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Analysis of Rheological Models of Modified Sewage Sludge

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1. Introduction

Sewage sludge represents a multi-phase system with complex flocculent structure with specific yield stress value (Zhou et al. 2014, Zhou et al. 2017). The composition of sewage sludge can be varied, which determines its physical, chemical and biological properties (Piecuch et al. 2013, Zawieja 2016). Evaluation of sludge properties often does not take into consideration the rheological parameters which are important for the hydraulic transport. Neglecting of these parameters may generate substantial design errors, thus functional difficulties of the whole system of sludge treatment (Fryźlewicz-Kozak et al. 2015). Rheological examinations are connected with non-Newtonian flow of sewage sludge (Wolny et al. 2008, Liu et al. 2015).

Rheology deals with examination of the response of real substances to stress (Travnicek et al. 2013). Rheological problems do not concern the motion of the body as a whole but the motion of certain body components with respect to the other. The aim of the rheology is to anticipate body behaviour with regards to the applied force system or to anticipate the system of forces that will result in specific body behaviour (Dong et al. 2012). The main task of rheology is to develop models used for description of behaviour of bodies exposed to the effect of force (Liang et al. 2017).

Rheological models allow for approximation of flow curves (Sozański et al. 1993). The flow curve becomes a straight line only at a very high shear rate. The logarithmic diagram of the dependency of the shear stress and shear rate for the pseudoplastic fluid is often a straight line with the slope from 0 to 1. The simplest mathematical rheological model used to describe the flow curve for these fluids is the Ostwald-de Waele power model (Ferguson et al. 1995):

$$\tau = k \cdot (\gamma)^n \quad (1)$$

where: k – constant termed consistency coefficient, Pa·s; n – exponent, termed yield exponent.

In the Bingham model, fluids flow only after applying the shear stress τo, and, for smaller stress, they behave as a plastic solid:

$$\tau = \tau_o + \eta_{pl} \cdot \gamma \quad (2)$$

where: τ_o – yield stress, Pa; η_{pl} – plastic viscosity, Pa·s.

Herschel-Bulkley models are mostly composed of three parameters:

$$\tau = \tau_o + K \cdot (\gamma)^n \quad (3)$$

where: τ_o – yield stress, Pa; K – rheological parameter of the model; n – yield exponent.

The results of rheological measurements are approximated by means of specific rheological models, which can later be used for designing wastewater transport and storage or operation of wastewater treatment plants (Fryźlewicz-Kozak et al. 2008, Yang et al. 2009).

2. Materials and methods

Sewage sludge for the examinations was sampled from treatment of the wastewater from the cellulose and paper industry. Dry matter content was 16.82 g/dm^3, whereas initial hydration was 98.32%. Dry mass content and initial hydration of sludge was determined based on the standard PN-EN-12880. Modification of sludge was conducted using the process of sonication for 60s under static conditions. Sludge sonication used ultrasound field with intensity of: 2.2 (40%), 2.7 (60%); 3.2 (80%); 3.8 (100%) W/cm^2. The process of sewage sludge sonication used ultrasound processor Sonics VCX-1500 with maximal power output of 1,500 W. Frequency of ultrasound field vibration was 20 kHz whereas maximal wavelength for the amplitude of 100% was 39.42 µm. The device is used to transform electricity into mechanical energy supplied to the titanium tip in the form of wave. Volume of the samples for sonication was 500 cm^3 for sludge after fermentation both in the flasks and in the bioreactor.

Fermentation of initially prepared sludge samples was performed in order to determine the effect of stabilization on rheological parameters. The process occurred in glass flasks that represented models of fermentation chambers and bioreactor. The sludge samples were placed in 10 laboratory flasks with volume of V = 0.5 dm^3. On each day of the process, rheological models were determined after removing one of the flasks from the thermostat in order to evaluate rheological parameters. Rheological parameters were determined using the rheometer RC20, with the shear rate of 0-200s^{-1}, for the period of 120s.

3. Results and discussion

The examinations conducted in this study were used to evaluate properties of sewage sludge exposed to the effect of ultrasound field wave with different length and fermentation time. Presentation of the values in the form of models allows for evaluation of rheological parameters of sewage sludge necessary for characterization of their pumpability or hydraulic transport. Flow curves, which represent the relationship between shear stresses and velocity gradient, illustrate the pattern in rheological models. The values obtained for the correlation coefficient were high and ranged, for the non-conditioned sludge: from 0.922-0.997; for sludge + UD40%: 0.847-0.999; for sludge + UD60%: 0.854-0.999; for sludge + UD80%: 0.822-0.999 and for sludge + UD100%: 0.882-0.999. Fig. 1 presents the relationship between the consistency constant *K* and flow index *n* for the model of Ostwald-de Waele at the temperature of 22°C.

