatment of domestic sewage in waste water treatment plants. It consists of 90–99% water and an accumulation of settleable solids, mainly organic that are removed during primary, secondary or advanced wastewater treatment processes. The hydration of the sludge is one of its main properties which determines sludge management and waste disposal cost. The flow properties of the sewage sludge, such as settling properties and concentration of solids, may affect its hydraulics. Application of rheology in wastewater treatment is determined by the flow character of the sludge. The basic purpose of the investigation was to define the rheological properties of sludge taken from secondary settling tanks in a typical municipal wastewater treatment plant. A laboratory investigation was conducted using a coaxial cylinder with a rotating torque and gravimetric concentration of the investigated sludge ranged from 2.21 to 6.56%. Approximation was made after transforming the pseudo-curve obtained from the measurements into the true flow curve, which was made according to the equation provided by Krieger, Elrod, Maron and Švec. In order to describe rheological characteristics the 3-parameter Herschel-Bulkley model was applied. The correlation between rheological parameters τ_o, k, n and concentration C_s was calculated as well as between periods of time when the samples of sludge were taken. The research has allowed calculating the dimension of the main transport installation pumping sludge and optimizing the pump discharge pressure, when transporting viscous sludge in pipelines. Determination of rheological parameters, especially yield stress (τ_o), is important in sludge management, for instance in designing parameters transporting, storing, spreading.

INTRODUCTION

Sludge from a typical municipal wastewater treatment plant is characterized by putrescibility, low ability to give up water at high water content, and presence of pathogenic bacteria and parasites.

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The sewage treatment product is highly hydrated sludge and the purified municipal waste is composed of 1–2% [11]. The number of sewage treatment plants has been increasing lately, which is the reason for the systematic increase in the amount of sludge. The hydration of the sludge is one of its main properties which determines the sludge management and waste disposal cost.

Decreasing water content and thus increasing its concentration has been introduced lately in order to limit the overall unit cost in slurry pipeline technologies. The tendency of increasing slurry content was investigated by Heywood and Slatter [4, 12]. Sludge is often highly viscous, exhibits high shear and its handling and management depends not only on chemical and microbiological properties but also on its rheological properties.

Rheology is the science of plasticity deformation (strain) and material flow. Rheology describes the deformation of a body under the influence of stress. In the case of Newtonian fluids shear stress is proportional to shear rate, and viscosity is the ratio of the shear stress to the velocity gradient (shear rate) in a fluid. There is linear dependence between shear stress and shear rate in the case of Newtonian fluids therefore viscosity is a constant value, which can be changed only by the influence of temperature or pressure. The flow, in the case of two-phase systems, can be analyzed in the range of Newtonian and non-Newtonian flow. The rheological description of suspensions depends on:

- properties of dispersion phase,
- concentration,
- contents of inorganic and organic compounds, living organisms, colloid and their cooperation.

The first formula for dilute suspension viscosity which connects concentration and suspension viscosity had been quantified by Einstein and is as follows [1]:

$$\eta = \eta_0(1 + 2.5C_v) \tag{1}$$

where:

η, η_0 – the suspends and solvent viscosity,

C_v – volume fraction of the suspension occupied by particles.

According to the formula given above (1) there is a linear dependence between viscosity and volume concentration. However, particle cooperation induces strong departure from this rule. The intermolecular attraction and repulsion of dispersed phase also influence the rheological properties. Presence of these forces is a result of intermolecular interaction and chemical bonds. It determines the constitution, shape and structure of the sludge [13].

Description of non-Newtonian fluid cannot be based on the Newtonian model since, under certain pressure and temperature conditions, sludge viscosity is not a constant value, yet varies depending on deformation rate. In the case of a fluid such as sludge, viscosity is described with rheological parameters of the model. In vast majority of publications, the rheological parameters of non-Newtonian fluid fall, as a rule, show strong dependence with concentration increase [6–10, 13].

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Knowledge of the rheological characteristics of the sludge at various concentrations and temperatures allows for solving the similarity for flow in pipelines of circular cross-section based on generalized criterion $\lambda = f(Re)$ for laminar flow regime [7, 8].

