

ON THE RHEOLOGICAL CHARACTERISTICS OF SEWAGE SLUDGE

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Abstract

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The work is focused on characterization of rheological behavior of sewage sludges sampled at different stages of waste water treatment. The main attention was focused on dynamic viscosity dependence on temperature, and shear rate. The sludge samples were examined under temperature ranging from 1 °C to 25 °C and under shear rate ranging from 0.34 s⁻¹ to 68 s⁻¹. Rotary digital viscometer (concentric cylinders geometry) was used to perform the rheological measurements. The solids content of the sludge samples ranged from 0.43 % to 21.45 % (A and C samples, respectively) and ash free dry mass from 56.21 % to 67.80 % (A and B samples, respectively). The tested materials were found to be of non-Newtonian nature and temperature dependent. Measured data were successfully characterized by several mathematical models (Arrhenius, Bingham Plastic, Casson Law, Exponential, Gaussian, and IPC Paste) in MATLAB software with satisfying correlations between experimental and computed results. The best match ($R^2 = 0.999$) was received with use of Gaussian model, in both cases, shear rate and temperature dependence. The results are quite useful e.g. for the purpose of technological equipment design.

sewage sludge, apparent viscosity, modeling

Sewage sludge is a product of wastewater treatment and it is produced in different amount, quality, properties and different steps of waste water purification. The main component of sludge is water. Its amount depends on the sludge sort and the way of stabilisation (aerobic, anaerobic). The raw sludge has usually a water content of 93 % to 99 % (Werther and Ogada, 1998). Therefore a dewatering (up to approx. 25 % dry solid content) or drying (to over 88 % dry solid content) can be necessary for a further utilization. The second main component is the dry solid, which is made up of organic and inorganic substances. Basically sludge is sort as primary, secondary (excess) and tertiary (chemical). Primary sludge is produced through the mechanical wastewater treatment process. It consists of unsolved wastewater contaminations. Primary sludge consists of a high portion of organic matters, as faeces, vegetables, fruits, textiles, paper etc. The material is composed of a thick fluid with a water content ranging from 93% to 97%. The activated sludge flows from the biological aeration basin into the final clarifier. The activated sludge flakes settle down

to the bottom and can be separated from the cleaned wastewater. The main part of the separated sludge, which is transported back to the aeration basin, is called return activated sludge. To reach a constant sludge age the unused biomass has to be removed from the biological treatment system as secondary (excess) sludge. The excess sludge contains not-hydrolysable particulate materials and biomass due to metabolisms. Tertiary sludge is produced through further wastewater treatment steps e.g. by adding a flocculation agent.

Sludge is processed at the wastewater treatment plant in step, which is called sludge management. Sludge management is number of operation, (thickening, dewatering, transporting, storing, pumping, etc.), which requires sludge to be previously characterized by reliable and demonstrative procedures. Mechanical flow properties should be used for sewage sludge characterizing, but there is some limitation, especially from hydrodynamics point of view – sludge can be treated as solid as well as liquid.

The results of rheological measuring can be used as an useful tool for the characterization of sewage

sludge to control sludge treatment processes, such as dewatering, stabilization and advanced processes, such as value-addition (Brar et al., 2007; Giordano et al., 2007). In fact, torque rheology was demonstrated as an appropriate tool to measure sludge flocs' strength in mixing conditions, adjusting polymer dose and type to control suspension strength for optimizing sludge dewatering (Abu-Orf and Örmeci, 2005). In stabilization (aerobic and anaerobic digestion) and reutilization processes, the rheograms denoting principally two correlations: (1) shear stress as a function of shear rate and; (2) viscosity as a function of shear rate and time, describe the properties of sludge flow. These processes are important input design parameters in transportation, storage, operation of bioreactor and pumping (Seyssiecq et al., 2008). Viscosity, the basic rheological parameter has been demonstrated to play an important role in the increase of biodegradability of sludge, strongly influencing mass transfer in aerobic degradation during digestion and fermentation (Verma et al., 2007).

