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Analysis of rheological properties of thickened sewage sludge

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ABSTRACT

The knowledge of rheological parameters in sludge management is essential due to the unit operations they are subjected to. The rheological properties of sewage sludge are best described by mathematical models on the basis of which flow curves and viscosity curves are drawn. If they are omitted when designing, they may contribute to problems related to the operation of sludge management systems. Rheological parameters are also an important control indicator for the dewatering and stabilization processes. This article presents the results of rheological tests of excess and digested sludge, which were subjected to thickening after chemical conditioning with polyelectrolytes. The rheological analysis consisted in determining the stresses, viscosity, flow limits and rheological models for the sludge with different amounts of excess water removed. The conducted research showed that with the reduction of sludge hydration, the viscosity and shear stresses (flow limits) increased. The highest values were recorded for the sludge for which the greatest amount of excess water was removed.

Keywords: Sewage sludge; Rheology; Thickening; Chemical conditioning

1. Introduction

Municipal wastewater flowing into wastewater treatment plants contains among other compounds, also easily settleable suspended solids, which, when subjected to treatment, become a by-product. Conditioning is an activity leading to improving the capacity and efficiency of sludge dewatering and thickening. This process changes the structure and properties of sewage sludge and weakens the binding forces in the solid-water system [1–3].

The chemical method is the most commonly used conditioning method. It involves combining and mixing the sludge with organic (flocculants) or inorganic (coagulants) chemicals. In addition to conventional agents, polyelectrolytes are used for the pre-treatment of sewage sludge. Addition of polyelectrolytes in the form of natural and synthetic results in the formation of macromolecules. These substances lead simultaneously to coagulation and flocculation of suspended matter [4–6].

Any interference with the sludge structure by adding conditioning agents affects its rheological parameters. Knowledge of sludge rheology is critical as it provides basic information on pumping processes, pipeline design, and heat transfer [7,8]. A study on the effect of inorganic coagulants and polyelectrolytes and their combined effect on pre-unconditioned sludge and sonicated digested sludge was conducted by Bień and Bień [9]. Sonication of sludge samples was conducted under static conditions for 60, 120, and 180 s. An ultrasonic wave of f = 20 kHz and two different amplitudes A = 15.25 μm and 30.5 μm were used in the study. PIX123 coagulant and Zetag 8160 polyelectrolyte were used for conditioning. The lowest capillary suction times (CST) were obtained for the coagulant at a constant dose of 1.0 mg/g polyelectrolyte. This effect was observed

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both for non-sonicated and sonicated sludge. Final water content decreased with increasing doses of the chemical reagent used to condition the non-sonicated sludge. For non-sonicated sludge, better results were obtained using Zetag 8160. In the case of sonicated sludge, PIX123 was more effective.

A similar study to improve mechanical dewatering of sewage sludge by using polymers was conducted by Dieudé-Fauvel et al. [4]. The polymers used altered the structure of flocs, which affects the efficiency of dewatering. The study focused on the effect of different types of polymers on the rheological and microscopic properties of sludge. The polymer dose was found to be the main parameter to control sludge properties, and a calibration curve was obtained between the linear complex module and the polymer dose based on the optimum polymer concentration.

Urbanization affects the amount and processes of wastewater treatment. Optimizing liquid and sludge flow in existing plants is one of the methods to extend the life of such plants. One of the most expensive inputs in the sewage sludge dewatering process is the application of polymers as flocculants. Studies by Kotzé et al. [10] have shown that huge savings can be achieved by optimizing polymer dosing rates based on sludge rheology. The ultrasonic velocity profiling and pressure drop (PD) measurement system was specifically designed and commissioned for wastewater treatment plants. This system was installed to measure the rheological properties of sludge in real time prior to mechanical dewatering with a belt filter press.

The flow of sewage sludge between devices, as well as hydraulic transport of sediments in pipelines is highly dependent on rheological properties, which use many models to show the relationship between rheological parameters. Models are not sufficient for engineering design because they are limited to rheological fluid behavior [11]. There are many factors that affect the rheological properties of sludge by creating or changing the microstructure between particles. According to Liu and Deng [7], conventional methods to study the rheological properties of sludge are insufficient and inaccurate to understand the mechanism of changes in rheological properties due to the research on macroscopic phenomena. The study showed the dependence of the models and other factors (concentration of solids, temperature, organic matter) on the rheological properties.

