Archives of Environmental Protection
Vol. 45 no. 1 pp. 92–102

PL ISSN 2083-4772
DOI 10.24425/aep.2019.126425

Influence of sewage sludge conditioning with use of biomass ash on its rheological characteristics

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Keywords: sewage sludge, conditioning, biomass ash, thixotropy, viscosity, rheology.

Abstract: This study presents the rheological properties of sewage sludge after conditioning with the application of biomass ash. The impact of sewage sludge pre-treatment on its viscosity, flow curves and thixotropy was investigated. The increase of shear stress and the decrease of viscosity were observed with the increase of shear rate. Obtained results were compared with raw sewage sludge and the sludge after modification by means of polyelectrolyte in the dosage of 1.5 g·(kg d.m.)$^{-1}$. The findings proved that samples of raw and conditioned sewage sludge had thixotropic characteristics.

The correlation between moisture content and capillary suction time reduction as well as selected rheological parameters were also determined. On the basis of the obtained results it was stated that the Ostwald de Vaele model best fits the experimental data.

Nomenclature

CST – capillary suction time [s]
k – a consistency index [Pa·s^n]
m – coefficient associated with the viscosity
MC – moisture content [%]
n – a flow index
TI – the thixotropy index
γ – the shear rate [s^{-1}]
η – viscosity [mPa·s]
τ_y – the yield stress [Pa]

Introduction

Sewage sludge is defined as a residue of wastewater treatment which contains approximately 90% of water and 10% of solids (Seiple et al. 2017). The increasing amount of sewage sludge is a result of sewerage extension and the application of high-effective processes in treatment plants. In Poland, approximately 568 thousand megagrams (Mg) of sewage sludge dry mass (d.m.) was produced in 2016 (Central Statistical Office Report 2017). In Europe, the annual production of sewage sludge is at the level of 10 million Mg of sludge d.m. (Bianchini et al. 2016).

Apart from the increasing production of sewage sludge, its specific characteristic also caused a significant problem. Sewage sludge is non-uniform material whose properties depend on the wastewater source, treatment processes as well as the content of organic and inorganic compounds (Zhang et al. 2017). According to Szarek and Wojtkowska (2018), raw sewage sludge is characterized by the presence of heavy metals in different amounts, as well as, the microbiological activity. All the aforementioned factors influence the behavior of sewage sludge as well as its handling and utilization.

Dewatering is one of the most important processes which can reduce the sewage sludge volume significantly. It results in the decrease of operation costs related to its transport and utilization. However, raw sewage sludge indicates the low susceptibility to dewatering which is associated with the water binding by extracellular polymeric substances (EPS) (Wu et al. 2016). It influences the limitation of sludge dewatering. For this reason, sewage sludge conditioning is a necessity. Depending on the dewaterability of sludge and the pre-treatment method, the volume of sludge after dewatering might be reduced by even 70% (Schaum and Lux 2010). Nowadays, chemical conditioning with the use of polyelectrolytes is commonly applied. Because of lower efficiency, physical conditioning with the application of so called "skeleton builders" is less popular.

But the efficient and economic processing of sludge requires the knowledge concerning the sludge characteristic. The chemical and physical as well as the biological properties of sewage sludge are well known, but the rheological properties of sludge after previous conditioning are under examination.

The rheological characteristic of sewage sludge provides detailed information which is necessary for designing and exploitation of wastewater treatment plants. The understanding of sludge rheology can optimize the working conditions of tanks, settlers, pumps and other equipment connected with sludge processing, transport, storage and final management (Estiaghi et al. 2016). The rheology of sewage sludge is essential to calculate head losses and pumping power. As stated by Ratkovich et al. (2012), non-Newtonian liquids usually reach turbulent conditions at much higher fluid velocities due to their elasticity and are characterized by sludge thinning properties. This presents a critical problem as settleable solids accumulate at the bottom of horizontal pipe sections and lead to pipe blockage. Therefore, rheological characteristic should be included in designing and selection of devices associated with the sludge treatment. The knowledge of sewage sludge rheology is also essential for conditioning and dewatering (Tixier et al. 2003).

According to Slatter (1997) and Cao et al. (2016), research of rheological properties of sewage sludge should include three main steps: (1) measurement of viscosity (η), (2) selection of proper rheological model, and (3) correlation between different parameters which characterize sewage sludge.

Most of the rheological research is related to determination of viscosity and flowability. The viscosity (η) is defined as shear stress dived into shear rate. (γ). Viscosity is not a constant value and it depends on temperature and the content of solids (Estiaghi et al. 2013). Because sewage sludge is classified as a non-Newtonian fluid, the shear rate is not linearly proportional to the shear stress (Dentel 1997). It often results in the difficulties in the description of sewage sludge rheology.

Several models can be used to describe rheological properties of sewage sludge. The pseudoplastic characteristic of sludge is best described by means of Ostwald de Vaele model (1) (Liu et al. 2016):

$$\tau = k \cdot \gamma^n \tag{1}$$

where: k is a consistency coefficient associated with the model and n is a flow index.

The non-Newtonian fluid character of sewage sludge might be also expressed by means of Bingham (2) and Herschel-Bulkley (3) models. According to Liu et al. (2016), the aforementioned equations are more convenient for the sludge that contains the higher content of solids.

$$\tau = m \cdot \gamma + \tau_y \tag{2}$$

where: τ_y is the yield stress and m is a coefficient associated with the viscosity.

$$\tau = k \cdot \gamma^n + \tau_y \tag{3}$$

where: k and n are associated with the selected model.

Rheological characteristics of sewage sludge are closely related to its parameters, for example, density, solid content, the particle size and settling rates (Barber 2016). Changes in the sewage sludge structure, which are related to the sewage sludge conditioning and dewatering, also influence the sludge rheology. Liu et al. (2016) showed that the pretreatment of sewage sludge with the use of microwaves and H_2O_2 resulted in the improvement of sludge flowability and the decrease of viscosity. Wolski (2016) proved that sludge conditioning by means of ultrasound field affects the increase of shear stress. Wang et al. (2017) also tested the impact of chemical conditioning on the sludge rheology. They indicated that the viscosity of sludge after modification decreased as the shear rate increased. Sewage sludge after thermal conditioning was characterized by higher or lower viscosity depending on the shear rate and the time of heat treatment. Farno et al. (2014) noted that the conditioned sludge is less viscous in a low shear rate and more viscous in a high shear rate in comparison to raw sludge by keeping the high temperature for a period of time, for example 30 minutes. At low shear rates, the increase of the duration of heat treatment caused the decrease of interaction between sludge particles and for this reason, the viscosity decreased. At high shear rates, the viscosity is the function of particles fractions, as well as, interstitial fluid. As a result, the increase of viscosity of liquid medium and sewage sludge is observed (Farno 2014).

