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Analysis of rheological properties of modified sewage sludge

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ABSTRACT

Sewage sludge conditioning leads to the modification of its physical and chemical parameters. Determination of rheological models allows for a detailed identification of rheological properties. One- and multi-parameter models allow for the approximation of the flow curves, whereas determination of the values of yield limits for the modified sludge allows for the control of the processes of thickening, dewatering, and spreading of micropollutants contained in the sludge subjected to flow. The examinations were aimed to determine rheological parameters and rheological models of sewage sludge conditioned using physical methods before and after the process of anaerobic fermentation. Physical conditioning was conducted using the energy of the ultrasonic field emitted by means of ultrasound processor. The examinations revealed that the use of the conditioning factor for preparation of sewage sludge increases the value of shear stress, viscosity, and yield limits with respect to non-conditioned sludge. The conditioning process impacts on the value of yield stress, thus reducing the flow capability of the sludge. The fermentation process, which causes mineralization of organic compounds, has an effect on the reduction of the value of shear stress. Reduction in the value of rheological parameters is correlated with total decline in dry mass.

Keywords: Sewage sludge; Micropollutants; Rheological parameters; Ultrasonic field; Methane fermentation

1. Introduction

Various types of pollutants can be found in sewage sludge, with their sources usually unknown. Their composition depends on the type of sludge that flow into the sewage treatment plant. Part of pollutants is directly decomposed in the treatment processes and accumulates in the sewage sludge. Sewage sludge processing also does not impact on their reduction [1,2].

Spread of pollutants in the sludge can be harmful and dangerous to the environment and human health and life. These pollutants are potentially toxic and include heavy metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, adsorbable organic halides, polychlorinated dibenzodioxins (dioxins), and polychlorinated dibenzofurans (furans). Organic pollutants from sewage sludge can be transferred to human body through three ways: directly from soil, or indirectly from the soil fertilized with sludge, for example, by grazing, sludge adhered to plant surface, or dust from the soil fertilized with sludge and less through absorption of sludge pollutants by roots [3,4].

The spread of pollutants in the sludge environment is determined by their flow capability. Flow of sewage sludge is a process that consists in the movement of particles with respect to each other. Their movability is ensured by the flocculent structure and conditioning factors used in the study [5,6]. As sewage sludge is a multiphase system, intervention in its structure directly impacts on sludge capabilities of thickening, dewatering, and spread. The conditioning factor directly impacts on changes in the value of stress, viscosity, and yield limits [7,8].

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Previous studies have found that polymeric conditioning shows varied efficiency in the same medium. An increased dose of polymers leads to the increase in yield limits of the sewage sludge, thus reducing their flow capability. Coagulation of sewage sludge flocs is conducive to the formation of bigger conglomerates [9,10]. The use of other conditioning medium, such as ultrasound field energy, also causes an increase in the flow limit with respect to the non-conditioned sludge. The consistency coefficient (which is a measure of viscosity) and plastic viscosity increase as the ultrasound field intensity rises, while it is decreasing on consecutive days of anaerobic stabilization. Both the most efficient sonication dose and time have to be defined based on the preliminary research [11–13]. All these parameters have an effect on the correctness of technological processes and the potential to spread pollutants contained in the sludge.

Determination of the flow curves and viscosity, and determination of rheological models, can make it easier to characterize flow capability. Determination of the consistency coefficient *k* and flow coefficient *n* can contribute to a more detailed characterization of the phenomenon discussed. Rheological models allow for approximation of flow curves and viscosity. The flow curve becomes a straight line only at a very high shear rate. The logarithmic diagram of the dependency of the shear stress τ and shear rate γ for the pseudoplastic fluid is often a straight line with the slope from 0 to 1. In the Bingham model, fluids flow only after crossing the shear stress τ_o, and, for smaller stress, they behave as a plastic solid:

$$\tau = \tau_o + \eta_{pl} \bullet \gamma \tag{1}$$

τ—Shear stress, Pa; τ_o—yield limit, Pa; η_{pl}—plastic viscosity, Pa·s; and γ—shear rate, s^{-1}.

Measurement of rheological parameters can be useful for the final determination of transition between dispersive and coagulation areas of the medium [14–16]. In addition to the identification of rheological parameters important to pumpability and hydraulic transport, determination of these properties should contribute to evaluation of the capability of pollutants' migration.

2. Substrate and methodology

The substrate sewage sludge was sampled from cellulose and paper industry wastewater after the process of thickening and before conditioning and dewatering. Dry matter content of the substrate was 16.82 g/L, whereas initial hydration was 98.32%. Modification of sewage sludge was based on the use of ultrasonic field energy which was applied in static conditions for 600s. The VCX-1500 ultrasound processor with power output of 1,500 W and ultrasound field vibration frequency of 20 kHz was used for sonication of the sewage sludge. Maximal wavelength for the amplitude of 100% was 39.42 μm. Four intensity values were used in the study (2.2, 2.7, 3.2, and 3.8 W/cm²) to condition sewage sludge. The sonication process was used for sewage sludge samples with volume of 0.5 L.