Rheological studies of municipal sewage sludge for use in biorefineries in hydrothermal liquefaction were conducted by Edifor et al. [12]. The study aimed to elucidate the rheological properties of sewage sludge at different stages of treatment. The rheological parameters were used to estimate the pumping power needed to transport the sludge through pipelines as part of the preliminary engineering design stage. Sludge suspensions were determined to be non-Newtonian with shear-thickening characteristics and a Herschel–Bulkley rheological model best fitted the experimental data with the yield stress. The viscosity of municipal sewage sludge was measured within the shear rate range from 10 to 300 s^{-1}. For sludge without polymer, viscosity was 0.04–0.11 Pa·s, while for dewatered sludge with polymer, it was 0.1–0.2 Pa·s.

Apart from physical methods and application of polyelectrolytes, other conditioning methods are popular (ultrasonic and microwave exposure, freezing and defrosting, mechanical treatment), with their application influencing rheological parameters [13–15].

Pretreatment can effectively improve sludge dewatering. Zhou et al. [16] conducted research on the application of microwave and ultrasonic technologies and their combination with different microwave exposure times and by analyzing particle size distribution and water content in the sludge. The results show that the pretreatment effect was satisfactory when the microwave exposure time was 180 s, CST was 5.8 s, and the particle size was 5.423 μm. When the ultrasound exposure time was 30 s, the CST was 12.1 s, and the particle size was 4.509 μm. After heating with microwave for 60 s and the ultrasound exposure for 30 s, the total CST was 12.8, and the particle size was 3.731 μm. These data demonstrate that the pretreatment technology has an excellent dewatering effect and that analysis of particle size distribution can characterize changes in water content.

In a study conducted by Travnicek et al. [17], the authors described the rheological properties of activated sludge before and after disintegration. It is posited that fragmentation of activated sludge can alter rheological properties. These changes cause modification of the activated sludge structure after disintegration. The cause is the breakdown of the cell walls of the organisms of the activated sludge. Also, the study conducted by Vachoud et al. [18] aimed to investigate the rheological properties of activated sludge with respect to the nature of the compounds present in the solid and liquid phases. Rheological measurements were performed on raw sludge and sludge modified by mechanical techniques. The results showed that the concentration of suspended solids and their nature affect the rheological parameters of the sludge. The results contribute to a better understanding of the relationship between sludge composition and sludge rheological properties, which is useful for optimizing sludge mixing, pumping, and aeration, and for improving sludge dewatering. Compression tests on three tested sludge samples showed [19] that sewage sludge behaves as a viscoelastic body when the true strain is less than 0.05. When the elastic modulus is about 78 kPa, the viscosity is of the order of 104–105 Pa·s, and the yield point is about 4 kPa. Viscosity decreases with the increase of compression speed, confirming that the sludge is a shear-thinning fluid.

The effect of freeze/thaw conditions and polyelectrolyte addition on electro-dewatering efficiency was studied by Tuan and Sillanpää [20]. The study showed that an increase in freezing temperature and extended freezing times resulted in a significant increase in sludge dewatering capacity. The dry matter content in the final sludge cake after electro-dewatering was similar (39.3%–41.5%), regardless of the experimental strategy. During electro-dewatering using polymer-enriched sludge, the dry matter content of the final sludge cake was similar or slightly higher at the cathode using a high amount of polymers. It was found that polymer addition had an adverse effect on electroosmotic flow.

2. Substrate and methodology

Sewage sludge used in the study was collected from a mechanical-biological sewage treatment plant with a capacity of 90,000 m^3/d (which corresponds to 314,835 PE) collecting both municipal and industrial wastewater. Excess and digested sludge were used as a test substrate. Excess sludge was collected after the biological treatment of sewage from the sedimentation chambers of the secondary sedimentation tank. The digested sludge was collected after the fermentation chambers, before the conditioning and dewatering process. The physicochemical properties of the analyzed sludge are summarized in Table 1.

The amount of dry matter content, the sludge water content, the content of organic and mineral compounds, and the CST were determined according to the standards. Dry mass content and initial water content of sludge were determined based on the standard PN-EN-12880. CST was measured using the Baskerville and Galle methodology, which is based on the measurement of time of transition of frontal boundary layer of filtrate as a result of the effect of suction forces in the paper used (Whatman 17). The result presented in the study was time of absorption of the sludge by the filtration paper between the rings with diameter of 32 and 45 mm.