The impact of polyelectrolytes on sludge rheology was also tested by Bień (2011). She noted that the addition of cationic polymers in dosages of 3.5–5 g/kg d.m. affects the increase of thixotropy index and the shear stress in comparison to non-conditioned sludge. Additionally, Bień (2011) showed that sewage sludge after conditioning with the use of polyelectrolyte in dosages of 4.5 and 5 g/kg d.m. was characterized by the high shear stresses for low shear rates. The shear stresses also decreased dramatically as the shear rate increased.

Most papers are mainly related to rheological properties of raw sewage sludge or after chemical conditioning. Moeller and Torres (1997) examined the rheological properties of primary and secondary sewage sludge. Baroutian et al. (2013) described the influence of mixing of raw and secondary sludge on its rheology. But the information concerning the influence of physical conditioning on sludge rheology is relatively poor. Hou and Li (2003) indicated that the addition of coal fly ash resulted in the decrease of capillary suction time (CST), specific resistance to filtration (SRF) and viscosity. There are, however, not many papers referring to impact of biomass combustion by-products on rheological characteristics of sludge.

The current study aimed to characterize the rheological properties of sewage sludge after conditioning with the use of biomass ash. The influence of biomass combustion by-products on the viscosity, flow curves and thixotropy was examined. The correlation between selected rheological parameters and sewage sludge moisture content as well as capillary suction time (CST) reduction was investigated. All results were compared with non-conditioned sewage sludge and the sludge after modification with the use of SEDIFLOC 1050CMMW polyelectrolyte in the dosage of 1.5 grams per kilogram of sewage sludge dry mass ($g \cdot kg\ (d.m.)^{-1}$). The findings provide useful information concerning the influence of sewage sludge conditioning on its properties and might be helpful during the design and exploitation of devices dedicated to dewatering.

Materials

Raw sewage sludge

Samples of sewage sludge used in laboratory tests were derived from the thickening tank in the Świlcza WWTP (Podkarpacie region, Poland). It is a mechanical and biological wastewater treatment plant with the capacity of 1940 cubic meters per day ($m^3 \cdot d^{-1}$). The samples were transported to the laboratory in a plastic container at the temperature below 10°C and in a way that limited the access of light. By means of that, the change of sludge properties was not so quick. All laboratory tests were completed within 2 days. During this time, sewage sludge was stored in the temperature of approximately 4°C. Regarding the samples of raw sewage sludge, selected parameters were measured (Table 1).

Biomass ash

The ash used in this study is a residue of biomass combustion. Biomass ash was derived from the electrostatic precipitator in the "Łężańska" Power Plant in Krosno, Poland. It is a residue of biomass combustion at the temperature of approximately 900°C. In this power plant, woody biomass is mainly fired. The ash was not grounded and sieved before laboratory tests and for this reason, particles with a diameter in the range of 0.1 ÷ 600.0 micrometers (μm) were in this material. It was an intentional action; by means of that, the usefulness of unprocessed ash was tested.

Before the use, the biomass ash was washed with distilled water and dried at 105°C for 3 hours. For the obtained samples of ash, selected physical and chemical characteristics were investigated (Table 2). The density of ash was determined by means of a gas pycnometer. The specific surface area was established on the basis of the BET method. In order to calculate the chemical characteristic of biomass ash, the X-ray fluorescence (XRF) method was used.

Methodology

Sewage sludge conditioning

The sewage sludge conditioning was carried out in the following order. Five beakers of the volume of 1 dm^3 were filled with 500 cm^3 of raw sewage sludge. Biomass ash in the volume dosages of 5 (B 5.0); 7.5 (B 7.5), 15 (B 15.0) and 30 $kg \cdot m^{-3}$ (B 30.0) were added to four of the beakers. The dosages were selected on the basis of previous studies and were calculated on the basis of sewage sludge dry mass (Table 3).

The beaker with raw sewage sludge was a control sample. After that, all samples were stirred at a speed of 250 revolutions per minute (rpm) for 1 minute and then they were mixed at a speed of 50 rpm for 15 minutes. After conditioning with the use of biomass ash, capillary suction time (CST) was measured. Due to pozzolanic properties of ashes, the sewage sludge moisture content after conditioning was also determined. As a comparative criterion, samples of raw sewage sludge (R) and sludge after chemical conditioning by means of SEDIFLOC 1050CMMW cationic polyelectrolyte (P) in the dosage of 1.5 $g \cdot (kg\ d.m.)^{-1}$ were used. The polyelectrolyte was applied as 0.5% solution after 2 hours after the preparation.

The CST was determined with the use of Baskerville and Gaulle method and was based on the wetting time measurement. The mean value of CST of three measurements was calculated in line with Eq. 4:

$$\mathrm{CST} = \sum_{i=1}^{n} CST_i / n \tag{4}$$

where CST_i is the value of CST for each series and n is the number of findings.

The samples of raw and conditioned sewage sludge were dried at 105°C in order to determine the sludge moisture content (MC). It was calculated by the following equation (5):

$$MC_i = [(w - d)/w] \cdot 100\% \tag{5}$$

where w is the wet weight of sewage sludge (g) and d is the weight of sludge after drying (g).

On the basis of the results of each series, the mean MC was calculated (Eq. 6).

$$\mathrm{MC} = \sum_{i=1}^{n} MC_i / n \tag{6}$$

where MC_i is the value of MC for each series.

The pH of raw and conditioned sewage sludge was measured by the use of HQ40d pH-meter (HACH Company, United States). The mean pH was calculated as the mean hydrogen-ion concentration in line with Eq. 7.

$$\mathrm{pH} = \text{-log}\left(\sum_{i=1}^{n} [H^+]_i / n\right) \tag{7}$$

where $[H^+]_i$ is the value of the hydrogen-ion concentration for each series.