METHODS

The research was carried out on samples taken from the municipal sewage treatment plant in Namysłów. The treatment plant was built for Namysłów and is supplied with municipal and industrial wastes. The amount of supplied sewage is about 6000 m^3/day. The samples were taken from the secondary settling tank. The variation ranges of sludge samples were obtained by diluting the sludge with supernatant. The gravimetric concentration of mixture C_s is described as the mass ratio of dry component (m_s) to the mass of a mixture (m_m) and it was designated for each of the samples investigated.

The measurements were carried out using VT550 viscometer (manufactured by Haake) with a rotating coaxial cylinder. The temperature was stabilized with thermostat. The viscometer enabled measurement of the flow curves for a wide range of deformation velocity and shear stress. The device used ensures uniform stress distribution in the measuring gap and enables continuous measurements of shear stress τ at defined apparent deformation rate G_p. The coaxial cylinders are executed with various diameters. The measurement system MV1 with measuring gap width 0.96 mm was used. Definition of rheological parameters of the sludge relies on specifying the flow curves $\tau = f(G_p)$ in a laminar flow. The investigation was performed according to method described [7, 9]. At first the granulometric distribution of sludge was performed. It allowed for the use of the fine fraction (< 135.4 μm). Measuring conditions are summarized in the following procedure: stirring at shear rate of 300 s^{-1}, decreasing shear rate to 0 and then increasing to 300 s^{-1}, again decreasing shear rate from 300 s^{-1} to 0, and finally increasing shear rate to 300 s^{-1}. The yield stress was extrapolating through the stress axis.

RHEOLOGICAL CHARACTERISTICS OF THE SLUDGE

The purpose of the rheological investigation was to:

- define the rheological properties of the sludge by taking measurements of curves, $\tau(G_p)$;
- devise the optimal rheological model;
- estimate the parameter values for the rheological model;
- establish the influence of gravimetric concentration C_s of the sludge on the rheological parameters;
- define the critical concentration $C_{s,gr}$, which delimitates Newtonian and non-Newtonian behavior of sludge;
- formulate the empirical formula illustrating the influence of concentration and sludge sampling (when the samples were taken) on the rheological parameters.

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RESULTS AND DISCUSSION

The main reason to undertake the investigation was the non-Newtonian behavior of the sludge. The basic target of the research was to establish the rheological parameters of the sludge by means of the best possible model that describes its properties taking the variability of drawing samples into account. The investigation was made for a series of various gravimetric concentrations C_s of the sludge at a constant temperature. Examples of obtained flow curves for several concentrations are presented in Figure 1.

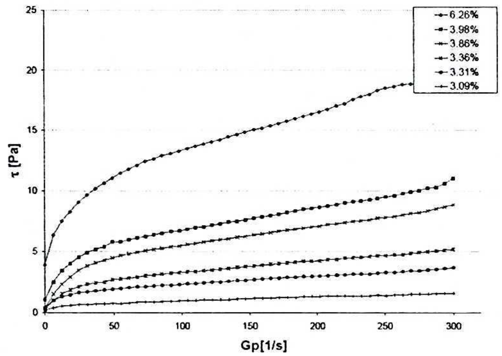

Fig. 1. Measured pseudo-curves of flow for various concentrations of sludge

The basic goal of rheology is to search for formulae enabling proper approximation of flow curves, which eliminate errors in calculating the frictional pressure loss in the pumping pipeline installations.

Selection of the rheological model and establishing the rheological parameters for a variety of concentrations (C_s) was possible with methods of statistical analysis. Selection of the rheological model was performed on the basis of determined true flow curves (using the equation provided by Krieger, Maron, Elrod and Švec), according to the method described by Czaban [2]. In order to describe rheological characteristics the 3-pararameter Herschel-Bulkley model was applied as follows:

$$\tau = \tau_o + kG^n \quad \text{for} \quad \tau > \tau_o \qquad (2)$$
$$G = 0 \quad \text{for} \quad \tau < \tau_o$$

Results indicate that in the range of analyzed gravimetric concentration the yield stress (τ_o – flow threshold) is present. The research confirmed that solids concentration is the main parameter affecting sludge rheology [3, 7–9, 12, 13]. Depending on sludge concentration rheological behavior can be described with the 3-parameter generalized Herschel-Bulkley model, which gets simplified to a 2- or 1-parameter model, as the gravimetric concentrations C_s reduces.