Two types of cationic polyelectrolytes were initially used in the sludge conditioning process: Praestol 857 BS and Praestol 853 BC. The mode of action of cationic Praestol products is based essentially on ion exchange between the electrical charges along the polymer chain present in aqueous solution and the surface charges on the suspended solid particles. The particle surfaces are destabilized, thus bringing about coagulation or flocculation. Based on preliminary studies, for both excess and digested sludge, Praestol 857 BS showed better results. Praestol 857 BS is very high molecular, strong cationic polyelectrolyte based on a cationic acrylic acid derivative. It is used mainly for waste water purification, as well as for thickening and dewatering of municipal and industrial sewage sludges (centrifuges, screen belt presses, chamber filter presses). The product is specially suitable for applications where the formed flocs are subject to high shear forces. Bulk density: approximately 650 kg/m^3; viscosity (0.5% in distilled water): approximately 3,500 mPa·s; effective in pH range: 1–10.

Praestol 853 BC is very high molecular, slightly cationic polyelectrolyte based on a cationic acrylamide derivative, used mainly for waste water purification, as well as for thickening and dewatering of municipal and industrial sewage sludges. Praestol 853 BC is used as a dilute solution (0.05%–0.1%). For preparation of stock solutions (approximately 0.5%) the original product is added to water with uniform stirring. Bulk density: approximately 650 kg/m^3; viscosity (0.5% in distilled water): approximately 900 mPa·s; effective in pH range: 1–14. The measured CST using Praestol 857 BS was shorter compared with the time obtained when conditioning with Praestol 853 BC polyelectrolyte. For digested sludge, the best dose was set at 4 mg/g d.m., while for excess sludge – at 2 mg/g d.m. The above doses were used in further studies. Doses were determined based on the measurements of CST. The polyelectrolyte doses were added to the sludge, mixed for 2 min quickly, and then slowly for about 5 min to form flocculants. The sludge was stored at a temperature of −5°C, while the thickening and testing process was carried out at a temperature of 20°C.

The process of sludge thickening was started by its conditioning. For this purpose, 100 mL of mixed sludge was placed into beakers each. Fourteen samples were prepared from digested sludge and the same number was prepared from excess sludge. Appropriate doses (digested sludge - 4 mg/g d.m.; excess sludge - 2 mg/g d.m.) of the previously prepared polyelectrolyte solution were added to 12 beakers of the same sludge, while the remaining two beakers were left without its addition. After the addition of the conditioning agent, the sludge was mixed and poured into 0.1 L cylinders. Therefore, from each sludge type, six double samples subjected to conditioning and two without polyelectrolyte addition were obtained.

The prepared sludge was left in the cylinders for 2 h and observed. No significant changes in sludge volume were observed after the set time. Consequently, the samples were left for additional 24 h of sedimentation. Both excess sludge and digested sludge after additional thickening time underwent flotation, as shown in the photographs (Fig. 1). From the prepared samples, 5, 10, 15, 20, 25, and 30 mL of sludge liquor were decanted successively using a pipette while changing the volume and final water content. Two sets of dewatered samples were obtained. One of them was subjected to rheological tests, whereas the other one was used to perform determinations of dry matter content, water content, and organic and mineral compounds content).

Rheological parameters were examined using a Rheotec RC 20 rotational rheometer. It consists of a rotating inner cylinder ended with a cone and a stationary outer cylinder. The fluid in the gaps between the cylinders is

Table 1
Results of determinations of the sludge tested

Parameters	Sludge	
	Excess	Digested
Capillary suction time (CST), s	15.27	292.0
Dry matter, g/L	18.5	22.8
Initial hydration, %	98.14	97.64
Dry organic matter, %	86.25	57.34
Dry mineral matter, %	13.75	42.66

