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RHEOLOGICAL PARAMETERS OF INITIALLY DISINTEGRATED SEWAGE SLUDGE AFTER FERMENTATION

PARAMETRY REOLOGICZNE WSTĘPNIE DEZINTEGROWANYCH OSADÓW ŚCIEKOWYCH PODDANYCH FERMENTACJI

Abstract: Yield point, viscosity, shear stress are technological parameters useful in practice to control the pumping of sludge, flow and other processes related to their processing. Increasing the efficiency of dewatering causes a decrease in their ability to flow through an increase in the limits of flow and thus the shear stress values. The variability of the stress and the viscosity is the result of changes in the structure occurring in the sludge during the flow. Any change in the structure of sludge by conditioning affected the same for their rheological parameters.

The aim of the study was to determine the dependence of shear velocity gradient (flow curves) pre-conditioned ultrasonic field sludge, and then fermented. In the process of sonication, four of the ultrasonic wave intensity *ie*: 2.2; 2.7; 3.2; 3.8 W/cm^2 were applied, and the time of sonication equals 600 s. The fermentation process was carried out in 10 glass flask with a capacity of 0.5 dm^3 which were models the digester. To describe the flow curves used the simplest mathematical rheological Ostwald-de Waele model. It also presents the total loss of dry mass of sludge undergoing stabilization. The studies reported an increase in shear stress with the application of higher intensity ultrasonic wave field. Reducing stress values were observed for fermented sludge with each day of anaerobic stabilization process.

Keywords: sewage sludge, rheological parameters, ultrasonic field, fermentation

Introduction

Rheology of sewage sludge is an important problem that has been explored in studies on the methods of its final use and control in the processes of stabilization and dewatering [1]. Determination of the rheological parameters allows for determination of the sewage sludge flowability during technological processes [2]. Affecting the sewage sludge structure through the application of the conditioning factors changes the value of

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stress and viscosity during the flow. Conditioning leads to the increase in the yield stress, thus intensifying dewatering ability. The increase in the ability to release water will be connected with reduction in the sewage sludge flowability [3].

Rheological properties of sewage sludge depend on its composition, concentration, temperature and pH value [4, 5]. Knowledge of these properties is useful for *eg* processes of flow, mixing and transport of heat in sewage sludge [6]. Studies have shown a correlation between rheological parameters and its properties [7]. The use of thermal, chemical and mechanical modifications and their combinations leads to changes in the values and characteristics of sewage sludge [8]. Conditioning leads to the release of intracellular matter and, consequently, to improved biodegradability of the sludge (increased biogas generation) [9–11]. Rheological properties of the excess sludge after the mechanical disintegration process point to a significant decline in viscosity, reaching 60%. Viscosity, which can be used for evaluation of the degree of disintegration of excess sludge, is reduced through the fermentation process [12].

Flow curves represent the relationship between sheer stresses and sheer rate. They can be approximated using rheological models. Determination of the rheological models of sewage sludge contributes to a more detailed description of the sludge and provides insights into the effect of the conditioning method on final parameters. The simplest mathematical rheological model used to describe the flow curve for these fluids is the Ostwald-de Waele power model [5]:

$$\tau = k \cdot (\gamma)^n,$$

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

The constant k, termed consistency coefficient, and the exponent n, termed the yield exponent, are the rheological parameters determined empirically at a specific temperature. The coefficient k represents the measure that describes viscosity of a substrate. The flow coefficient n adopts varied values. The value of $n < 1$ means that the process of shear thinning is observed; if $n > 1$, shear thickening occurs; if $n = 1$, the fluid becomes Newtonian.

Material and methods

The substrate for the study was provided by sewage sludge from treatment of cellulose and paper sewage sludge. The initial dewatering of 98.32% and dry mass of 16.82 g/dm^3 were calculated based on the standard PN-EN-12880:2004 [13]. Initial conditioning of sewage sludge was performed using the energy of the ultrasonic field with the intensity of: 2.2 (40%), 2.7 (60%); 3.2 (80%); 3.8 (100%) W/cm^2. The sonication was performed under static conditions for 600 s. Initial power output of the ultrasound processor was 1500 W, vibration frequency was 20 kHz, whereas maximal wavelength at maximal intensity of 3.8 W/cm^2 was 39.42 μm (100%). The sonication process was used for sewage sludge samples with volume of 500 cm^3.