The aim of the present work was to study the rheological profile of wastewater sludge in different stages of its pre-treatment. The main attention was focused on viscosity shear rate dependence and temperature dependence. Changes in viscosity, and change in dry-matter content was also investigated. The study is based on the hypothesis that treatment of wastewater sludge will modify the rheological properties of wastewater sludge to enhance the dewaterability for eventual disposal as well as assimilation of nutrients by microorganisms during value-addition.

MATERIAL AND METHODS

Sewage sludge

Three samples of sewage sludge from Brno Wastewater Treatment Plant (Czech Republic) from different stages of treatment (primary, secondary and

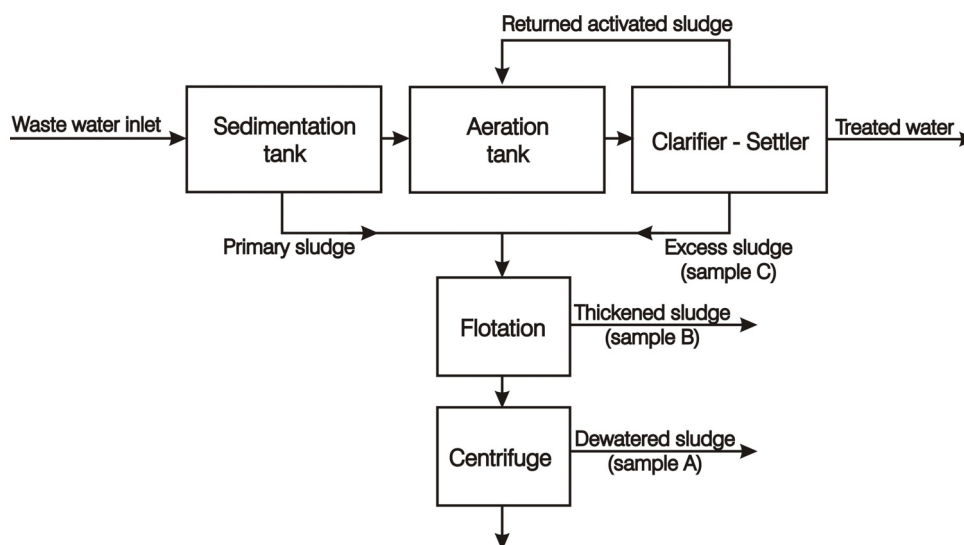
excess sludge) were used. The sludge samples are hereinafter denoted as sample A, sample B, and sample C. The points of sludge sampling are shown on Fig. 1.

The collection of samples was based on ČSN-ISO Standard No. 10381-6:1998 Soil Quality – Sampling – Section 6. On the day of collection, the respective samples were transported to a laboratory. The methodology applicable to physical analysis of sludge, i.e. determination of the total content of solids annealing residue and ash-free dry mass is stipulated in ČSN Standard No. 83 0550 (Section 3).

Total solid content and ash-free dry mass in sludge samples were determined by use of electric muffle furnace LMH 07/12 which is designed to measure incineration processes, drying, degradation, re-heating, thermal treatments etc. Analytical laboratory balances Radwag AS 220/X, for precise weighing, readability to 0.0001 g. A well-mixed sample (10 g) is evaporated in a weighed dish and dried to constant weight in an electric muffle furnace at 103 °C to 105 °C. The increase in weight over that of the empty dish represents the total solids TS [%]. After total solid assessment the dish with sample is put back to electric muffle furnace at 550 °C. The increase in weight over that of the dish after total solid assessment represents the ash-free dry mass [%].

Viscosity measurement

There are several methods how to measure dynamic (or apparent) viscosity of fluid or semi fluid materials and different geometries may be utilized: concentric cylinders, cone and plate, and parallel plates. Extensive overview of measuring techniques usable for sludge testing is presented in Boger (2009). Presented data have been obtained from measurements performed on laboratory digital viscometer Anton Paar DV-3 P (Austria), which is designed to measure dynamic or kinematic viscosity (η , ν), shear stress (τ), and shear rate ($\dot{\gamma}$). The DV-3 P is a rotational viscometer, based on measuring the torque



1: The points of sewage sludge sampling

of a spindle rotating in the sample at a given speed. Shear stress is expressed in [g/(cm.s²)], shear rate in [s⁻¹], dynamic viscosity in [mPas], and speed of spindle in revolutions per minute [rpm]. The experiments have been performed with use of R3 spindle. Due to the parallel cylinder geometry shear stress, except other values, can be determined. Sample preparation for viscosity measurements corresponded to a typical sampling procedure. The adequate volume (300 ml) of sludge was put into the apparatus cuvette without previous heavy mixing or any other kind of preparation.