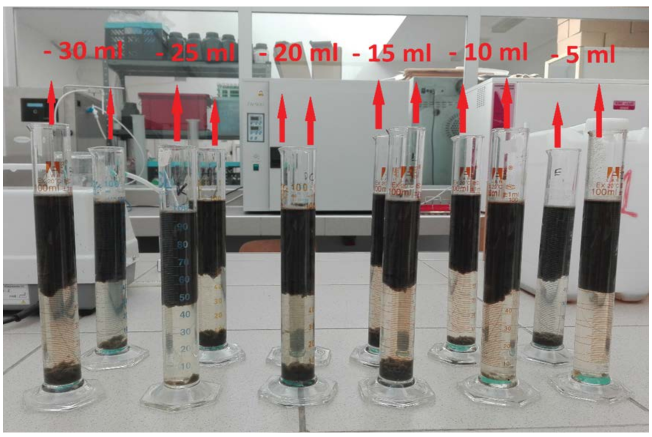

Fig. 1. Decantation of sludge liquor from the tested sludge.

subjected to shear due to the movement of one of them. The principle of operation of such a device is based on the determination of the torque and shear stress. The tested sludge was placed in the gap between the cylinders, and then the rheological parameters (stress, viscosity, yield stress) were determined in a program working with a rheometer, and the rheological models proposed by Ostwald, Bingham, and Herschel–Bulkley were determined. The shear rate was measured in the range from 0 to 200 s^{-1}, testing time of one sample: 120 s, quantity of measuring points: 15. All determinations were performed for the same measurement conditions. The scale of measurement error was ±1% of the maximum measurement value.

3. Results and discussion

The thickened sludge was subjected to determinations of final water content and dry matter content (Table 2). The initial water content for the digested sludge was 97.64%, while it decreased to 97.03% after the thickening process by decanting in 30 mL of water. In the case of excess sludge, the initial water content was 98.14%, while after the removal of 30 mL of water and the respective change in volume, this value decreased to 97.65%. The results provide evidence for a better ability of excess sludge to dewater compared with digested sludge. The dry matter content of the sludge increased proportionally to the decrease in water content. The dry matter content in the digested sludge increased from 23 g for the unconditioned sludge to 28.43 g compared with the sludge thickened to a volume of 70 mL. For excess sludge, the increase was observed from a value of 18.5 g (unconditioned sludge) to 23.14 g after thickening to 70 mL. They obtained similar dependencies through the use of a conditioning factor Bień and Bień [9], and Dieudé-Fauvel and Dentel [4].

The analysis of rheological models allowed for considering the sludge studied as a non-Newtonian shear-thinning liquid. The flow coefficient *n*, determined by rheological models [21], is less than one for both types of sludge (Tables 3 and 4). The flow and viscosity curves for both types of sludge were directly proportional to the increasing shear rate. As the shear rate increased, the shear stress became higher, whereas the opposite is true for the viscosity value, which decreased as the shear rate increased. A similar relationship was demonstrated by Liang et al. [19].

Observation of the flow curves of the unconditioned digested sludge revealed a constant upward trend in shear stress values with increasing shear rate. The highest stress values of 4.37 Pa were recorded at the highest tested rate of 200 s^{-1}. The lowest viscosity value of 0.022 Pa·s was also obtained for the same rate. The maximum viscosity value was obtained in the lowest range of the set rate and was 0.082 Pa·s (Fig. 2).

For excess sludge, an increase in shear stress was observed with increasing shear rate. The maximum stress

Table 2
Dry matter and water content of thickened sewage sludge

	Sludge volume	Dry matter	Hydration
	mL	g	%
Digested sludge	100	23	97.64
	95	22.74	97.6
	90	23.22	97.56
	85	24.12	97.44
	80	25.63	97.35
	75	26.4	97.24
	70	28.43	97.03
Excess sludge	100	18.5	98.14
	95	17.89	98.12
	90	19.11	98.01
	85	19.53	97.92
	80	22	96.96
	75	21.6	97.32
	70	23.14	97.65

Table 3
Rheological parameters of digested sludge

Non-conditioned digested sludge		
	Rheological parameters UNIT	Results
Ostwald model	Consistency coefficient – *k*, Pa·s	0.326
	Flow coefficient – *n*	0.453
	R – correlation coefficient	0.99
	S – standard deviation	0.074
Bigham model	Flow limit, Pa	0.875
	Viscosity, Pa·s	0.015
	R – correlation coefficient	0.95
	S – standard deviation	0.29
Herschel–Bulkley model	Flow limit, Pa	0.645
	Rheological parameter of the model – Kn	0.086
	Flow coefficient – *n*	0.675
	R – correlation coefficient	0.99
	S – standard deviation	0.018