An increase in flow index was found for each amplitude on each day of the fermentation process (see Fig. 1). For all the conditioning methods, the index value was below 1 ($n<1$), ranging, for the non-conditioned sludge from 0.521 (0 day of fermentation) to 0.629 (25th day of fermentation). For the sludge after conditioning with the ultrasound field with intensity of 3.8 W/cm^2, the flow index ranged from 0.382 (0 day of fermentation) to 0.539 (25th day of fermentation).

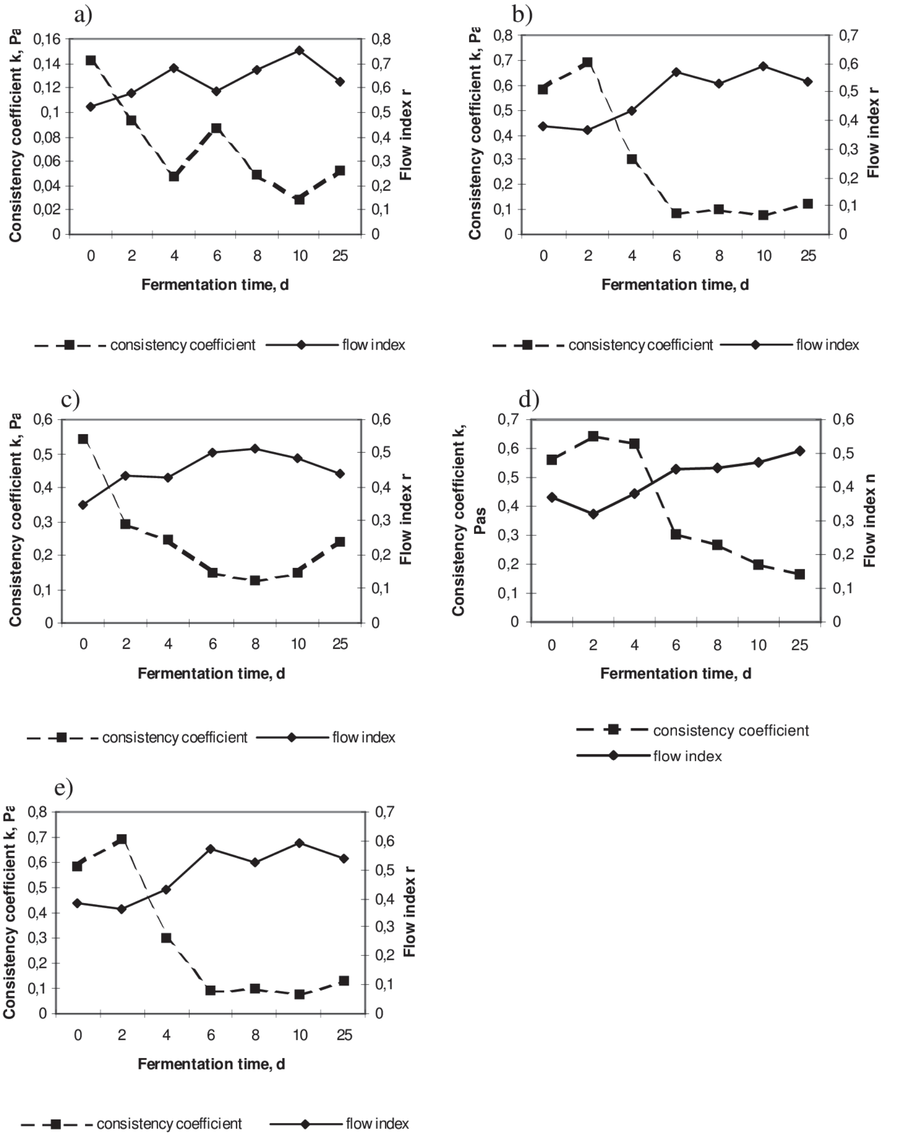

Fig. 1. Relationship between the consistency constant *K* and flow index *n* for Ostwald-de Waele model; a) non-conditioned sludge, b) sludge + UD40%, c) sludge + UD 60%, d) sludge + UD80%, e) sludge + UD100%

Rys. 1. Zależność stałej konsystencji *K* od wskaźnika płynięcia płynu *n* dla modelu Ostwalda-de Waele'a; a) osady niekondycjonowane, b) osady + UD40%, c) osady + UD 60%, d) osady + UD80%, e) osady + UD100%

Furthermore, sludge stabilization caused a reduction in consistency coefficient on each day of stabilization. The consistency constant, which is a measure of viscosity, was the lowest for the non-conditioned sludge compared to the sludge subjected to disintegration with ultrasound field (Table 1 to 5).