The sewage sludge fermentation process occurred in glass flasks that represented models of fermentation chambers and bioreactor. The laboratory flasks, which represented the models of fermentation chambers, were put into the laboratory thermostat (10 flasks) in order to maintain mesophilic conditions. On each day of the fermentation process, the parameters and values of the rheological models were determined after removing one of the flasks from the thermostat. Flask volume was $V = 0.5$ dm^3. The process of 25-day stabilization was performed in the bioreactor with the capacity of 5 dm^3. The Reometr RC20 rheometer was used, with shear rate of 0–200 s^{-1} for the period of 120 s.

Results and discussions

Analysis of the results demonstrated that the highest values of stress in the case of sewage sludge initially non-conditioned with the ultrasound field were found for the non-stabilized sludge (Fig. 1a). The increase in the velocity gradient led to the increase in shear stresses, and, with the shear rate of 200 s^{-1}, the highest value was obtained (2.328 Pa). Using the fermentation process with respect to non-conditioned sewage sludge led to the reduction in the parameters studied. They were lower on consecutive days of fermentation compared to the non-fermented sludge. The lowest values of shear stresses were found for the sludge after the 10th day of fermentation, for which the values of stresses at the shear rate of 200 s^{-1} were 1.565 Pa. Similar values of stress were found for sewage sludge after 25 days of fermentation in the bioreactor. Stresses in sewage sludge were correlated with its viscosity. The highest viscosity was recorded for the non-fermented sludge. Fermentation led to a reduction in this parameter, with its values for the shear rate 200 s^{-1} on the 10th an 25th day maintained at the level of 0.008 Pa · s.

Application of initial conditioning using the energy of the ultrasound field led to the increase in shear stresses and viscosity of sewage sludge on each consecutive day of the fermentation process (Fig. 1b). In the case of non-fermented sludge after initial modification with the ultrasound field with intensity of 2.2 W/cm^2, stresses at the shear rate of 200 s^{-1} were 3.419 Pa, whereas viscosity was 0.017 Pa · s. For the sludge subjected to fermentation, the obtained values were the lowest on the 10th day of stabilization, with shear stresses for the shear rate of 200 s^{-1} reaching the level of 1.888 Pa and viscosity of 0.009 Pa · s. Elongation of the intensity of the ultrasound field led to another increase in the value of shear stresses (see Fig. 1c). Analogously to the use of the ultrasound field with intensity of 2.2 W/cm^2, the stresses rose to the level of 3.604 Pa, viscosity rose to 0.018 Pa · s (non-fermented sludge) and 2.031 Pa and 0.01 Pa · s (sludge on the 10th day of fermentation and shear rate of 200 s^{-1}).

Conditioning of sewage sludge with the ultrasound field with intensity of 3.2 an 3.8 W/cm^2 yielded specific changes in the values of stresses (Fig. 1d, e). The highest stresses were recorded for the sewage sludge on the 2nd day of fermentation, for which the values at the shear rate of 200 s^{-1} was 6.252 Pa, whereas viscosity increased to 0.031 Pa · s. The analogous relationship was observed for the highest ultrasound field