Table 4
Rheological parameters of excess sludge

Non-conditioned excess sludge		
	Rheological parameters	Results
Ostwald model	Consistency coefficient – *k*, Pa·s	0.148
	Flow coefficient – *n*	0.494
	R – correlation coefficient	0.99
	S – standard deviation	0.034
Bigham model	Flow limit, Pa	0.445
	Viscosity, Pa·s	0.009
	R – correlation coefficient	0.93
	S – standard deviation	0.152
Herschel–Bulkley model	Flow limit, Pa	0.252
	Rheological parameter of the model – Kn	0.059
	Flow coefficient – *n*	0.648
	R – correlation coefficient	0.99
	S – standard deviation	0.02

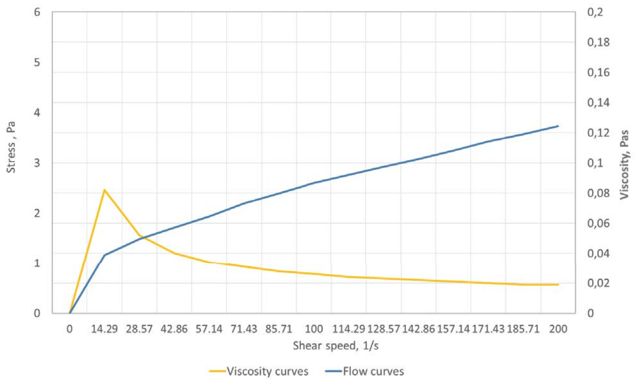

Fig. 2. Flow curve and viscosity non-conditioned digested sludge.

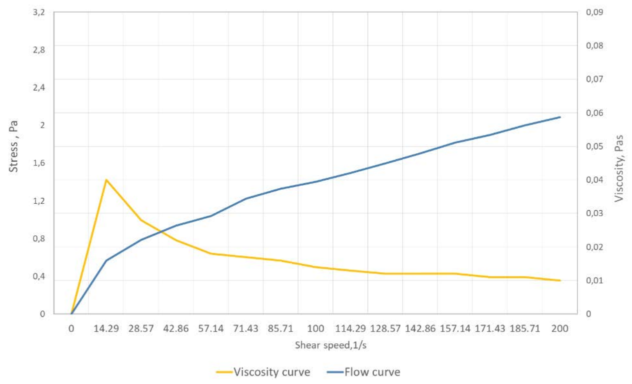

Fig. 3. Flow curve and viscosity non-conditioned excess sludge.

value was 2.09 Pa and was obtained at a maximum shear rate of 200 s^{-1}. Viscosity also decreased for excess sludge with respect to increasing velocity values. Its highest value of 0.04 Pa·s was obtained at the rate of 14.29 s^{-1} (Fig. 3).

3.1. Analysis of rheological parameters of digested sludge subjected to conditioning and thickening

The digested sewage sludge subjected to conditioning and thickening significantly altered its rheological properties. The changes shown in the rheological model and on the graphs indicate the relationship between water content and rheological parameters. The obtained high values of the correlation coefficient (from 0.77 to 0.99) characterize the correct course of the flow curve and viscosity. Analysis of the data contained in the tables reveals a very large increase in the consistency coefficient (Tables 5 and 7).

A comparison of the initial value for the unconditioned sludge and the sludge subjected to the greatest thickening (70 mL of sludge) shows that the value of this coefficient increased six-fold and five-fold. This means that the sludge increased its viscosity with increasing water content. The numerical value describing the yield point is the stress above which the tested fluid flows. For the sludge described by Bingham's mathematical model, this value increased from 0.875 Pa (unconditioned sludge) to 2.875 Pa (sludge thickened to a volume of 70 mL) (Table 6).

Analysis of flow curves of thickened and unconditioned raw sludge revealed an increase in stress with increasing shear rate and water content in the sludge. For the unconditioned sludge, the maximum stress was 3.73 Pa, while it increased to 8.43 Pa when the sludge was thickened to a volume of 70 mL. The analysis also shows the effect of thickening on sludge viscosity, with viscosity increasing with thickening efficiency from an initial value of 0.082 to 0.301 Pa·s. The results obtained are analogous to those carried out by Edifor et al. [12]. The preset shear rates and the resulting viscosities are in similar ranges.