Dynamic viscosity η [Pas], which is the ratio of shear stress τ [Pa] and shear rate $\dot{\gamma}$ [s⁻¹] as shown in following equation

$$\eta = \frac{\tau}{\dot{\gamma}} \text{ [Pas]},$$

depends on several quantities or variables, such as physical-chemical structure of the sample, temperature, pressure, time, and shear rate. This basic equation then can be expressed as

$$\eta(T, p, t, \dot{\gamma}) = \frac{\tau}{\dot{\gamma}} \text{ [Pas]}.$$

Mathematical models

Mathematical models have been created with use of software MATLAB® v. 7.1.0.246(R14) Service Pack 3, Curve fitting application (The MathWorks, Inc., USA). The suitability of the fitted models was evaluated by the determination coefficient (R²) and the significance level ($p < 0.05$).

Different rheological models were considered using the viscosity input information as follows:

- Bingham Plastic: $\tau = \tau_0 + \eta_p \cdot \dot{\gamma}$
- Casson Law: $\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta_p \cdot \dot{\gamma}}$
- IPC Paste: $\eta = K \cdot R^n$
- Gaussian: $\eta = a1 \cdot \exp(-((x - b1)/c1)^2) + \dots + a5 \cdot \exp(-((x - b5)/c5)^2)$
- Exponential: $\eta = a \cdot \exp(b \cdot x) + c \cdot \exp(d \cdot x)$
- Arrhenius $v = f(T) = A \exp(E_a/R \cdot T)$,

where τ represents shear stress, μ and η represent dynamic viscosity, $\dot{\gamma}$ is used for shear rate, v for kinematic viscosity, K , E , R , a , b , c and R represent constants, and T is used for temperature.

RESULTS AND DISCUSSION

Samples of sludge collected at wastewater treatment plant contained different amounts of total solids. The results of basic measurements are listed in Tab. I.

I: Content of total solid and ash-free dry mass in sludge samples

Sample	Total solid [%]	Ash free dry mass [%]
A	21.45	56.21
B	0.86	67.80
C	0.43	65.00

Viscosity measurement as a function of shear rate

Samples were examined at room temperature (~20 °C). The dynamic viscosity of the sludge samples was measured as a function of strain rate. The measurements were carried out with increasing shear rate. The shear rate varied from 0.17 s⁻¹ to 68 s⁻¹, which correspond to 0.3 rpm to 200 rpm. The duration of experiment was generally set to 10 min but other durations were carried out with similar results. Similar experimental procedure and set-up was reported also for measuring of other materials eg. in Severa and Los (2008) or Severa et al. (2010).

Fig. 2 shows the dependence of viscosity on shear rate for sample A. The dependence shows that sludge exhibit shear-thinning behavior, i.e., the dynamic viscosity decreases with shear rate. The shear-thinning behavior was expected and previously documented in e.g. Pham et al. (2009). The fall in viscosity of sludge with shear rate seems to be a result of internal bond breaking. The relationship between shear stress and shear rate was non-linear, showing non-Newtonian behaviour for all three sludges. More significant viscosity change was documented for sample A, which was characterised by markedly higher total solid and dry matter content. The maximum viscosity value changed from 1465 mPas to 1619 mPas for sample C and B, respectively and reached 14910657 mPas in case of sample A. All the values are valid for shear rate of 0.17 s⁻¹ (0.3 rpm). The minimum values were, in accordance with common assumption, found for maximum shear rate of 68 s⁻¹ (200 rpm) and ranged from 20 mPas to 26 mPas for sample C and B, respectively, and reached 93800 mPas in case of sample A at shear rate of 17 s⁻¹ (50 rpm). The measurements with higher shear rates in case of sample A were not performed due to technical limits of measuring device.