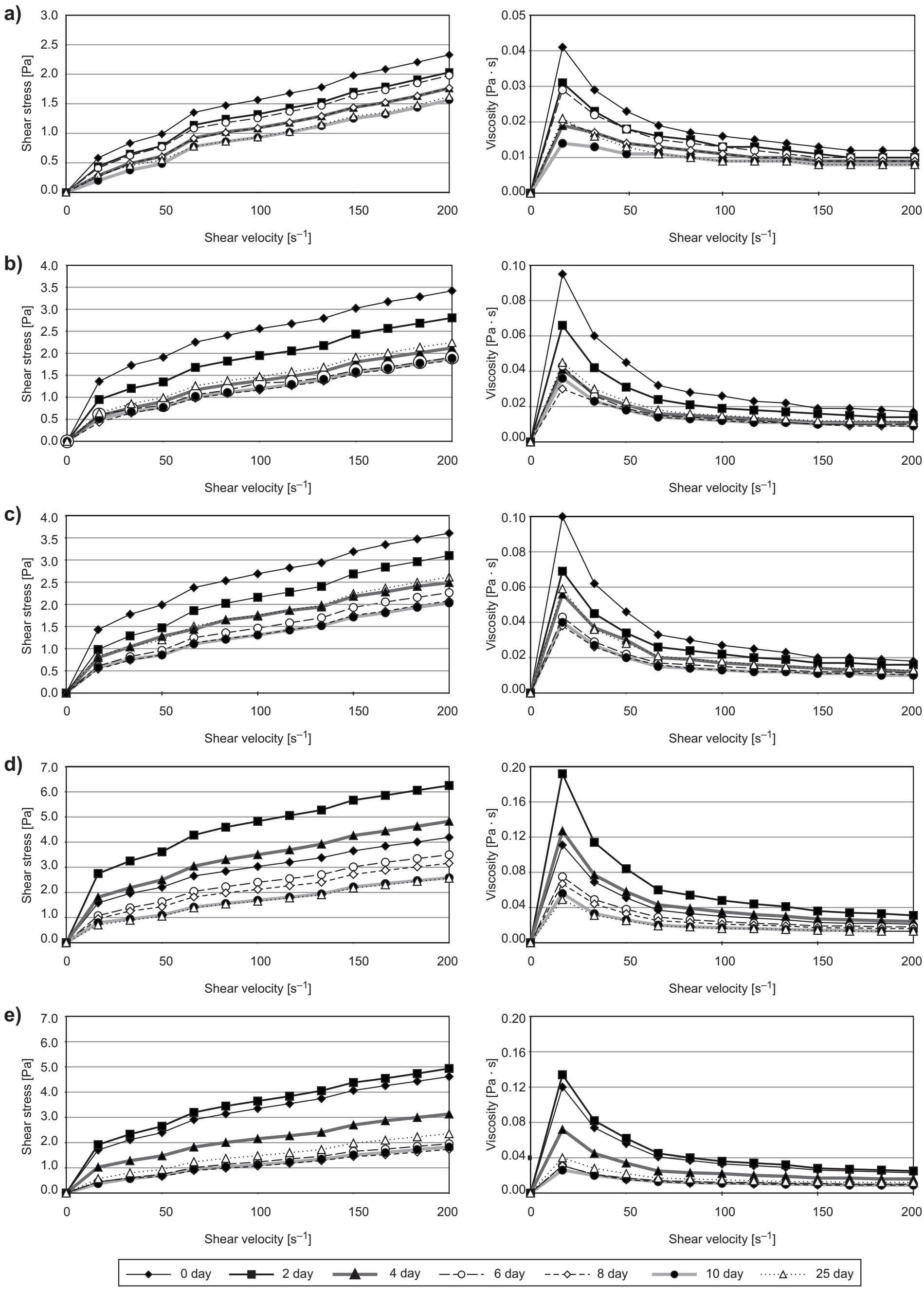

Fig. 1. Flow curves and viscosity curves for sewage sludge after fermentation: a) non-conditioned sludge; b) sewage sludge + UD40%; c) sewage sludge + UD60%; d) sewage sludge + UD80%; e) sewage sludge + UD100%

(3.8 W/cm^2), with stresses at the shear rate of 200 s^{-1} reaching the level of 4.937 Pa, and viscosity – the level of 0.025 Pa · s.

The coefficient *n* was below 1 for all the conditioning methods and fermentation times, which means that the sewage sludge was thinned as a result of the shear process (Fig. 2).