Table 1. Selected parameters of sewage sludge used in the laboratory research

Parameter	pH [–]	MC [%]	d.m. [%]	CST [s]	organic matter [% d.m.]	total N [% d.m.]	ammonium nitrogen [% d.m.]
Value	6.67	98.23	1.77	139.26	49.20	3.97	0.23
d.m. – dry mass; MC – moisture content; CST – capillary suction time							

Table 2. Selected physical and chemical parameters of biomass ash used in the laboratory test

Parameter	density [$g \cdot cm^{-3}$]	specific surface area [$m^2 g^{-1}$]	Chemical composition [$mg \cdot g^{-1}$]						
			Ca	Si	K	S	P	Mg	other (Al, Fe, Cl, Cr, Na, Mn)
Value	2.58	1.88	260.60	56.57	64.91	24.22	16.04	20.35	55.73

Rheological measurements

The flow curves and the viscosity of samples were determined by means of the rotation method. In a laboratory test, a rotational rheometer (Anton Paar Company, Physica MCR301, Austria) was used. The constant shear (C_{SR}) and the constant shear stress (C_{SS}) for the device were 18.832 Pa(mNm)$^{-1}$ and 1.289 min·s^{-1}, respectively. The rheometer was equipped with a cylinder (Anton Paar CC27, inner diameter 27 mm).

The viscosity and the flow curves were made with a logarithmic variable shear profile for the increasing shear rate in the range of 1 ÷ 500 s^{-1} in 75 seconds. The thixotropic loops were examined in 3 steps:

- measurement with the linear increase of the shear rate from 2 s^{-1} to 100 s^{-1} in 5 s,
- measurement with the constant shear rate at 100 s^{-1} for 5 s,
- measurement with the linear decrease of the shear rate from 100 s^{-1} to 2 s^{-1} in 5 s.

The sewage sludge rheology was determined by means of coaxial cylinders at the measuring gap which strives for infinity. The selection of the measuring cell was determined by the characteristic of samples and the content of particles with a diameter below 1 mm, as well as agglomerates. The shear rate was determined on the basis of a preliminary test. The upper limit of shear stress was established at the level of 500 s^{-1}. It was a value for which the flow was still laminar.

The rheology tests were carried out in three series for all the conditioned samples. The beaker with raw sewage sludge was a control sample. In order to obtain reproducible results, each measurement was preceded by pre-mixing at the shear rate of 600 s^{-1}. It was caused by the ability of samples to sedimentation.

For all samples of sewage sludge, the flow rate and viscosity were examined. On the basis of the thixotropic loops, the thixotropy index (TI) was calculated (Eq. 8). The dependence between shear stress and shear rate was determined with Ostwald de Vaele model. The correctness of the model selection was assessed by means of the Regression coefficient (R^2).

$$TI = \eta_u - \eta_d \tag{8}$$

where η_u is the viscosity for the increasing shear rate and η_d is the viscosity for the increasing shear rate for the same shear stress.

Results and discussion

Impact of biomass ash on the sewage sludge conditioning

Sewage sludge conditioning by the use of biomass ash improved its dewaterability in a significant way, which was shown in Figure 1a. The effect of sludge conditioning on the removal of water was varied, depending on the dosage of ash. CST for raw sewage sludge was approximately 139 s. It was found that this parameter decreased dramatically as the dosage of biomass ash increased. The addition of the lowest tested dosage of biomass ash (5 kg·m^{-3}) resulted in the decrease of CST by approximately 21% to the value of about 110 s. However, great usefulness in the improvement of sewage sludge dewaterability indicated the dosage of 30 kg·m^{-3}. The aforementioned dosage caused the decrease of CST by approximately 88% to the value of about 17 s. Lower CST indicates higher sludge dewaterability. The addition of polyelectrolyte in the dosage of 1.5 g·(kg d.m.)$^{-1}$ resulted in the 90% reduction of CST. The results for polyelectrolyte were slightly better than for the sludge after conditioning by means of biomass ash in a dosage of 30 kg·m^{-3}, but differences between E4 and P samples were relatively small.

The influence of ashes on CST was also confirmed by other researchers. Kuglarz et al. (2008) in their research obtained approximately 20% reduction of CST after the addition of coal fly ash. Wójcik et al. (2017) also reported that the addition of willow ash is beneficial in reducing the aforementioned parameter. The change of CST value is a result of the modification of sludge structure. According to Wójcik et al. (2018), ash particles are incorporated in the sludge flocs matrix, which results in the change of their shape and size. In the case of creating specific skeleton, the permeability and strength of sewage sludge cake is improved (Wu et al. 2017). By means of that, its filterability is boosted.

The pH of the experimental sludge was, on average, 6.67. The application of biomass ash influenced the increase of pH of the conditioned sewage sludge (Fig. 1b). With a biomass ash dosages of 5 and 7.5 kg·m^{-3}, pH increased, respectively, by approximately 1 and 2 units. The addition of ash in the amount of 15 and 30 kg·m^{-3} affects the growth of pH by approximately 5 and 6 units, respectively. The change of pH was caused by the content of alkaline ions, especially Ca^{2+} in the applied ash. Due to the high leaching, calcium ions are transported into the sludge and the growth of pH is observed (Wang and Viraraghavan 1998). The impact of biomass ash on the pH of

Table 3. Details concerning the sewage sludge conditioning

Symbol	method of conditioning	volume dosage [kg·m^{-3}]	dosage in the adjusted sewage sludge d.m. [g·(kg d.m.)$^{-1}$]	Per cent dosage of the adjusted sewage sludge d.m. [%]
R	–	–	–	–
B 5.0	physical[1]	5.00	188.70	18.00
B 7.5	physical	7.50	283.00	28.30
B 15.0	physical	15.00	566.00	56.60
B 30.0	physical	30.00	1132.10	113.21
P	chemical[2]	0.05	1.50	0.15

[1]physical conditioning with the use of biomass ash; [2]chemical conditioning with the application of cationic polyelectrolyte

sludge was also proved in our previous papers (Wójcik et al. 2017, 2018). Therefore, biomass ash might be considered as an alkalizing substance of sewage sludge. On the other hand, chemical conditioning with the use of cationic polyelectrolytes did not influence the pH of sludge.