The best match between experimental and computed values was obtained using Gaussian model. Correlation of $R^2 = 0.999 \pm 0.009$ was gained in the case and with use of following formula:

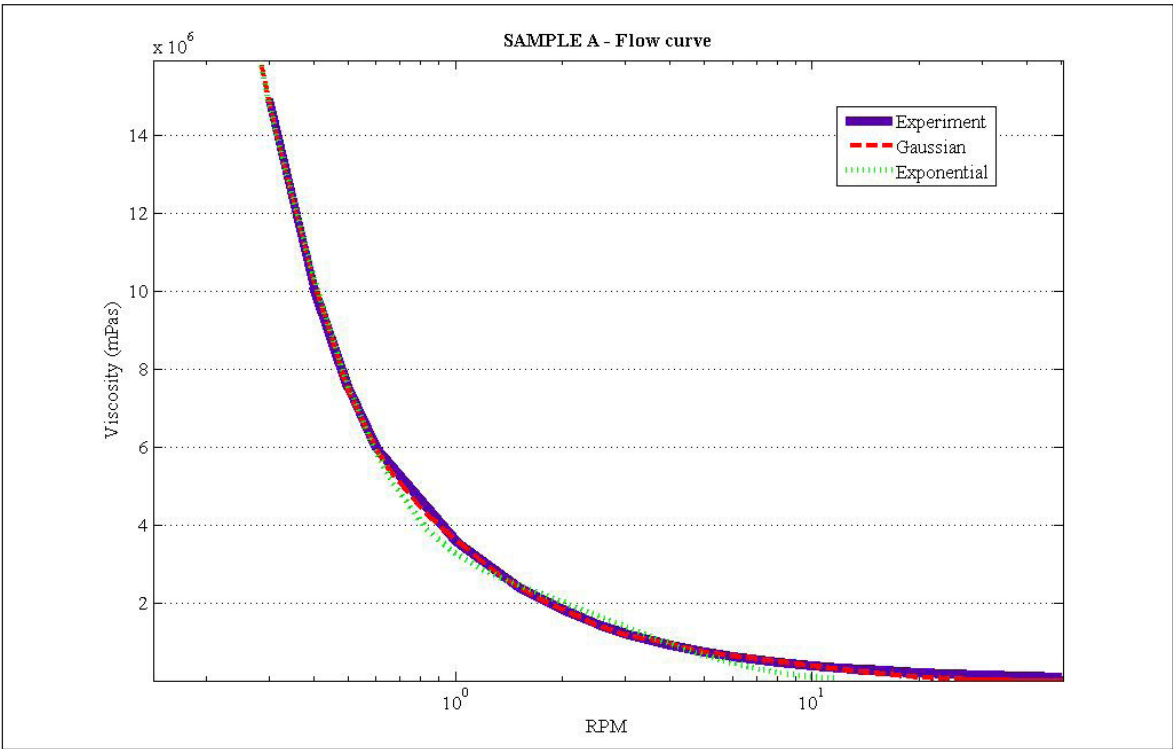
$$\eta = a1 \cdot \exp(-((x - b1)/c1)^2) + \dots + a5 \cdot \exp(-((x - b5)/c5)^2)$$

The results of application of other models, namely correlation coefficients between experimental and computed data are listed in Table II.

General overview of shear rate dependent viscosity changes of all three sludges is given in Figs. 3, 4, and 5. The charts contain also the data on temperature, which influences the viscosity values together with rate of shear.