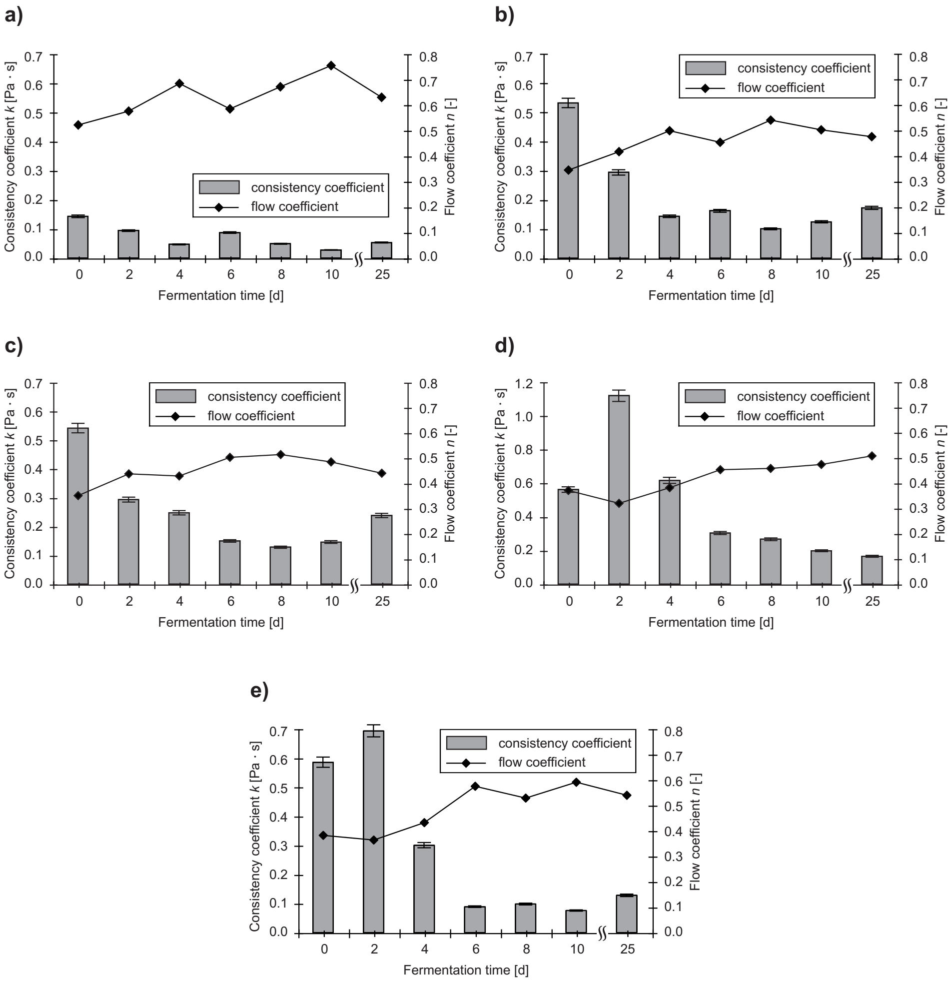

Fig. 2. Values of consistency coefficient, *k,* and flow coefficient, *n*, for the model Ostwald-de Waele sludge subjected to conditioning and fermentation: a) non-conditioned sludge; b) sewage sludge + UD40%; c) sewage sludge + UD60%; d) sewage sludge + UD80%; e) sewage sludge + UD100%

Lower values of the flow coefficient *n* for the sludge modified with the ultrasound field were also observed with respect to the non-conditioned sludge. Exposure of sewage sludge to the ultrasound field caused an increase in the value of the consistency coefficient *k*, which reflects an increase in its viscosity. In the case of the sewage sludge modified with the ultrasound field with the highest intensity (3.8 W/cm^2), the value of coefficient *k* was 4 times higher compared to the non-modified sewage sludge. Regardless of the method of conditioning, sludge fermentation led to the reduction in sludge viscosity on each consecutive day of the process. The values of the parameters obtained for the model were correlated with the empirical data. The correctness and accuracy of the results obtained in the study are demonstrated by the correlation coefficients *B*, which, for all the samples studied, were high and ranged from 0.97 to 0.99 (Table 1).

Table 1

Values of correlation coefficient (*B*) and standard deviation (*S*) for the Ostwald-de Waele model of sewage sludge subjected to conditioning and fermentation

Parameters conditioning sewage sludge		Fermentation time [d]						
		0	2	4	6	8	10	25
Non-conditioned sludge	*B*	0.996	0.995	0.994	0.996	0.995	0.992	0.988
	S	0.033	0.032	0.035	0.031	0.032	0.037	0.045
Sewage sludge + UD40%	*B*	0.990	0.983	0.988	0.978	0.990	0.984	0.986
	S	0.063	0.076	0.054	0.063	0.043	0.056	0.060
Sewage sludge + UD60%	*B*	0.991	0.990	0.989	0.987	0.985	0.981	0.981
	S	0.065	0.065	0.055	0.059	0.061	0.064	0.079
Sewage sludge + UD80%	*B*	0.988	0.992	0.990	0.959	0.986	0.977	0.985
	S	0.090	0.096	0.094	0.079	0.083	0.090	0.073
Sewage sludge + UD100%	*B*	0.991	0.992	0.983	0.994	0.979	0.993	0.988
	S	0.088	0.084	0.089	0.038	0.061	0.036	0.061