The fermentation process was performed in glass flasks that represented the models of fermentation chambers and a bioreactor. The sludge samples were added to 10 laboratory flasks with volume of V = 0.5 L, which, in order to ensure mesophilic temperature, were placed in a laboratory thermostat and then mixed. For each of 10 d of the process, parameters and rheological models were determined after removing one of the flasks in order to evaluate rheological properties and ability to spread pollutants. Analogous examinations were performed for the sludge sampled from the bioreactor in which the fermentation process was performed also in mesophilic conditions (37°C) for 25 d. Rheological parameters were determined using the RC20 rheometer with the shear rate of 0–200 s^{-1} and for the period of 120 s. The rheometer RC20 is a rotational viscometer. The most important technical data: speed range, 0.7–800 min^{-1}; viscosity range, 10^{-3} to 3×10^3 Pas; shear stress, 0.7–3.4×10^4 Pa; accuracy, ±1% of maximum value.

3. Results and discussion

The determination of the rheological parameters allows for the determination of the sewage sludge flow capability during technological processes. Characteristics of their flow allow for the evaluation of the capability of migration of pollutants and micropollutants present in the environment. The present examinations used the ultrasonic field energy with various field intensities and sewage sludge stabilization process (mainly the effect of fermentation time) to assess changes in rheological parameters.

The use of sonication for preparation of sewage sludge caused the increase in shear stresses proportionally to the intensity of the ultrasound field (Figs. 1 and 2). The lowest value of stresses was found for non-conditioned sludge (2.328 Pa), whereas the highest value was found for the sludge subjected to sonication at the highest level of the ultrasound field intensity (4.616 Pa).

The increase in the value of stresses correlated with viscosity of the conditioned sludge, which also increased with the increase in ultrasound field energy intensity (Fig. 3). Viscosity for non-conditioned sludge was 0.012 Pas, whereas in the case of sonication with the highest intensity, it rose to 0.023 Pas. The results reveal a deterioration of the capability of thickening and dewatering of sewage sludge and, therefore, the ultrasonic conditioning process reduced their hydraulic capabilities. This impacted directly on the

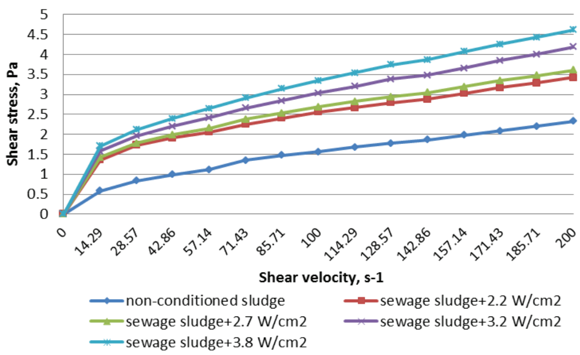

Fig. 1. The flow curves of conditioned sewage sludge.

deterioration of sludge flow capability and consequently the spread of pollutants and micropollutants in the environment.

Changes in sludge flow characteristics were recorded by subjecting sewage sludge to fermentation. On consecutive days of anaerobic stabilization, initially non-conditioned sludge demonstrated a reduction in the value of shear stresses. The tendency for decreasing the values of the parameters studied was maintained until the last (25th) day of the process, when reduction was 69%. An analogous pattern was observed for viscosity of sewage sludge after sonication, which reduced from 0.012 to 0.008 Pas (67%).

Furthermore, a similar pattern of changes in the values was observed for the sludge after initial sonication of ultrasound field energy and fermentation process (Figs. 2 and 3). For the ultrasound field intensity of 2.2 and 2.7 W/cm^2, values of stresses and viscosity were analogous to the case of non-conditioned sludge. Values of the parameters discussed were reduced on the 10th day of stabilization with respect to non-fermented sludge by ca. 55%. In the case of higher intensities of the ultrasonic field of 3.2 and 3.8 W/cm^2, an increase in stresses and viscosity was observed on the second day of fermentation, with a reduction in the value observed on each day of the stabilization process. The reduction in stresses and viscosity of sewage sludge at the level of 29% reflects the effect of the conditioning factor and stabilization on characterization of rheological parameters of sludge.