Viscosity measurement as a function of temperature

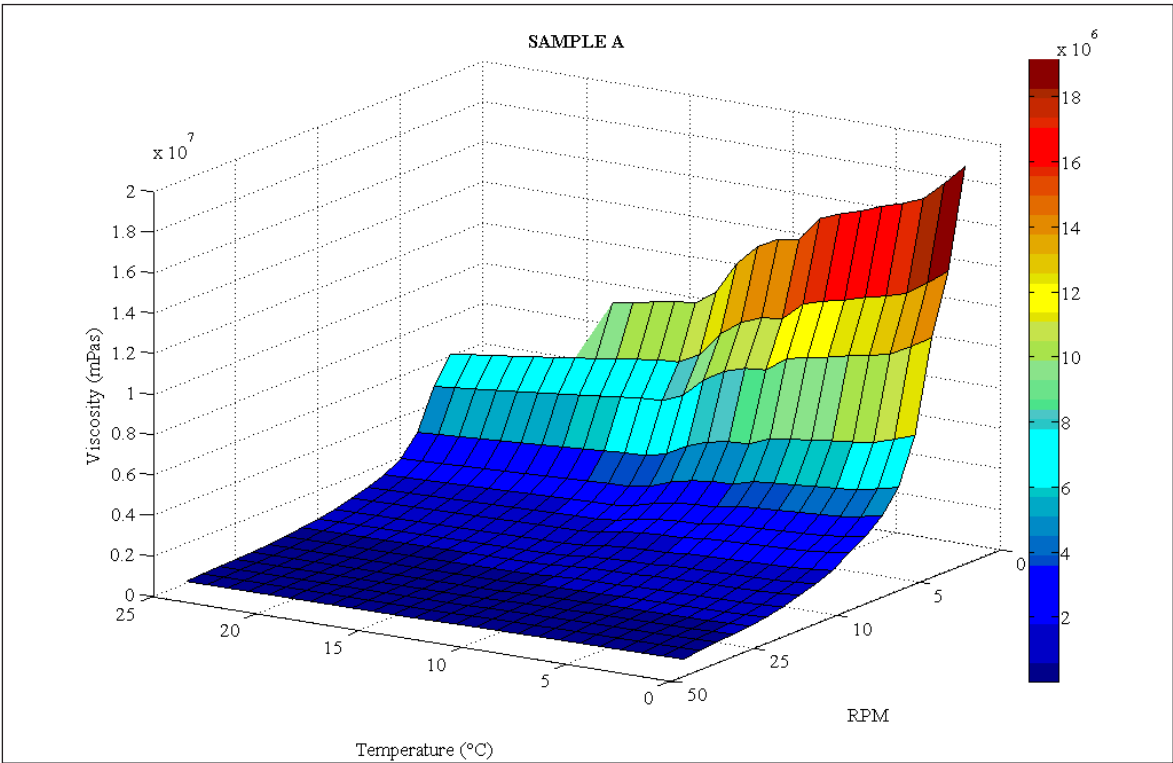
Dynamic viscosity as a function of temperature of sample A, B, and C was considered. Figure 3, 4, and 5 show the overview of experimental data of viscosity-temperature dependence. The difference between values determined for sample B and C can be e.g. explained by partially different composition of indi-



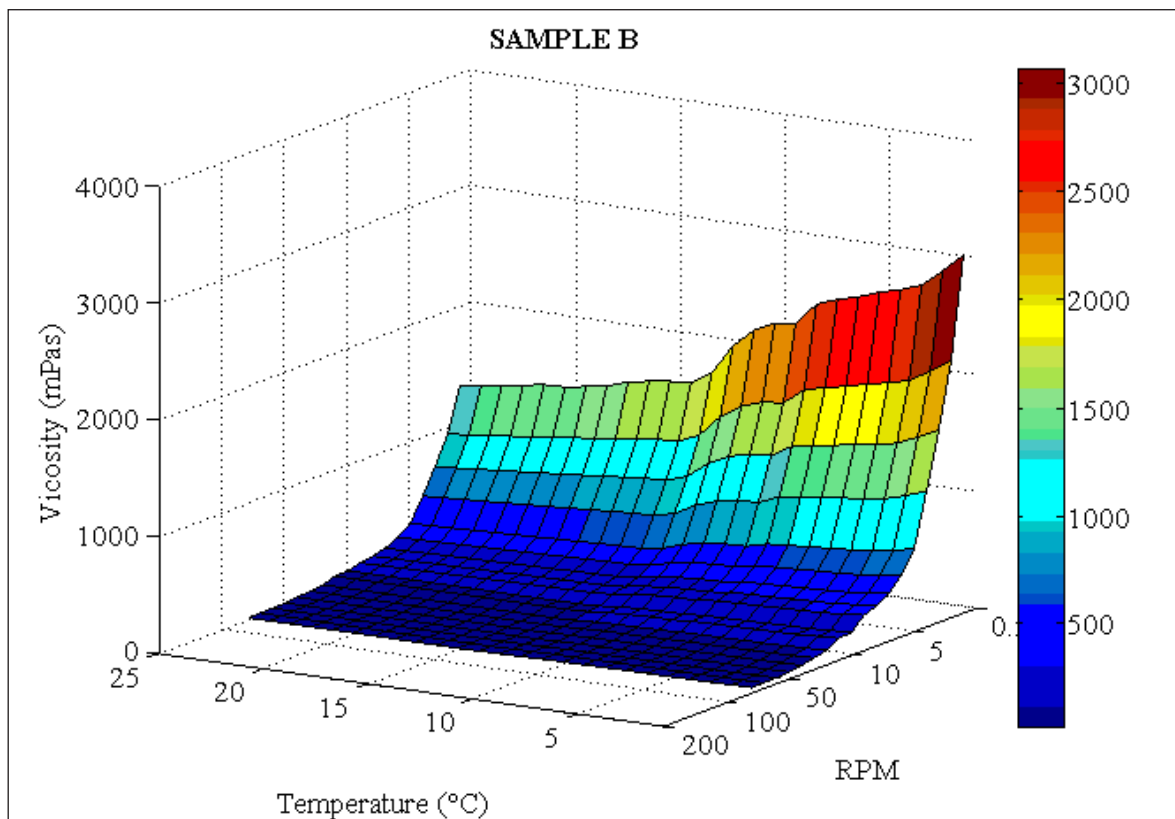
2: Flow curve of the sample A; experimental and modeled data