The critical concentration $C_{s,gr}$ delimitating Newtonian and non-Newtonian behavior of the sludge has been determined from an approximation of dependence $\tau_o(C_s)$ – extrapo-

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lating $\tau_o = 0$. For the concentration from 3.09 to 6.26 (illustrated series of measurements in Fig. 1), the $C_{s,gr}$ is 2.90%. The sludge with gravimetric concentration $C_s < C_{s,gr}$ behaves like Newtonian fluid, whereas with the concentration of solid constituent $C_s > C_{s,gr}$ it appears as non-Newtonian fluid.

Rheological characteristic of sewage sludge was conducted on samples taken from the same site but at different time.

Figures 2, 3, and 4 illustrates the examples of setting-up the sludge rheological parameters for Herschel-Bulkley model in dependence of concentration regarding period of time when the samples of sludge were drawn for analysis.

The variability of rheological parameters, for concentration from $C_s = 2.21$ to 6.56%, with the date of sampling was correlated by regression model. These models were developed in order to provide a best-fit model describing relationship $\tau_o = f(C_s)$, $k = f(C_s)$ and $n = f(C_s)$. The presented exponential model, which was applied in this investigation, shows satisfactory accuracy to the measurement (Figs. 3 and 4).

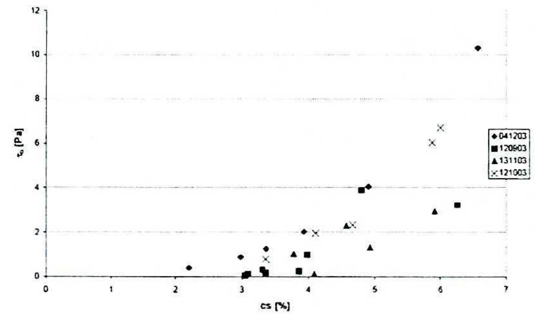

Fig. 2. Dependence of yield stress τ_o for Herschel-Bulkley model on sampling

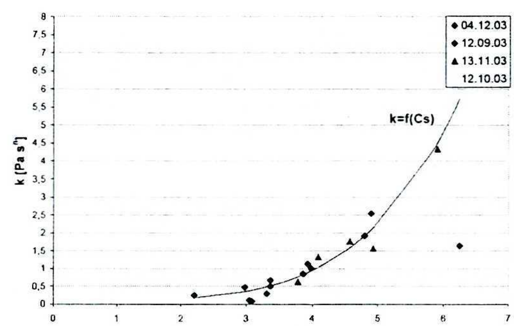

Fig. 3. Dependence of rigidity coefficient k for Herschel-Bulkley model on sampling

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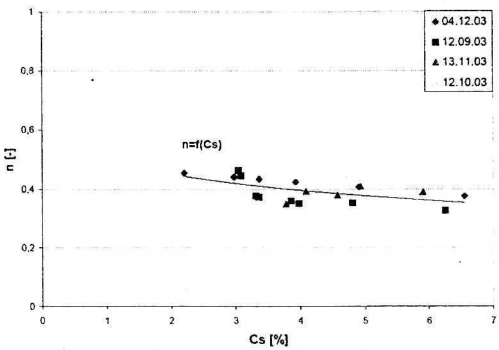

Fig. 4. Dependence of structural number n for Herschel-Bulkley model on depending on sampling

$$y = ax^b \tag{3}$$

It was noticed that there seemed to be a wild discrepancy between measured values in the case of the relationship between yield stress (τ_0) and gravimetric concentration (C_s) regarding the sampling. On the other hand, there is evidence of correlation in the case of function $k = f(C_s)$ and $n = f(C_s)$ with the sampling. The rigidity coefficient k and the structural number n (the points on the diagram) exhibit sharply outlined correlations.

The proposed model has a correlation coefficient from 0.87 to 0.95 and allows for the accurate prediction of measured values.

The approximated correlation coefficient value is as follows:

- for $k = f(C_s)$ in dependence on sampling: a = 0.00303, b = 4.11926
- for $n = f(C_s)$ in dependence of sampling: a = 0.529856, b = -0.212202

The best-fit models are shown in Figures 3 and 4.