Biomass ashes are characterized by the pozzlanic properties and the hydration ability. For this reason, the decrease of MC after conditioning was observed (Fig. 1c). The MC of raw sewage sludge was approximately 98.2%. The sludge conditioning resulted in the decrease of MC with the increase of biomass ash. The application of 30 kg·m^{-3} dosage of ash decreased the MC by approximately 3.5% to the value of 96.8%. The effect of polyelectrolyte on the MC after conditioning was not noted. The knowledge related to the influence of biomass ash on the initial MC had a significant impact on the evaluation of the effectiveness of sludge dewatering.

Impact of biomass ash on the sludge rheology

The research of sludge rheology enables to examine the shear stress of sewage sludge flocs after conditioning. The flow curves for samples of raw and conditioned sewage sludge are presented in Figure 2. It was observed that the shear stress (τ) increased non-linearly as the shear rate increased. This dependence was noted both for raw and conditioned sewage sludge. It means that all samples behaved like non-Newtonian liquid.

A clear relationship between the dosage of biomass ash and the increase of shear stress was not observed. Samples of raw and physically conditioned sludge indicated similar shear stress in the whole range of the shear rate. Sewage sludge after the addition of polyelectrolyte was characterized by the lowest values of shear stress for all stress rates. It was particularly evidenced for shear rates above 200 s^{-1}. Additionally, the course

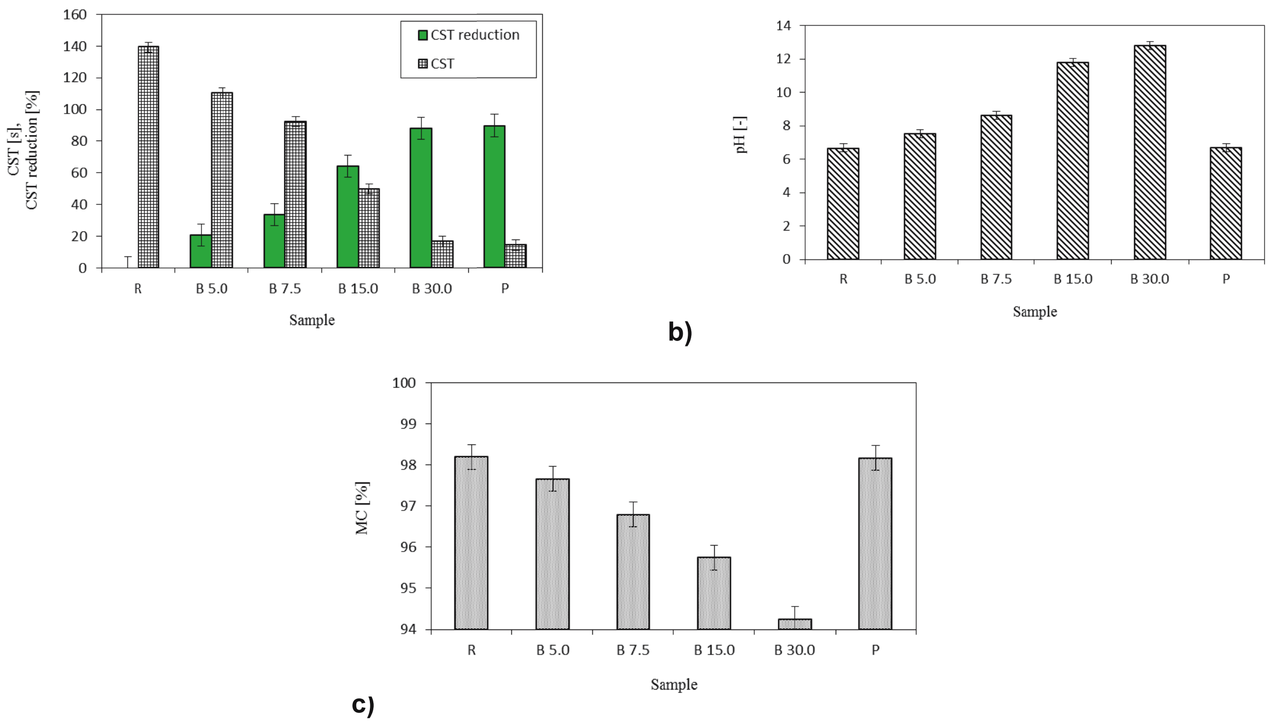


Fig. 1. The impact of biomass ash on CST (a), pH (b) and the MC (c)

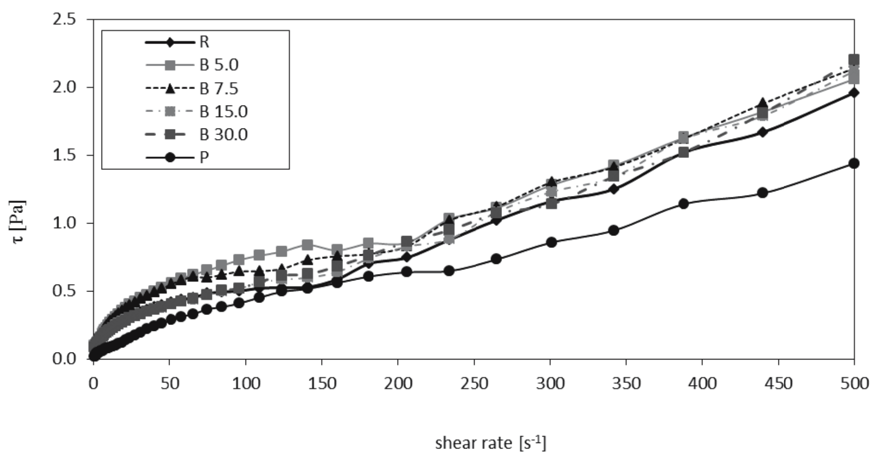


Fig. 2. Flow curves for samples of sewage sludge

of the flow curve for the P sample was gentler in comparison to other samples. The gentler slope of the curve suggests that flocs that were formed after the addition of polyelectrolyte, have higher strength and are less susceptible to destruction (Bień 2011).