II: Different models and their matches with experimental data

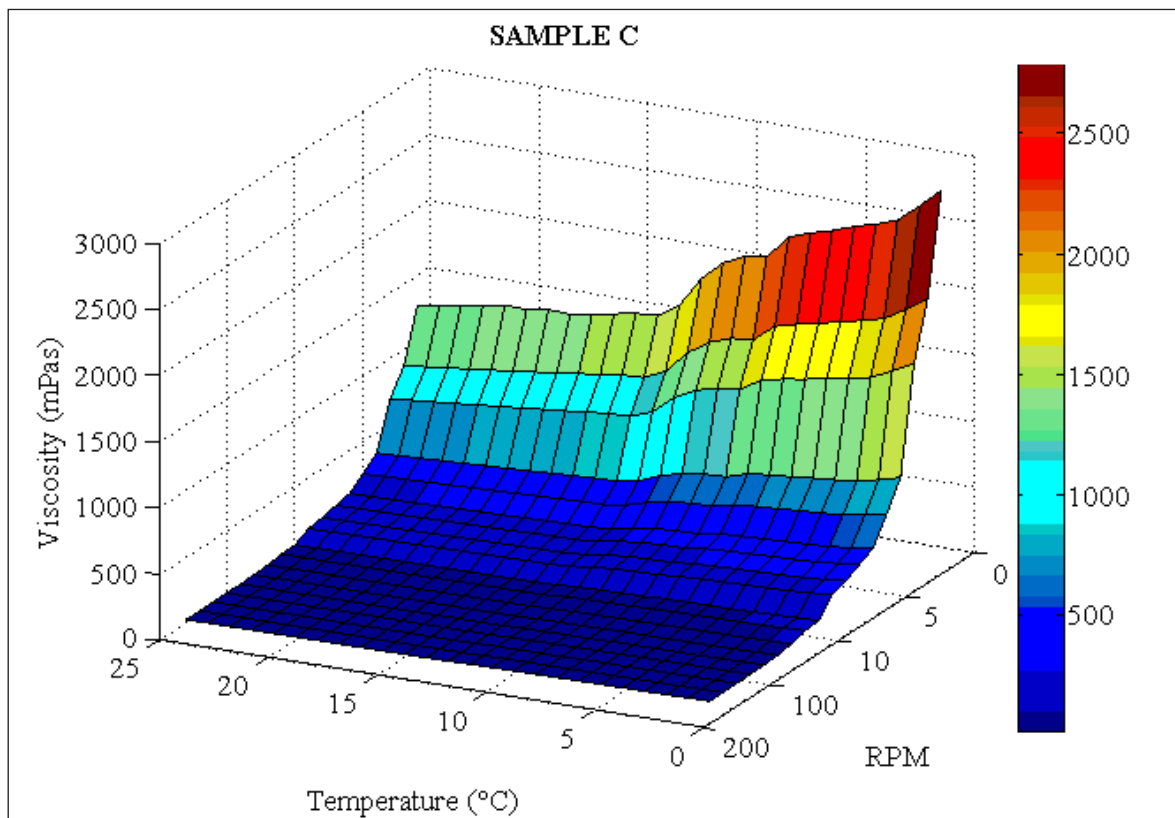
Model:	Bingham Plastic	Casson Law	IPC Paste	Gaussian	Exponential
R ²	0.987	0.949	0.968	0.999	0.997