The changes in viscosity and stresses caused by fermentation are connected with the depletion of the dry mass in the sludge. The use of the conditioning factor before sludge stabilization led to the increase in the dry matter content on each day of the process (Fig. 3). Total depletion in dry mass was increasing in proportion to the fermentation time and was the highest in the case of the sludge subjected to the effect of the

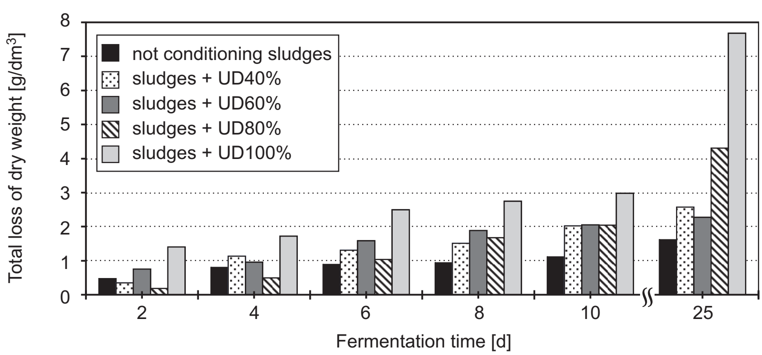

Fig. 3. Total depletion of dry mass of sewage sludge after conditioning and fermentation

ultrasound field with intensity of 3.8 W/cm^2. For the sludge after fermentation in flasks on the 10th day of the process, total depletion was at the level of 2.98 g/dm^3, whereas in the case of sewage sludge subjected to stabilization in the bioreactor, this value was 7.68 g/dm^3. Dispersion of the sludge flocs caused by the ultrasound field caused the release of organic compounds whereas stabilization led to their mineralization, which translated into the increase in the number of dry mass.

Interference with the structure induced by the conditioning factor of sludge as well as a fermentation process is shown in Fig. 4.

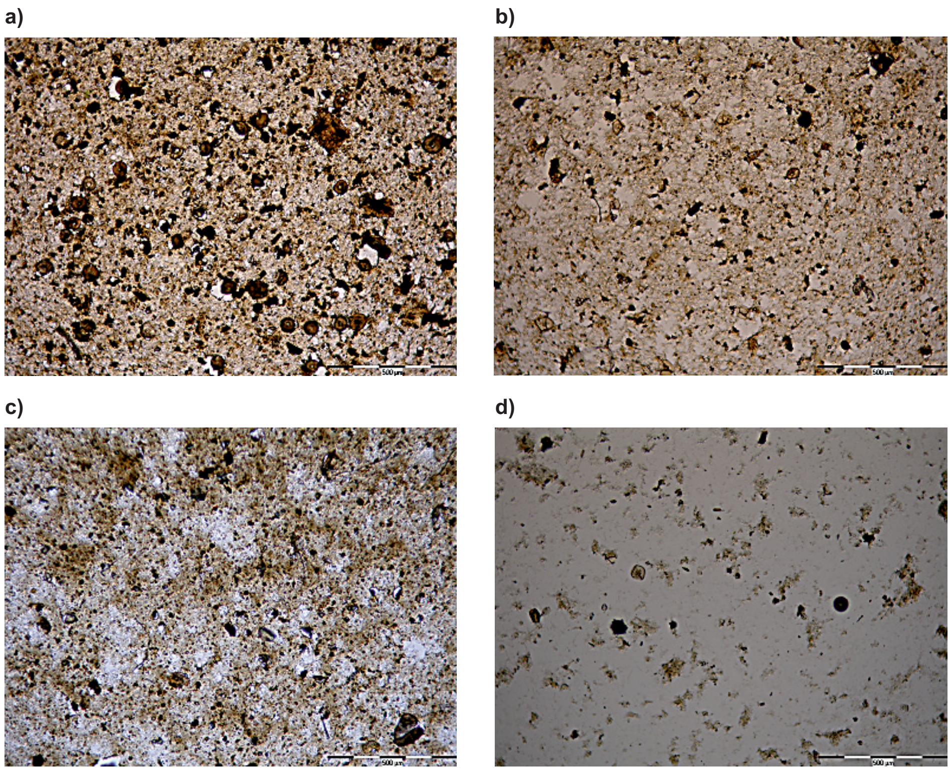

Fig. 4. Non conditioned structure and pre-conditioned of ultrasonic field sludge: a) non-conditioned sludge and unfermented; b) non-conditioned sludge on the 10th day of fermentation; c) The conditioned sludge by ultrasonic field by 3.8 W/cm^2 (100%) untreated fermentation; d) The conditioned sludge by ultrasonic field by 3.8 W/cm^2 (100%) on the 10th day of fermentation