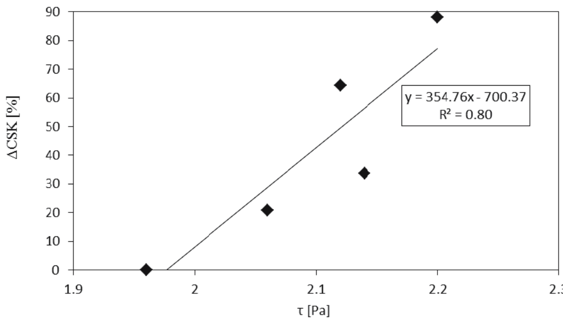
The dependence between the shear stress, the MC as well as the CST reduction for the highest shear rate (500 s^{-1}) is shown in Figures 3a and 3b. The figures indicate that the shear stress increases with the decrease of MC and CST. According to Forster et al. (1982), the increase of shear stress is related to the content of polysaccharides and proteins in sewage sludge. With the decrease of sludge MC, the amount of the aforementioned chemical compounds increased. Additionally, the analysis of results indicated the relationship between the aforementioned parameters for the highest tested shear rate (ANOVA, $p<\alpha$, $p = 0.062$, $R^2 = 0.74$ for ΔMC – shear stress dependence; $p<\alpha$, $p = 0.043$, $R^2 = 0.80$ for ΔCST – shear stress dependence). But the significant correlation was not observed.

In order to describe better the sludge rheology, the viscosity (η) was examined. The obtained results are illustrated in Figure 4. With the increase of the shear rate, the viscosity of sewage sludge decreased. It was noted both for raw as well as conditioned sewage sludge, but a clear relationship between the dosage of biomass ash and the decrease of viscosity was not observed. Samples of raw and physically conditioned sewage sludge indicated similar values of viscosity in the whole range of the shear rate. Small differences between raw and conditioned sewage sludge might be caused by high susceptibility of samples to sedimentation.

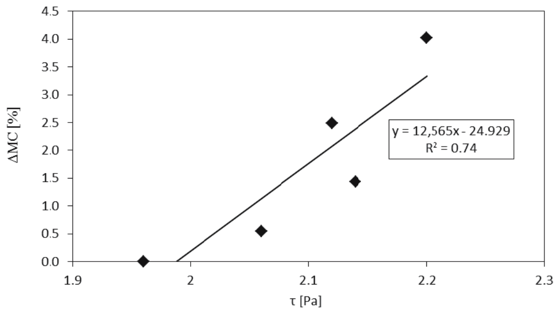
Some differences between the value of viscosity for different methods of conditioning were observed. The sample of sewage sludge after chemical conditioning with the use of polyelectrolyte was characterized by lower viscosity for the shear stress below 50 s^{-1}. Due to this reason, the course of the curve was gentler than for other samples. It confirms the more stable structure of sludge after chemical conditioning, but for the higher stress rate, the viscosity for all the tested samples was almost the same.

The dependence between viscosity, MC reduction (ΔMC) as well as CST (ΔCST) reduction for the stress rate of 500 s^{-1} was shown in Figures 5a and 5b. It was noted that the viscosity increased with the decrease of water in sewage sludge. The increase of viscosity suggests that after physical conditioning the sludge is denser. The analysis of results also showed the statistical relationship between viscosity, ΔMC as well as ΔCSK (ANOVA, $p<\alpha$, $p = 0.062$, $R^2 = 0.74$ for ΔMC – viscosity dependence; $p<\alpha$, $p = 0.043$, $R^2 = 0.80$ for ΔCST – viscosity dependence). The R^2 coefficient was satisfactory and the dependence might be described linearly.

During this experiment, a thixotropic behavior of sewage sludge was observed. Samples of raw and conditioned sewage sludge formed the thixotropic loops which are illustrated in Figure 6. It was noted that the shear stresses of up-curves were higher than down-curves at the same shear rate. Similar observations were noted by other researchers (Yen et al. 2002, Liu et al. 2016) for different conditioning methods. According to Liu et al. (2016), the thixotropy of sludge is a result of its internal structure and the presence of colloidal forces between



a)



b)

Fig. 3. The dependence between shear stress and ΔCST (a) and between the shear stress and ΔMC (b) for the shear rate of 500 s^{-1}

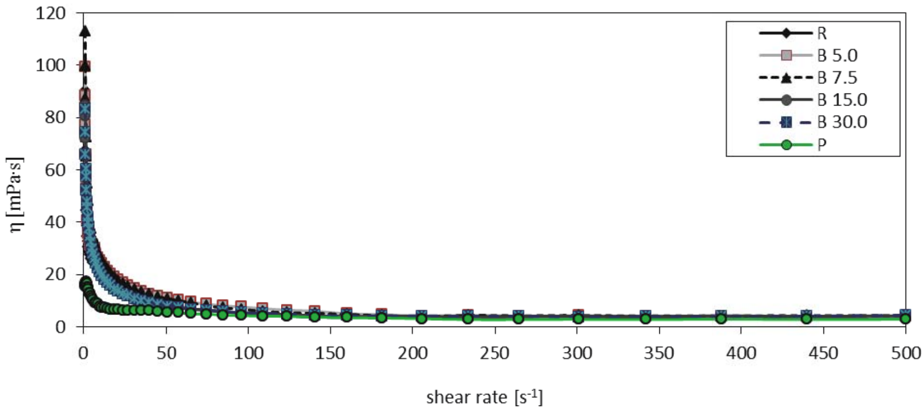
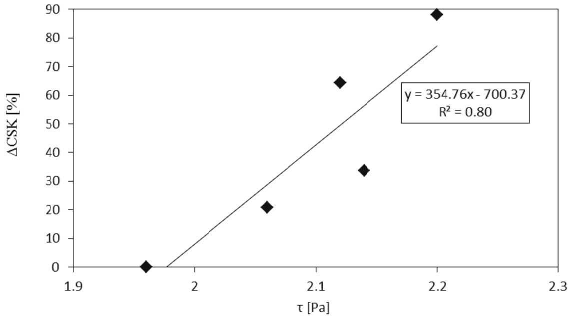
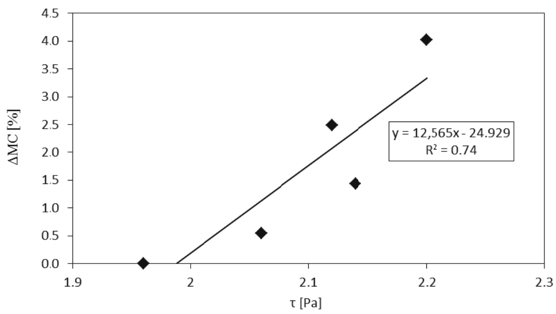