3.2. Analysis of rheological parameters of excess sludge subjected to conditioning and thickening

Similar to the digested sludge, the conditioned excess sludge altered its rheological properties after the thickening process. Excess sludge was characterized by higher initial water content, which significantly affected the parameter values for non-conditioned sludge. Excess sludge is characterized by twice lower values of the flow limit (Bingham's model) compared with digested sludge (Table 9). Analysis of the values of rheological

Table 5
Rheological parameters of digested sludge described by the Ostwald model

Ostwald model							
		Conditioned digested sludge					
Rheological parameters	Non-conditioned digested sludge	Sludge – 5 mL water	Sludge – 10 mL water	Sludge – 15 mL water	Sludge – 20 mL water	Sludge – 25 mL water	Sludge – 30 mL water
Consistency coefficient – *k*, Pa	0.326	0.521	0.69	0.903	1.056	1.028	1.993
Flow coefficient – *n*	0.453	0.254	0.37	0.342	0.439	0.366	0.267
Correlation coefficient – *R*	0.992	0.896	0.996	0.997	0.994	0.994	0.985
Standard deviation – *S*	0.074	0.227	0.057	0.050	0.087	0.11	0.166

Table 6
Rheological parameters of digested sludge described by the Bingham model

Bingham model							
		Conditioned digested sludge					
Rheological parameters	Non-conditioned digested sludge	Sludge – 5 mL water	Sludge – 10 mL water	Sludge – 15 mL water	Sludge – 20 mL water	Sludge – 25 mL water	Sludge – 30 mL water
Flow limit, Pa	0.875	1.368	1.545	1.885	1.628	2.264	2.875
Viscosity, Pa·s	0.015	0.015	0.019	0.021	0.022	0.028	0.015
Correlation coefficient – R	0.251	0.775	0.858	0.829	0.913	0.861	0.925
Standard deviation – S	0.29	0.532	0.519	0.63	0.46	0.754	0.29

Table 7
Rheological parameters of digested sludge described by the Herschel–Bulkley model

Herschel–Bulkley model							
		Conditioned digested sludge					
Rheological parameters	Non-conditioned digested sludge	Sludge – 5 mL water	Sludge – 10 mL water	Sludge – 15 mL water	Sludge – 20 mL water	Sludge – 25 mL water	Sludge – 30 mL water
Consistency coefficient – k, Pa	0.645	0.669	0.679	0.672	0.819	1.329	3.111
Rheological parameter of the model – Kn	0.086	0.012	0.339	0.522	0.186	0.371	0.251
Flow coefficient – n	0.675	0.986	0.479	0.423	0.608	0.526	0.579
Correlation coefficient – R	0.999	0.968	0.998	0.998	0.999	0.998	0.999
Standard deviation – S	0.018	0.125	0.036	0.036	0.028	0.059	0.045

parameters given for the Ostwald model revealed an increase in the consistency coefficient from 0.148 Pa·s (non-thickened sludge) to 0.368 Pa·s (sludge thickened to 70 mL) (Table 8). Similar relationships were observed for the Herschel–Bulkley model (Table 10).

A change in this coefficient indicates an increase in sludge viscosity with decreasing water content. When the excess sludge was thickened to 70 mL, the value of stress needed to force the flow increased from 0.445 to 0.853 Pa.

The flow curves of non-thickened and thickened sludge show two relationships:

- an increase in stress with increasing shear rate and increase of thickening,
- an increase in viscosity with increasing degree of thickening, and its decrease with increasing shear rate.

The maximum stress of 3.088 Pa was recorded at 200 s^{-1} for sludge thickened to 70 mL. The highest initial viscosity value of 0.08 Pa·s was observed for the same sludge at the lowest set shear rate of 14.29 s^{-1}.

4. Summary and conclusions

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. Determination of the rheological parameters allows for determination of the sewage sludge flowability during technological processes [22]. Affecting the sewage sludge structure through the application of the conditioning factors changes the value of 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 [12].