3: Shear rate and temperature dependent viscosity behavior of sample A



4: Shear rate and temperature dependent viscosity behavior of sample B



5: Shear rate and temperature dependent viscosity behavior of sample C

vidual sludges – see Table I. The viscosity of sludge is temperature dependent and for either dynamic or kinematic viscosity to be meaningful, the reference temperature must be quoted.

Decrease of sludge viscosity with increasing temperature was expected and corresponds with conclusions reported in literature (Nges and Liu, 2009). It is obvious that dependence is far to be linear. The reason can be explained as an effect of different composition and different chemical bonding.

Temperature dependence of sludge dynamic viscosity can be also modeled. Modeling provides a means of representing a certain quantity of rheological data in terms of a simple mathematical expression. Many forms of the equations are possible and one master model, suitable for all situations, does not exist (Steffe, 1996).

Very good match between experimental and computed values can be obtained using Gaussian or exponential model. Satisfying result of $R^2 = 0.912 \pm 0.02$ (for all tested sludges) was achieved with exponential model. Even better match with $R^2 = 0.999 \pm 0.008$

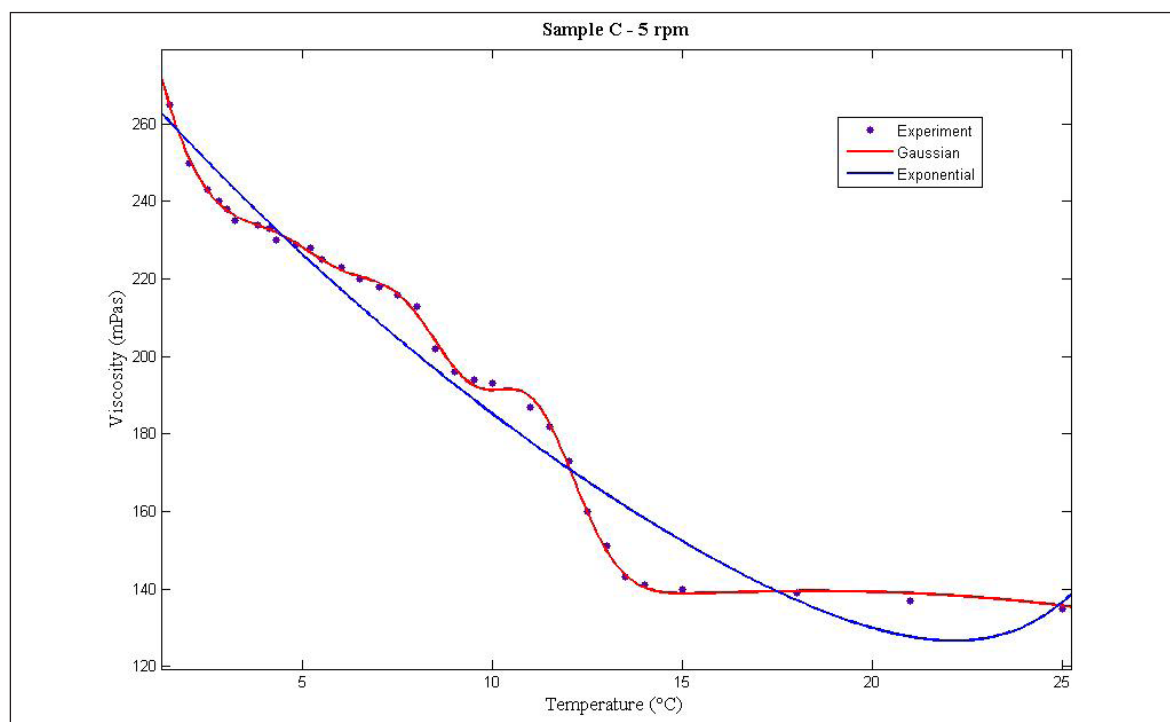
was gained in the case of Gaussian fit and following formula:

$$\eta = a1 \cdot \exp(-((x - b1)/c1)^2) + \dots + a5 \cdot \exp(-((x - b5)/c5)^2)$$

Example of exponential and Gaussian fit for sample C sheared at 5 rpm in the range of (1 – 25) °C is given in Fig. 6.