Fig.4. Viscosity curves for samples of sewage sludge

particles. The physical conditioning with the use of biomass ash also influenced the increase of the hysteresis area for all tested dosages of ash. The sludge after conditioning with the use of 5 kg·m^{-3} dosage of ash was characterized by the highest hysteresis area. As stated by Liu et al. (2012) and Baudez (2008), this phenomenon might be caused by the increasing inter-particle friction and the possibility of collision in samples for which MC is lower. Another cause might be the ability of the tested sewage sludge to thickening, but Baudez (2006) in his research suggests that the hysteresis loop often comes from the rheological procedure and the accuracy of rheometer.

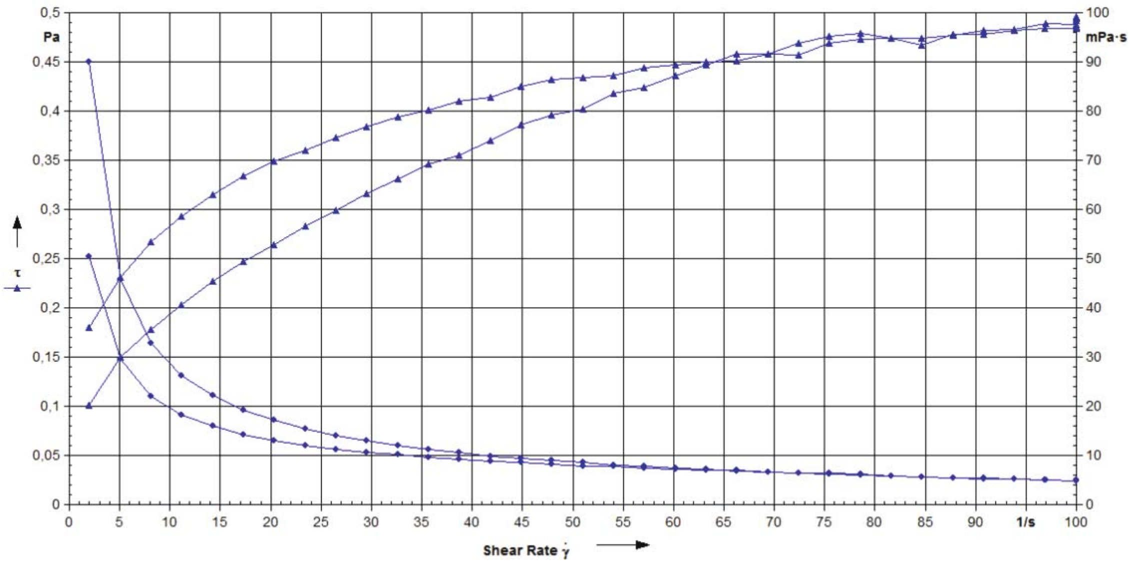


a)

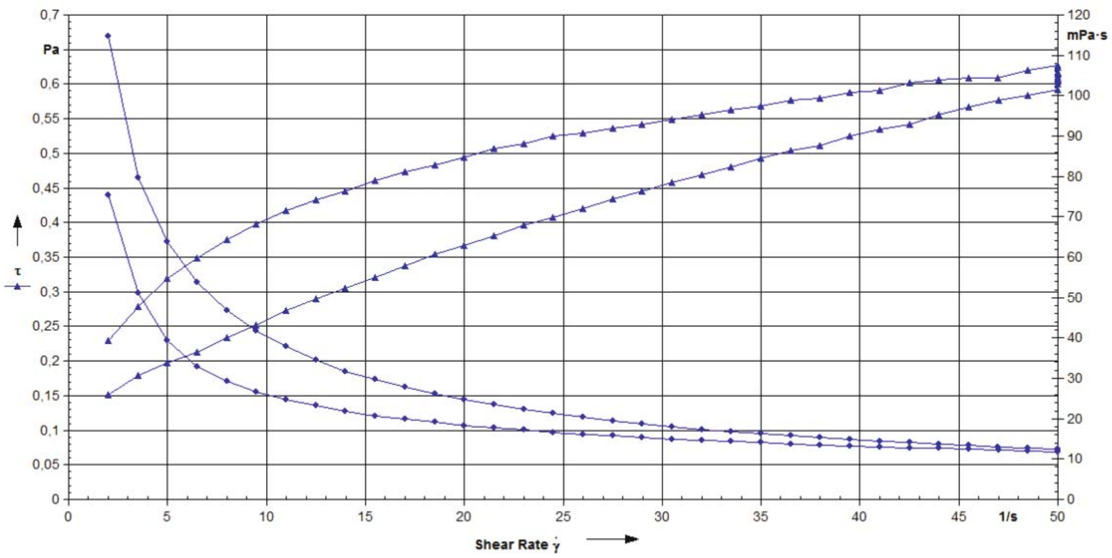


b)

Fig. 5. The dependence between shear stress and ΔCST (a) and between the shear stress and ΔMC (b) for the shear rate of 500 s^{-1}



a)