The research showed that dependence of rheological parameters (k, n) of Herschel-Bulkley model on sampling date were properly approximated by exponential functions at specified concentration C_s. Therefore proposed model can be used to estimate value of the rheological parameters (k, n) for other measurements.

This relationship was not noticeable in the case of yield stress (τ_0), especially in range of high concentration C_s. The biggest discrepancy between data is in the case of high concentration. Maximum change of the yield stress was observed for the sludge sampled on 04.12.03 and 12.09.03 (Fig. 2). The observed change in the same range of examined concentration from different WWTPs could be connected with flow variability.

This research indicates that rheological parameters exhibit distinct variability with sampling. Significant change in flow characteristic can be linked together with mass density and hydration of sludge change, which is connected with sewage sludge inflow variability. Sewage supplies on waste water treatment plant distinguish day variability load pollution therefore the rheological parameters should be considered within other technical parameters.

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CONCLUSION

The rheological characteristic of sludge was conducted using a viscometer with a coaxial cylinder and rotating torque of Couette-Searle type made by Haake. The mixture of sludge with water depending on tested gravimetric concentrations C_s in shear conditions of measuring gap acts as rheostable fluid, not dependent on time of shearing.

Rheological behavior of examined sludge depends on its gravimetric concentration C_s. For the concentration $C_s < C_{s,gr}$ it behaves as Newtonian, whereas with the concentration of solid constituent $C_s > C_{s,gr}$ it appears a non-Newtonian fluid.

To approximate true flow curves, the 3-parameter generalized Herschel-Bulkley model was applied on basis of statistical analysis.

The relationship between rheological parameters τ_o, k, n and gravimetric concentration C_s was established. The yield stress and rigidity coefficient of Herschel-Bulkley model increase, while the structural number decreases with rising gravimetric concentration C_s.

The significant correlation of the rheological parameters k and n was observed in range of examined concentration with the date of sampling while the yield stress was not varied significantly (Figs. 3 and 4).

NOTATION

C_s	– gravimetric concentration,
$C_{s,gr}$	– critical concentration,
G	– shear rate,
G_p	– apparent shear rate, deformation rate,
n	– structural number,
k	– rigidity coefficient for Herschel-Bulkley model,
τ	– shear stress,
τ_o	– yield stress.

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ZMIENNOŚĆ PARAMETRÓW REOLOGICZNYCH W FUNKCJI CZASU POBIERANIA PRÓB DO ANALIZ

Osady ściekowe są dwufazową mieszaniną powstającą w procesie oczyszczania ścieków. Składają się one z około 90–99% wody i cząstek opadających, głównie organicznych, usuwanych w dalszym procesie oczyszczania. Uwodnienie osadów jest jedną z najważniejszych własności osadów ściekowych decydujących o gospodarowaniu osadami i kosztach ich utylizacji. Podstawowym celem przeprowadzonych badań było określenie cech reologicznych osadów ściekowych pochodzących z osadników wtórnych typowych oczyszczalni mechaniczno-biologicznych ścieków komunalnych. Badania reologiczne przeprowadzono przy pomocy wiskozymetru rotacyjnego z obrotowym cylindrem wewnętrznym. Koncentracja badanych osadów wynosiła od 2.21 do 6.56%. Do aproksymacji rzeczywistych krzywych płynięcia, określonych na podstawie eksperymentalnie otrzymanych pseudokrzywych płynięcia zgodnie z metodyką Krigera-Marona, wykorzystano trójparametrowy uogólniony model reologiczny Herschela-Bulkley'a. Określono zmienność parametrów modelu reologicznego τ_0, k, n z koncentracją wagową C_s, jak również określono zmienność parametrów reologicznych w funkcji czasu pobierania prób do analiz. Przeprowadzone badania pozwalają na wymiarowanie instalacji pompowo-rurowych ciągu technologicznego oczyszczalni ścieków przepompowujących osad czynny. Określenie parametrów reologicznych ma istotne znaczenie w gospodarowaniu odpadami np. projektowaniu parametrów ciągu technologicznego oczyszczania, składowania, rozsiewania.