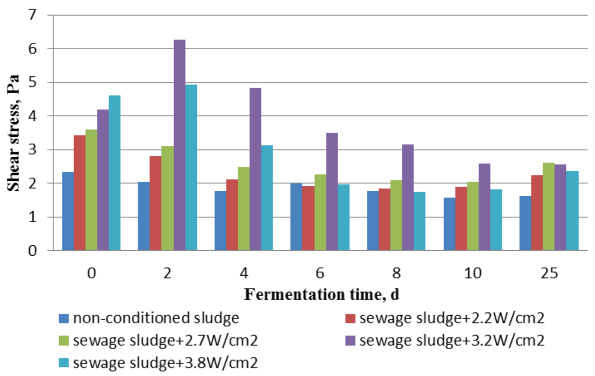

Fig. 2. Shear stress in sewage sludge subjected to sonication and anaerobic stabilization.

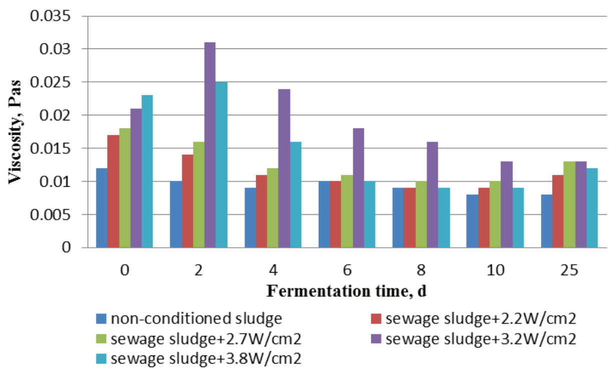

Fig. 3. Viscosity in sewage sludge subjected to sonication and anaerobic stabilization.

The reduced stresses in sewage sludge and lower viscosity have a significant effect on the improvement in transport capability of sludge.

Another parameter which can be determined in rheological measurements and therefore leading to a more detailed characterization concerning sludge flow was determination of the yield limit (Fig. 4). This parameter represents the value which shows whether the body is a solid or a liquid. Conditioning with ultrasonic field energy shifts the yield limit, thus deteriorating the ability to spread pollutants. Reduction in this parameter occurred through the use of anaerobic stabilization, causing a more intensive flow of sewage sludge.

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. Right choice of the supporting factors impacts on the properties. Furthermore, adjustment of the rheological model to the behavior of real liquid minimizes errors of the calculated values, such as character of flow, flow resistance in the circulation system and particle sedimentation or spread of pollutants and micropollutants.

Analysis of the rheological model confirmed the results obtained empirically and demonstrated that viscosity expressed using the consistency coefficient k was increased following the sonication process (Table 1).

The use of fermentation contributed to the reduction in consistency, causing that the sludge was characterized by greater yield. The yield exponent n was increased for each amplitude on each day of the fermentation process. The value of the yield exponent n for non-conditioned and non-fermented sewage sludge was 0.521. The use of the ultrasonic field led to the reduction in the index ranging from 0.344 (sludge + UD40%) to 0.382 (sludge + UD100%). However, sonication led to the increase in the consistency coefficient k, with its value for non-conditioned sludge of 0.143, whereas for the sludge subjected to sonication with the highest wavelength, the value of the discussed index was 0.585. A decline in the consistency coefficient was caused by the stabilization process, with longer fermentation time leading to the decrease in the coefficient value. Fermentation has also an effect on the increase in the yield exponent, with

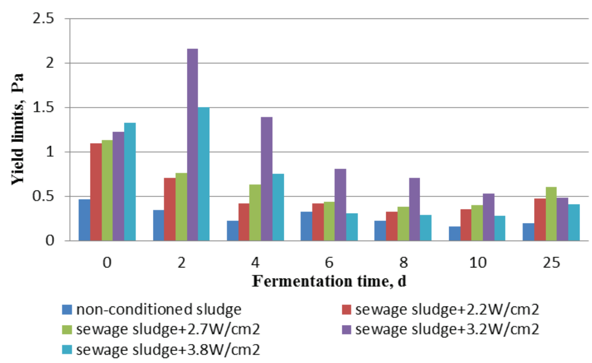

Fig. 4. Yield limits in sewage sludge subjected to sonication and anaerobic stabilization.

Table 1
Values of consistency coefficient *k* and yield exponent *n* of sewage sludge for shear rate of $\gamma = 0$–$200 s^{-1}$ (according to the Ostwald–de Waele model)

		Fermentation time, d						
		0	2	4	6	8	10	25
Non-conditioned sludge	*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
Sewage sludge + UD40%	*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
Sewage sludge + UD60%	*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
Sewage sludge + UD80%	*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
Sewage sludge + UD100%	*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

its value increasing for individual methods used to prepare sludge. However, the value of the yield exponent *n* was for each case below unity ($n < 1$).

The inherent component of examinations of rheological parameters is to be familiarized with the structure of the research substrate. Non-conditioned sludge was characterized by the compact structure, without the possibility of observation of free water (Fig. 5). Fermentation caused opaqueness, leading to the formation of a homogeneous sludge structure over the whole field of vision. With the use of ultrasonic field energy as a conditioning factor, individual sludge flocs were observed, with noticeable areas of free water (Fig. 6). The 10 d of the process of fermentation of the sonicated sewage sludge led to the homogenization of the structure observed. Flocs with free water were mixed, forming a uniform mass with individual focal points of the sewage sludge.