Table 1. Values of parameters of selected rheological models of unconditioned sewage sludge for γ = 0-200 s^{-1}; k – consistency coefficient, n – power exponent, τ_o – yield stress, η – viscosity, K – rheological model parameter
Tabela 1. Wartości parametrów wybranych modeli reologicznych niekondycjonowanych osadów ściekowych dla γ = 0-200 s^{-1}; k – współczynnik konsystencji, n – wykładnik potęgi, τ_o – granica płynięcia, η – lepkość, K – parametr reologiczny modelu

Rheological models		Fermentation time, d						
		0	2	4	6	8	10	25
Ostwald-de Waele	k	0.143	0.094	0.047	0.087	0.049	0.028	0.053
	n	0.521	0.575	0.683	0.584	0.671	0.754	0.629
Bingham	τ_o	0.466	0.348	0.227	0.325	0.225	0.154	0.196
	η_{pl}	0.1	0.009	0.008	0.009	0.008	0.007	0.007
Herschel-Bulkley	τ_o	0.157	0.057	0.074	0.091	0.011	0.073	0.181
	K	0.087	0.075	0.07	0.06	0.054	0.048	0.014
	n	0.604	0.613	0.611	0.648	0.656	0.661	0.87

Table 2. Values of parameters of selected rheological models of sewage sludge conditioned with the ultrasound field UD 40% for γ = 0-200 s^{-1}; k – consistency coefficient, n – power exponent, τ_o – yield stress, η – viscosity, K – rheological model parameter
Tabela 2. Wartości parametrów wybranych modeli reologicznych kondycjonowanych osadów ściekowych polem UD 40%, dla γ = 0-200 s^{-1}; k – współczynnik konsystencji, n – wykładnik potęgi, τ_o – granica płynięcia, η – lepkość, K – parametr reologiczny modelu

Rheological models		Fermentation time, d						
		0	2	4	6	8	10	25
Ostwald-de Waele	k	0.53	0.293	0.143	0.162	0.1	0.124	0.172
	n	0.344	0.416	0.498	0.452	0.539	0.501	0.474
Bingham	τ_o	1.093	0.707	0.417	0.418	0.326	0.357	0.474
	η_{pl}	0.013	0.011	0.009	0.008	0.008	0.008	0.009
Herschel-Bulkley	τ_o	0.856	0.677	0.374	0.422	0.258	0.356	0.444
	K	0.117	0.04	0.028	0.02	0.027	0.019	0.028
	n	0.58	0.747	0.782	0.807	0.766	0.83	0.781

Table 3. Values of parameters of selected rheological models of sewage sludge conditioned with the ultrasound field UD 60% for γ = 0-200 s^{-1}; k – consistency coefficient, n – power exponent, τ_o – yield stress, η – viscosity, K – rheological model parameter
Tabela 3. Wartości parametrów wybranych modeli reologicznych kondycjonowanych osadów ściekowych polem UD 60%, dla γ = 0-200 s^{-1}; k – współczynnik konsystencji, n – wykładnik potęgi, τ_o – granica płynięcia, η – lepkość, K – parametr reologiczny modelu

Rheological models		Fermentation time, d						
		0	2	4	6	8	10	25
Ostwald-de Waele	k	0.541	0.293	0.248	0.15	0.128	0.146	0.238
	n	0.351	0.437	0.428	0.503	0.514	0.484	0.44
Bingham	τ_o	1.134	0.758	0.633	0.439	0.382	0.403	0.602
	η_{pl}	0.014	0.013	0.01	0.01	0.009	0.008	0.011
Herschel-Bulkley	τ_o	0.877	0.584	0.469	0.4	0.371	0.425	0.616
	K	0.122	0.071	0.065	0.028	0.021	0.018	0.028
	n	0.584	0.672	0.649	0.79	0.825	0.848	0.803