Non-conditioned sludge on the first day of fermentation characterized by the compacted structure, homogeneous, no free water is observed. Subjecting of sludge of conditioning ultrasonic field individual clusters of sludge floc with free water areas were observed. In the view field extended sludge floc was recorded. The ten-day fermentation process caused the homogenization of the observed structures. The sludge floc with free water were mixed, forming a homogeneous mass of individual foci of sludge.

Conclusions

Knowledge of characteristics of sewage sludge in a technological line of the wastewater treatment plant can be acquired based on the evaluation of technical and technological parameters. The rheological examinations represent the basis for optimization of technological processes that occur in the wastewater treatment plant. The correlation between rheological parameters and sludge water content represents the significant property. This study allowed for development of a more accurate rheological characterization of sewage sludge after disintegration and fermentation.

The results obtained in this study lead to the following final conclusions:

– the use of ultrasonic energy in sewage sludge preparation causes an increase in shear stresses with the increase in the ultrasonic field intensity;

– stabilization of initially conditioned sewage sludge leads to a reduction in the value of shear stresses. The lowest values were recorded for the 10^{th} (flasks) and 25^{th} (bioreactor) days of fermentation;

– analysis of the Ostwald model demonstrated the increase in viscosity (expressed with the consistency coefficient) following the sonication process. Stabilization led to the reduction in the value of the parameter discussed;

– the highest total decline in dry matter of sewage sludge subjected to conditioning and fermentation (7.68 g/dm^3) was found for the highest ultrasound field intensity (3.8 W/cm^2) and stabilization performed in the bioreactor.

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PARAMETRY REOLOGICZNE WSTĘPNIE DEZINTEGROWANYCH OSADÓW ŚCIEKOWYCH PODDANYCH FERMENTACJI

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Abstrakt: Granica płynięcia, lepkość, naprężenia styczne są parametrami technologicznymi przydatnymi w praktyce do kontroli pompowania osadów, płynięcia oraz innych procesów technologicznych związanych z ich przeróbką. Zwiększenie efektywności odwadniania osadów powoduje spadek zdolności ich płynięcia poprzez wzrost granic płynięcia, a tym samym wartości naprężeń stycznych. Zmienność naprężeń i lepkości jest wynikiem zmiany struktury zachodzącej w osadach w trakcie płynięcia. Każda zmiana struktury osadów poprzez kondycjonowanie wpływała tym samym na ich parametry reologiczne.

Celem prowadzonych badań było wyznaczenie zależności naprężeń stycznych i lepkości od gradientu prędkości (krzywych płynięcia i lepkości) osadów ściekowych wstępnie kondycjonowanych polem ultradźwiękowym, a następnie poddanych fermentacji. W procesie sonifikacji zastosowano cztery natężenia fali ultradźwiękowej: 2,2; 2,7; 3,2; 3,8 W/cm^2, natomiast czas sonifikacji przyjęto 600 s. Proces fermentacji prowadzono w 10 kolbach szklanych o pojemności 0,5 dm^3, stanowiących modele komór fermentacyjnych. Do opisu krzywych płynięcia zastosowano najprostszy matematyczny model reologiczny tzw. model Ostwalda. Przedstawiono również sumaryczny ubytek suchej masy osadów poddanych stabilizacji. W wyniku przeprowadzonych badań odnotowano zwiększenie naprężeń stycznych wraz z zastosowaniem wyższych natężeń fali pola ultradźwiękowego. Zmniejszenie wartości naprężeń zaobserwowano dla osadów poddanych fermentacji z każdym dniem prowadzenia procesu stabilizacji.

Słowa kluczowe: osady ściekowe, naprężenia styczne, lepkość, pole ultradźwiękowe, fermentacja