4. Conclusions

Conditioning and stabilization of sewage sludge is a very important problem that has a significant effect on sewage sludge management. Conditioning is usually achieved through thickening and dewatering of sludge, whereas stabilization is used for already dewatered sludge. Combination of the above processes helps further modify the properties and physicochemical parameters of the sludge. Initial conditioning of sewage sludge subjected to fermentation is now at the stage of explorations of the processes of hydrolysis, dewatering, and rheological parameters.

Sewage sludge conditioning improves efficiency of thickening and dewatering. Thickened sewage sludge subjected to stabilization changes their characteristics concerning the content of micropollutants. Changes in sludge characteristics, its liquidity, viscosity, and yield limit have a direct effect on its spread.

Knowing rheological parameters of conditioned and fermented sewage sludge allows for a more detailed analysis of its flow capability. Changes in these parameters impact on hydraulic properties and, consequently, on the migration of pollutants and micropollutants in the sludge environment. Improved dewatering capability deteriorates sludge flow capability. Coagulation of sewage sludge flocs deteriorates their spread, which is connected with the shift in the yield limit. Easier migration of pollutants to the environment is connected with improved hydraulic properties of the sludge. Organic pollutants from sewage sludge can be transferred to human body and directly impact on human health and life.

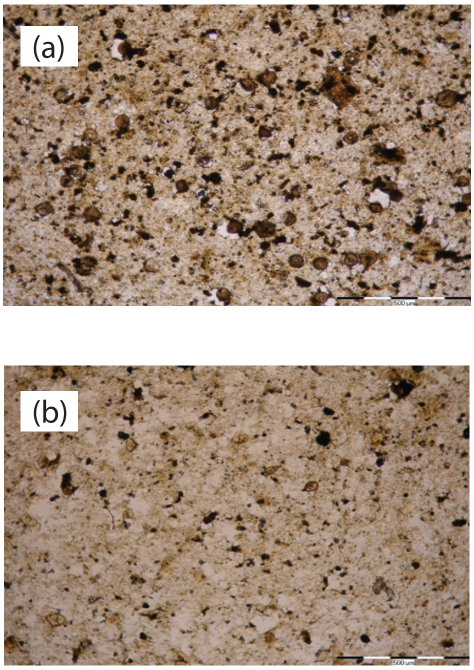

Fig. 5. Structure of the non-conditioned sewage sludge: (a) on 0th d of fermentation and (b) on 10th d of fermentation.

The findings of the study lead to the following conclusions:

- Sonication of sewage sludge leads to the increase in the value of shear stress, viscosity, and yield limit with the increase in ultrasonic field intensity. This impacts directly on the reduction in hydraulic properties and deterioration of sludge flow capability and consequently the spread of pollutants and micropollutants in the environment.

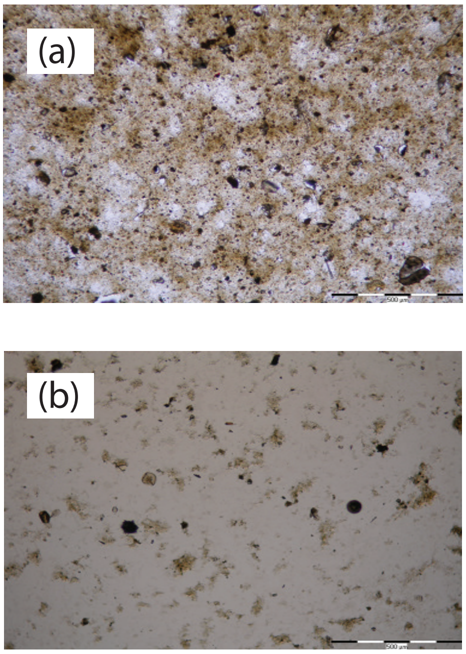

Fig. 6. Structure of the sewage sludge conditioned initially with ultrasound field: (a) on 0th d of fermentation and (b) on 10th d of fermentation.

- Through liquidization, fermentation of sewage sludge led to the reduction in shear stress, viscosity, and yield limits, thus contributing to the increase in the potential spread of pollutants. In order to reduce the sludge flow capacity, prior to their final management, structure-forming substances can be added.
- Determination of the Ostwald–de Waele rheological model confirmed the results obtained empirically. Consistency coefficient, which is the measure of viscosity, and the values of yield limits increased following the sonication processes. After the fermentation process, yield limit decreased with elongation of the fermentation time. Anaerobic stabilization also contributed to the reduction in consistency, leading to higher sludge liquefaction.

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