Table 4. Values of parameters of selected rheological models of sewage sludge conditioned with the ultrasound field UD 80% for γ = 0-200 s^{-1}; k – consistency coefficient, n – power exponent, τ_o – yield stress, η – viscosity, K – rheological model parameter
Tabela 4. Wartości parametrów wybranych modeli reologicznych kondycjonowanych osadów ściekowych polem UD 80%, dla γ = 0-200 s^{-1}; k – współczynnik konsystencji, n – wykładnik potęgi, τ_o – granica płynięcia, η – lepkość, K – parametr reologiczny modelu

Rheological models		Fermentation time, d						
		0	2	4	6	8	10	25
Ostwald-de Waele	k	0.561	0.642	0.616	0.303	0.266	0.198	0.165
	n	0.37	0.32	0.381	0.453	0.457	0.473	0.507
Bingham	τ_o	1.227	2.161	1.387	0.808	0.707	0.526	0.481
	η_{pl}	0.016	0.023	0.019	0.014	0.013	0.011	0.011
Herschel-Bulkley	τ_o	1.059	1.606	1.107	0.666	0.653	0.581	0.464
	K	0.098	0.273	0.131	0.065	0.044	0.02	0.027
	n	0.651	0.535	0.63	0.712	0.763	0.871	0.819

Table 5. Values of parameters of selected rheological models of sewage sludge conditioned with the ultrasound field UD 100% for γ = 0-200 s^{-1};
k – consistency coefficient, n – power exponent, τ_o – yield stress, η – viscosity, K – rheological model parameter
Tabela 5. Wartości parametrów wybranych modeli reologicznych kondycjonowanych osadów ściekowych polem UD 100%, dla γ = 0-200 s^{-1};
k – współczynnik konsystencji, n – wykładnik potęgi, τ_o – granica płynięcia, η – lepkość, K – parametr reologiczny modelu

Rheological models		Fermentation time, d						
		0	2	4	6	8	10	25
Ostwald-de Waele	k	0.585	0.693	0.3	0.089	0.098	0.076	0.128
	n	0.382	0.364	0.432	0.574	0.528	0.59	0.539
Bingham	τ_o	1.325	1.502	0.749	0.308	0.29	0.276	0.404
	η_{pl}	0.018	0.019	0.013	0.009	0.007	0.008	0.01
Herschel-Bulkley	τ_o	1.046	1.109	0.732	0.208	0.319	0.189	0.364
	K	0.128	0.173	0.04	0.031	0.012	0.027	0.027
	n	0.627	0.583	0.771	0.759	0.893	0.769	0.811

The use of sludge conditioning with the ultrasound field increased the level of yield stress. In the Bingham model, the value τ_o for non-conditioned and non-stabilized sludge was 0.466Pa. In the case of modification with the ultrasound field, the value of yield stresses were: 1.093 (UD40%); 1.134 (UD60%); 1.227 (UD80%); 1.325Pa (UD100%). Exposure of sludge modified with energy of ultrasound field to fermentation led to a reduction in the values of the parameter discussed. They were lower on consecutive days of stabilization compared to the sludge which was not modified before. Similar relationship was found for the three-parameter Herschel-Bulkley model.

4. Conclusions

One of the most basic problems of contemporary civilization is manufacturing, processing, utilization and degradation of liquid compounds. Therefore, it is essential to properly determine physical properties and rheological and technological parameters of liquids. Proper adjustment of the rheological model to behaviour of real liquid minimizes errors of the calculated values, such as character of flow, flow resistance in the circulation system and particle sedimentation. This study aimed to evaluate rheological parameters of the sludge from the cellulose and paper industry subjected to conditioning at different intensities of the ultrasound field and then stabilization in flasks and a bioreactor.

The findings of the study lead to the following conclusions:

- the sewage sludge analysed in the study belongs to shear-thinning fluids. The values of flow index for all the tests is n<1;
- the examined types of sewage sludge had a yield stress values. The values of the discussed index increased with the intensity of the ultrasound field wave. With the use of the fermentation process, yield stress decreased as fermentation time elongated;
- the rheological models used for characterization of sewage sludge represented the rheological parameters accurately for different values and modification methods. The consistency coefficient (which is a measure of viscosity) and plastic viscosity increased as the ultrasound field intensity rose, while it was decreasing on consecutive days of anaerobic stabilization.

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References

Dong, Y., Wang, Y. (2012). Steady rheological characteristics of the concentrated water treatment residuals (CWTR). *Acta Scientiae Circumstantiae,* 678-682.

Ferguson, J., Kembłowski, Z. (1995). *Reologia stosowana płynów*. Łódź: MARCUS,.

Fryźlewicz-Kozak, B., Jamróz, J., Pachołek, M. (2015). Badania właściwości reologicznych ścieków. *Inż. i Ap. Chem., 54(2)*, 33-35.