The aim of the study was to analyze changes in final water content in conditioned sludge and their impact on rheological parameters. Water content is one of the key parameters characterizing sewage sludge. It has a major effect on the volume occupied by the sludge and thus the size and efficiency of the sludge treatment and disposal facilities. Furthermore, rheological properties influence the course of technological processes and the effective operation of the entire treatment plant. Knowledge of parameters such as stress, viscosity, and yield point is essential for the proper design of sludge pumping, mixing, and dewatering equipment.

Two types of sludge were analyzed: digested sludge and excess sludge. Digested sludge was characterized by a higher dry matter content (23 g) and lower water content (97.6%) compared with excess sludge (dry matter content: 18.5 g, water content: 98.1%). The sludge was thickened in order to change its water content and then its rheological properties were examined.

The thickening process altered the final water content of the sludge. The final water content decreased in proportion to the volume change during the thickening process. Water content decreased from 97.64% for non-conditioned digested sludge to 97.03% for digested sludge thickened to a volume of 70 mL. The water content of raw excess sludge was reduced from 98.14% to 97.65% after thickening to a volume of 70 mL.

The research presented in this paper allowed for the evaluation of the effect of the water content of sewage sludge on its rheological parameters. A significant effect of changes in water content on rheological parameters was demonstrated for both types of sludge. As observed in viscosity curves and flow curves, both digested and excess sludge showed a decrease in viscosity and an increase in stress with increasing shear rate gradient.

Table 8
Rheological parameters of excess sludge described by the Ostwald model

Ostwald model							
		Conditioned excess sludge					
Rheological parameters	Non-conditioned excess sludge	Sludge – 5 mL water	Sludge – 10 mL water	Sludge – 15 mL water	Sludge – 20 mL water	Sludge – 25 mL water	Sludge – 30 mL water
Consistency coefficient – *k*, Pa	0.148	0.114	0.188	0.282	0.393	0.334	0.368
Flow coefficient – *n*	0.494	0.536	0.403	0.471	0.383	0.409	0.395
Correlation coefficient – *R*	0.994	0.994	0.984	0.994	0.989	0.993	0.988
Standard deviation – *S*	0.034	0.038	0.067	0.041	0.064	0.054	0.069

Table 9
Rheological parameters of excess sludge described by the Bingham model

Bingham model							
		Conditioned excess sludge					
Rheological parameters	Non-conditioned excess sludge	Sludge – 5 mL water	Sludge – 10 mL water	Sludge – 15 mL water	Sludge – 20 mL water	Sludge – 25 mL water	Sludge – 30 mL water
Flow limit, Pa	0.445	0.369	0.53	0.658	0.891	0.811	0.853
Viscosity, Pa·s	0.009	0.009	0.01	0.01	0.012	0.012	0.012
Correlation coefficient – *R*	0.936	0.956	0.903	0.930	0.883	0.897	0.894
Standard deviation – *S*	0.152	0.125	0.216	0.178	0.294	0.27	0.281

Table 10
Rheological parameters of excess sludge described by the Herschel–Bulkley model

Herschel–Bulkley model							
		Conditioned excess sludge					
Rheological parameters	Non-conditioned excess sludge	Sludge – 5 mL water	Sludge – 10 mL water	Sludge – 15 mL water	Sludge – 20 mL water	Sludge – 25 mL water	Sludge – 30 mL water
Consistency coefficient – *k*, Pa	0.252	0.237	0.338	0.598	0.693	0.558	0.699
Rheological parameter of the model – Kn	0.059	0.04	0.044	0.063	0.088	0.096	0.074
Flow coefficient – *n*	0.648	0.715	0.712	0.654	0.624	0.611	0.657
Correlation coefficient – *R*	0.998	0.999	0.998	0.999	0.998	0.999	0.998
Standard deviation – *S*	0.020	0.014	0.024	0.016	0.025	0.022	0.025

The analysis of the results obtained in the present study leads to the following conclusions:

- The change in water content in the sludge affected the rheological parameters studied. The values of viscosity and shear stress (yield points) increased with decreasing water content;
- Stress values for all types of sludge studied increased in proportion to the shear rate gradient. The highest stress values were recorded for the maximum set shear rate of 200 s^{-1};
- The highest increase in stress and viscosity was observed for the sludge thickened to a volume of 70 mL. Both digested and excess sludge after thickening to this volume were characterized by the highest value of yield point;
- The digested sludge was characterized by higher values of shear stress and viscosity compared with excess sludge.

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