Analogical mathematical models were presented by many researchers (e.g. Pham et al., 2010) in order to describe the temperature dependence of viscosity behavior of different materials. General material behavior and achieved results of modeling were analogical in above mentioned work and presented study.

It is possible to conclude that knowledge of viscosity behavior of sewage sludge as a function of its temperature is of relevant importance. Viscosity influences the sludge's ability to flow which in-turn influences the motivating force, or pressure, required to push the sludge sufficiently to develop the necessary flow.



6: Experimental data and mathematical models for sample C sludge

SUMMARY

The paper deals with problematic of rheological characteristics of sewage sludge, which is a product of wastewater treatment and it is produced in different quality, amount, properties and different steps of waste water purification. The knowledge of sludge behavior can be used as an useful tool for designing the procedure of sludge treatment processes, such as dewatering, stabilization and advanced processes. The sewage sludges were sampled at different stages of waste water treatment. The material was tested with use of rotary digital viscometer Anton Paar with concentric cylinders geometry. The dynamic viscosity was measured as a function of temperature and shear rate. The samples were tested in the range of 1 °C to 25 °C and 0.34 s^{-1} to 68 s^{-1} . Total solid content and ash-free dry mass in

sludge samples were determined by use of electric muffle furnace LMH 07/12 and ranged from 0.43 % to 21.45 % in case of solid content (A and C samples, respectively) and from 56.21 % to 67.80 % in case of ash free dry mass (A and B samples, respectively). All sludge samples exhibited non-Newtonian character and temperature dependence. Several mathematical models (Arrhenius, Bingham Plastic, Casson Law, Exponential, Gaussian, and IPC Paste) were successfully used for characterization of experimental data. Software MATLAB® was used and satisfying correlations between experimental and computed results were obtained. The best match ($R^2 = 0.999$) was received with use of Gaussian model, in both cases, shear rate and temperature dependence. The results are quite useful e.g. for the purpose of technological equipment design.

SOUHRN

Reologické chování kalů z odpadních vod

Práce se věnuje problematice reologických charakteristik kalů z odpadních vod. Kalý vznikají jako produkt úpravy odpadních vod, a to v různém množství a kvalitě v různých fázích procesu úpravy vody. Znalost reologického chování kalu může být využita při dimenzování technických zařízení a technologických procesů. Vzorky kalu byly odebrány v několika fázích postupné úpravy odpadní vody. Materiál byl testován pomocí digitálního rotačního viskozimetru Anton Paar s měřicí geometrií dvou souosých válců. Byla měřena dynamická viskozita, a to jako funkce teploty a rychlosti deformace. Měření proběhla v rozsahu 1 °C až 25 °C a 0,34 s⁻¹ až 68 s⁻¹. Obsah sušiny a ztráty žíháním byly ve vzorcích stanoveny pomocí elektrické pece LMH 07/12 a jejich obsah se pohyboval v rozmezí 0,43 % až 21,45 % v případě sušiny a v rozmezí 56,21 % až 67,80 % v případě ztrát žíháním. U všech vzorků kalů bylo zjištěno nenewtonovské chování a teplotní závislost. Chování materiálu bylo modelováno pomocí několika matematických vztahů a rovnic (Arrheniova, Binghamova, Cassonova, exponenciálního, Gaussova a IPC), a to v prostředí softwaru MATLAB®. Pomocí těchto postupů bylo dosaženo uspokojivých shod mezi experimenty a modely. Nejvyšší shody v případě závislosti na teplotě i rychlosti deformace bylo dosaženo v případě Gaussova modelu ($R^2 = 0,999$).

kal z odpadních vod, dynamická viskozita, modelování

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