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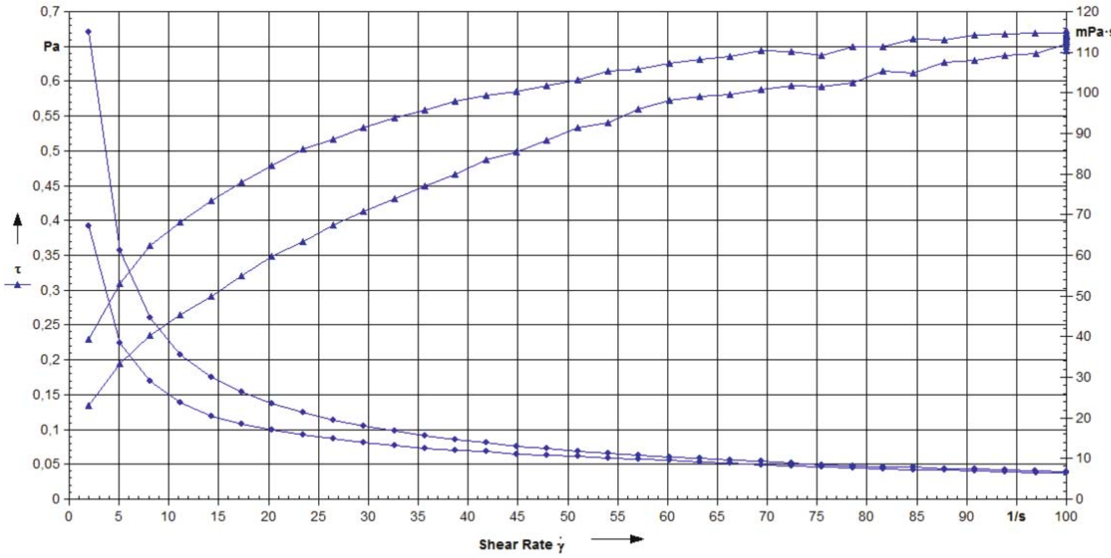
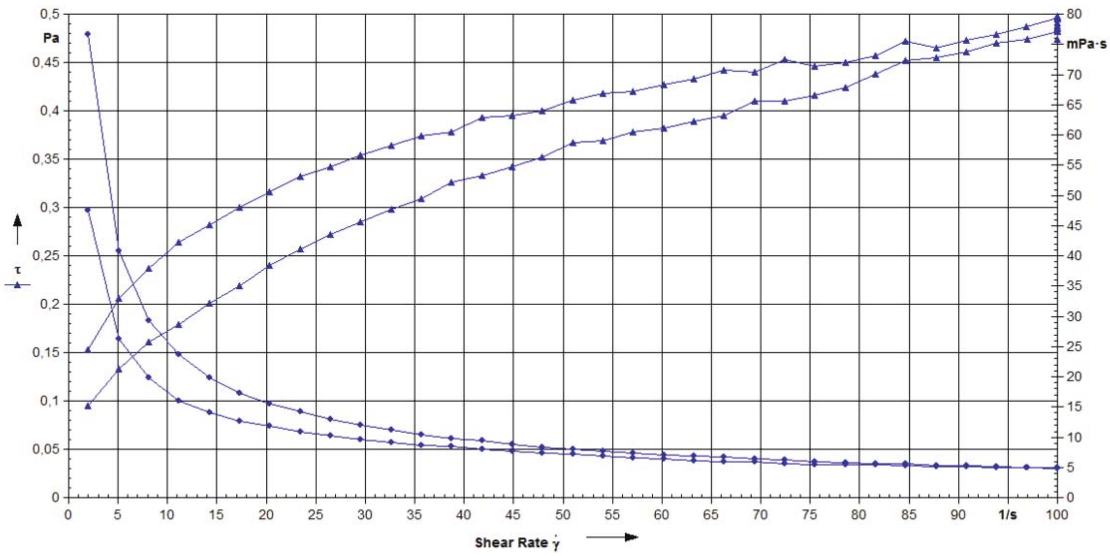
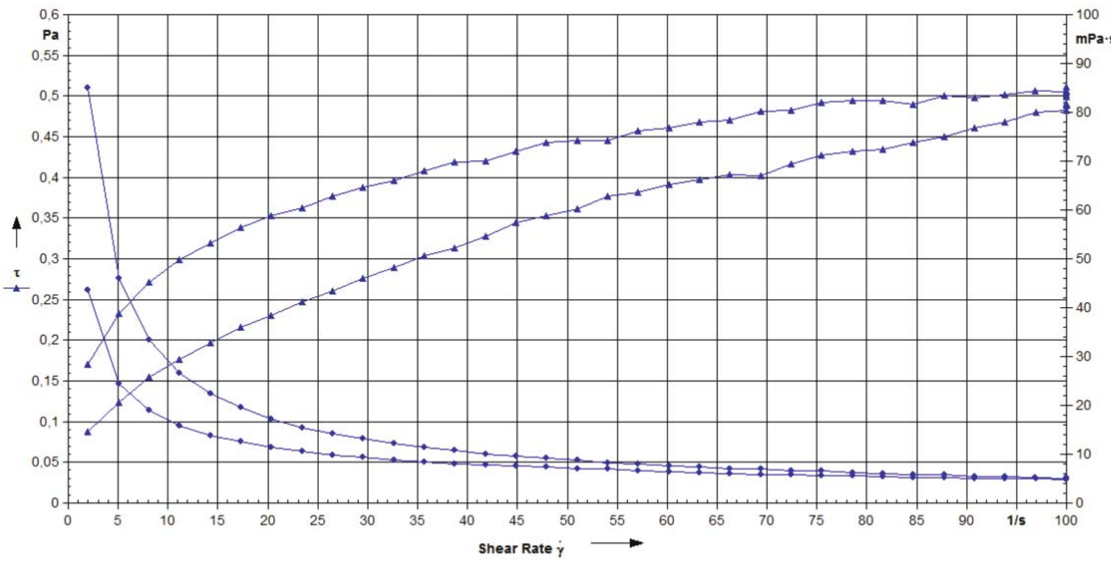


c)



d)



e)

Fig. 6. Hysteresis loops for samples of raw sewage sludge (a) and after conditioning with the use of biomass ash in the dosage of 5 (b); 7.5 (c); 15 (d) and 30 (e) kg·m^{-3}

On the basis of hysteresis loops, the thixotropic index (TI) was calculated (Fig. 7). The thixotropic index for raw sewage sludge was 3.8. It was noted that the TI value decreased as the dosage of biomass ash increased. For 5 and 7.5 kg·m^{-3} dosages of ash, TI values were higher than those for non-conditioned sludge. On the other hand, the samples of sewage sludge after the addition of the highest tested dosages of biomass ash (15 and 30 kg·m^{-3}) were characterized by lower values of TI than for raw sludge. Among all the tested samples, the lowest value of TI was achieved for sewage sludge after the addition of polyelectrolyte. According to Bień (2011), it suggests more stable structure in comparison to physically conditioned sludge.