Fryźlewicz-Kozak, B., Tal-Figiel, B. (2008). Theoretical and experimental analysis of floc structure of an activated sludge under sonication. *Chemical Proc. Eng., 29*, 87-98.

Liang, F., Sauceau, M., Dusserre, G., Arlabosse, P. (2017). A uniaxial cyclic compression method for characterizing the rheological and textural behaviors of mechanically dewatered sewage sludge, mechanically dewatered sewage sludge. *Water Res., 113*, 171-180.

Liu, G.J., Liu, Y., Wang, Z.Y., Lei, Y.H., Chen, Z.A., Deng, L.W. (2015). The effects of temperature, organic matter and time-dependency on rheological properties of dry anaerobic digested swine manure. *Waste Manage., 38(1)*, 449-454.

Piecuch, T., Piekarsk,i J., Malatyńska, G. (2013). Filtration of mixtures forming compressible sediments. *Rocznik Ochrona Środowiska, 15*, 39-58.

PN-EN 12880 – charakterystyka osadów ściekowych. Oznaczanie suchej pozostałości i zawartości wody.

Sozański, M., Jeż-Walkowiak, J. (1993). Charakterystyki reologiczne osadów i ich znaczenie w rozwiązywaniu problemów projektowych i eksploatacyjnych. [w:] Bien J.,(red.). *Materiały Konf. Naukowo-Technicznej, Czestochowa.* 153-173.

Travnicek, P., Vitez, T., Junga, P., Krcalova, E., Sevcikova, J. (2013). Original research of rheological measurements of disintegrated activated sludge. *Pol. J. Environ. Stud.*, 1209-1212.

Wolny, L. Wolski, P., Zawieja, I. (2008). Rheological parameters of dewatered sewage sludge after conditioning. *Desalination*, 382-387.

Yang, F., Bick, A., Shandalov, S., Brenner, A., Oron, G. (2009). Yield stress and rheological characteristics of activated sludge in an airlift membrane bioreactor. *J. Membrane Sci.*, *334*, 83-90.

Zawieja, I. (2016). Characteristics of Excess Sludge Subjected to Disintegration. *Rocznik Ochrona Środowiska*, *18*, 124-136.

Zhou, C.H., Ling, Y., Zeng, M., Li, X.Y. (2017). Analysis of particle size distribution and water content on microwave/ultrasound pretreated sludge. *Chinese Journal of Environmental Engineering, 11(1)*, 529-534.

Zhou, C.H., Ling, Y., Zeng, M., Li, X.Y. (2014). Influence of microwave and ultrasound on sludge dewaterability. *Advanced Materials Research, 955-959*, 2074-2079.

Analiza modeli reologicznych modyfikowanych osadów ściekowych

Streszczenie

W artykule przedstawiono wyniki badań prowadzone na osadach ściekowych z przemysłu celulozowo-papierniczego. Celem prowadzonych badań było wyznaczenie modeli reologicznych (Ostwalda-de Waele, Binghama, Herschela-Bulkley'a) dla osadów ściekowych niekondycjonowanych oraz poddanych działaniu pola ultradźwiękowego przy różnych jego natężeniach, a następnie stabilizacji w kolbach i bioreaktorze. Poznanie właściwości reologicznych osadów umożliwia dokładną charakterystykę ich pompowalności oraz zdolności podczas transportu hydraulicznego. W wyniku przeprowadzonych badań stwierdzono zwiększenie granicy płynięcia, jak również konsystencji poprzez zastosowanie energii pola ultradźwiękowego. Wartości omawianych parametrów ulegały obniżenie podczas kolejnych dni prowadzenia procesy stabilizacji.

Abstract

This paper presents the results of examinations of sewage sludge from cellulose and paper industry. The aim of the study was to determine rheological models (the Ostwald-de Waele, Bingham and Herschel-Bulkley models) of non-conditioned sewage sludge and the sludge exposed to the effect of the ultrasound field at its different intensities and then stabilized in flasks and in the bioreactor. Evaluation of rheological properties of sewage sludge allows for a detailed characterization of their pumpability and abilities during the hydraulic transport. The examinations revealed the increase in the yield stress and consistency coefficient through application of the energy of the ultrasound field. The values of the parameters discussed were reduced on consecutive days of the stabilization process.

Słowa kluczowe:
osady ściekowe, modele reologiczne, nadźwiękawianie, stabilizacja

Keywords:
sewage sludge, rheological models, sonication, stabilization