Selection of the rheological model

In order to determine the relationship between shear stress and shear rate, the rheological model was used. According to the value of Regression coefficient (R^2), the best fitting was indicated by the Ostwald de Vaele model (see Formula 1). For all samples, R^2 was very high (≥ 0.98) (Table 4). It was also noted that the R^2 coefficient increased as the sludge MC decreased. According to Lotito (2014), the increase of the aforementioned parameter might suggest the deepening of pseudoplastic properties of sewage sludge. CaO et al. (2016) also proved that the Ostwald de Vaele model was the best for describing of sewage sludge with the dry mass at the range of 4÷7%. For this reason, the aforementioned rheological model might be used for describing the rheological characteristic of conditioned sewage sludge with a low content of dry mass.

The k and n parameters for the Ostwald de Vaele model are shown in Table 4. Because the n parameter has a value lower than one, the shear-thinning is characteristic of the samples (Wolski 2016). It should be noted that n and k are dependent on the moisture content of sewage sludge; k increased and n decreased as the MC of conditioned sludge decreased. With the decrease of MC, the pseudoplastic behavior was more visible. Additionally, sewage sludge after the addition of biomass ash was denser and behaved more like a non-Newtonian liquid. Similar observations were noted by Cao et al. (2016).

The chemical conditioning of sewage sludge also influenced the change of k and n in comparison to raw sludge, but k and n values are different than for sewage sludge after physical conditioning. Among all the considered samples, k was the lowest and n was the highest. It might suggest that the behavior of sludge after chemical conditioning is the most similar to Newtonian liquid among all the samples.

Conclusions

The main conclusions that are drawn as follows:

1. Sewage sludge conditioning with the application of biomass ash influences its parameters. The MC

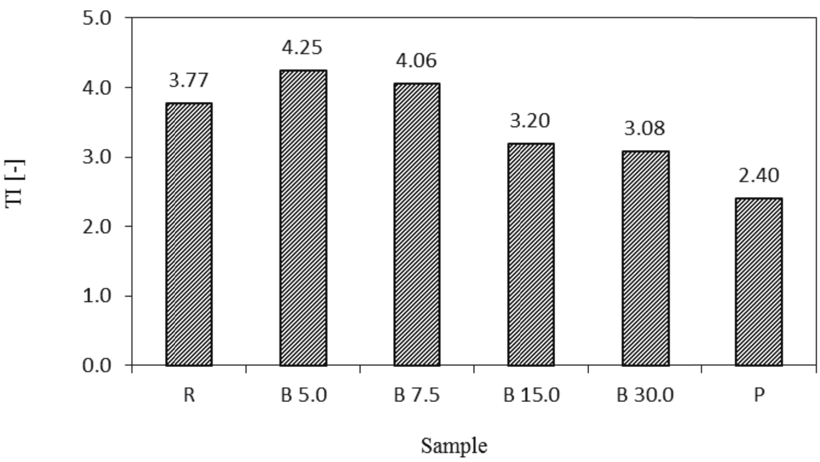


Fig.7. The thixotropic index for samples of sewage sludge

Table 4. Fitting of the Ostwald de Vaele model for sewage sludge samples

Symbol	MC [%]	Parameter		
		k [Pa·s^n]	n [–]	R^2 [–]
R	98.23	0.07	0.54	0.98
B 5.0	97.67	0.07	0.52	0.99
B 7.5	96.80	0.08	0.46	0.99
B 15.0	95.75	0.08	0.41	0.99
B 30.0	94.25	0.09	0.41	0.99
P	98.17	0.01	0.76	0.98

and CST decreased as the dosage of biomass ash increased.
2. After sludge conditioning, the flowability was improved. It was noted that the shear stress increased with the increase of the shear rate. It suggests that sewage sludge behaved like a non-Newtonian liquid. Sewage sludge after the addition of polyelectrolyte, was characterized by the lowest values of shear stress for all stress rates.
3. The addition of biomass ash had an impact on the decrease of viscosity. With the increase of shear rate, the viscosity of sewage sludge decreased.
4. On the basis of the obtained results, the correlation between the MC and CST reduction as well as rheological parameters was observed.
5. Sewage sludge used in the laboratory research was characterized by the thixotropic behavior. It was noted that the shear stresses of up-curves were higher than down-curves at the same shear rate.
6. The thixotropic behavior of sewage sludge was also confirmed by means of the thixotropy index (TI). It was noted that TI value decreased as the dosage of biomass ash increased. Among all the tested samples, the sludge after chemical condition was characterized by the lowest value of TI.
7. The Ostwald de Vaele model was used to describe the rheological behavior of sewage sludge. For all the samples, the aforementioned model indicated the best fitting ($R^2 \geq 0.98$).

Acknowledgements

This work was financially supported by Research Funds "The analysis of the possibility the recycling of different fractions of waste in sludge management in terms of the implementation of circular economy idea" [No. DS/M.MP.18.001], Rzeszow University of Technology, Poland.

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Wpływ kondycjonowania osadów ściekowych popiołem ze spalania biomasy na ich charakterystykę reologiczną

Streszczenie: Artykuł przedstawia wyniki badań dotyczących wpływu kondycjonowania osadów ściekowych z użyciem popiołów ze spalania biomasy na ich charakterystykę reologiczną. Zbadano lepkość oraz właściwości tiksotropowe osadów po ich kondycjonowaniu. Odnotowano wzrost naprężeń stycznych wraz ze wzrostem prędkości ścinania. Uzyskane rezultaty porównano z wynikami badań dla surowego osadu, jak i dla osadu kondycjonowanego z użyciem polielektrolitu w dawce 1,5 g·(kg s.m.)$^{-1}$. Stwierdzono również, że próbki kondycjonowanych osadów ściekowych wykazują właściwości tiksotropowe. Wyznaczono również zależności pomiędzy uwodnieniem, czasem ssania kapilarnego oraz wybranymi parametrami reologicznymi osadów. Na podstawie uzyskanych rezultatów stwierdzono, że najlepsze dopasowanie wykazuje model Ostwalda de Vaele.