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Dewatering of sewage sludge treated by the combination of ultrasonic field and chemical methods

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ABSTRACT

In order to enhance the effects of concentration and dewatering, sludge is prepared (treated) before. The aim of conditioning sludge before dewatering is to reduce, not only its resistance but also its compressibility. The article presents the analysis of the impact of combined methods of conditioning (ultrasonic field, inorganic coagulant, cationic polyelectrolyte) on the changes in final hydration of sewage sludge in the process of pressure filtration. The study involved sewage sludge after the process of methane fermentation and stabilization in open digesters. The aim of the work was to show that by using the energy of ultrasound and chemical substances, it is possible to change the properties of sewage sludge through changing the dimensions and the capacity of particle packing, thus improving the effectiveness of dewatering. Digested sludge is hard to dewater, which is proved by its capillary suction time (CST), amounting to 1,859 s. The lowest CST value (29.3 s) and final hydration (65%) were obtained for sludge sonicated for 60 s (amplitude 30.5 μm) prepared with PIX 113 (coagulant) in the dose of 1.0 mg/$g_{d.o.m}$. (d.o.m. - dry organic mass) and Zetag 8180 (polyelectrolyte) in the dose of 7.0 mg/$g_{d.o.m.}$ The application of an ultrasonic wave and chemicals to modify sewage sludge caused the reduction in the value of final hydration and thus led to better results of sludge dewatering in the process of pressure filtration. In addition, the combined use of ultrasound, PIX 113 and Zetag 8180 reduced the content of suspended solids, phosphorus and ammonium nitrogen in sludge liquids.

Keywords: Sewage sludge; Conditioning; Dewatering; Ultrasonic field; Pressure filtration

1. Introduction

During the process of sewage treatment in treatment plants, large amounts of sludge are generated [1–4]. Its high hydration undoubtedly translates into considerable volume, and thus, high operation costs of sewage treatment plants. The treatment of sewage sludge includes the reduction of organic compounds and the removal of water from the sludge, which results in decreased volume [5–7]. Sludge dewatering is difficult due to the high compressibility and low permeability of the sludge filter cake during the filtration process [8]. A significant stage of sewage sludge processing, improving the efficiency of sludge dewatering, is the stage of conditioning. It leads to improved speed of dewatering as a result of reducing the specific resistance and compressibility of the sludge [8–10]. However, the choice of conditioning chemicals and methods (the kind of the flocculant, its dose and mixing conditions) is still difficult. This is connected with the properties of sludge, especially the high content of water occurring in different forms, which is often hard to remove [11–13]. Conditioning can be done at different stages of the process of sludge treatment in the

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plant, that is, during the sedimentation, sludge thickening and sludge dewatering. In practice, sludge is usually conditioned chemically, using organic flocculants (polyelectrolytes), which bind the particles of sludge into macroflocculi, facilitating and improving the removal of water from the sludge. However, in order to reduce the consumption of chemicals, the standard processes of conditioning are sometimes modified. The effectiveness of chemical conditioning has been confirmed by many researchers [14–17]. Jin et al. [18] used a cationic polyacrylamide to improve the dewatering of sludge. Kuglarz et al. [19] proved that the use of cationic polyelectrolyte Praestol 610BC in the dose of 2.5 g/kg DM caused the reduction in hydration and specific filtration resistance by approx. 4% and 81%, respectively. Adding inorganic or organic flocculants may cause the agglomeration of little colloids of sludge, forming large flocculi by the neutralization of charge and bridging, which may contribute to the easier separation of water [20,21]. Advanced technologies aimed at the improvement of sewage sludge dewatering properties include Fenton and photo-Fenton oxidation processes [22–24], hydrothermal processing [25,26], treatment with acid and base [27,28], enzymatic treatment [29], microwave processing [30], ultrasound processing [31], freezing [32] and integrated processes. Recently, adding different waste fractions to sewage sludge has also been tested. Examples of the fractions are sawdust, fly ash, gypsum, rice powder, wood chips and wheat bran [1,33–36]. The influence of energy waste on the effectiveness of sludge dewatering has been studied, too. However, in some cases it was found that physical conditioners did not significantly improve sludge dewatering [37]. Out of the above-mentioned methods, the ultrasonic field is beneficial to prepare sludge, since it is considered as a simple method that does not cause secondary contamination. Furthermore, ultrasound facilitates the migration of moisture through natural channels or other channels formed by the propagation of waves [38]. Many researchers have shown that the ultrasonic field with proper parameters may reduce the capillary suction time (CST) of sludge and the content of bound water by over 50% [38–40]. On the other hand, there are also reports which show negative effects of the ultrasonic field on sludge dewatering [41,42]. Intensive sonication may increase the CST of sludge and the consumption of polyelectrolytes [39,42]. Such ambiguous results and conclusions of the presented works call for further studies, which will be used to assess the effect of the ultrasonic field in sludge conditioning and the optimization of the process. So the aim of this study was to analyze the influence of the combined effect of the ultrasonic field and selected chemical substances on the effectiveness of dewatering. The final content of water in dewatered sludge was used to assess the dewatering rate of the sludge. The obtained sludge liquids were also analyzed.

2. Material and methods

2.1. Research material

The substrate in the experiments was digested sludge from a municipal sewage treatment plant. The sludge was collected from a pipeline that transports sludge from open digesters to belt presses.

Before dewatering, the sludge was pretreated. First, it was treated with an ultrasonic field; then, a 10% solution of PIX 113 coagulant and 0.1% solution of Zetag 8180 polyelectrolyte was added. PIX 113 is a ferric coagulant – ferric sulfate. It is a dark brown, odorless water solution of ferric sulfate with total iron (Fe) content of 11.8% ± 0.4%, and iron ions Fe^{+2} content of 0.4% ± 0.3% [43,44]. PIX 113 is produced by Kemipol, the Kemira Group's water treatment chemicals company. Zetag 8180 is a copolymer of acrylamide and quaternized cationic monomer. It is provided as a loose white powder by Brenntag NV [45,46].

2.2. Procedure

The study included two stages (Table 1). In the first stage, we studied digested sludge treated with ultrasonic field with amplitude A = 15.25 μm and sonication time (t): 30, 60, and 90 s; next, we added selected chemicals to it: PIX 113 in a constant dose of 1.0 mg/$g_{d.o.m.}$ and Zetag 8160 polyelectrolyte in changing doses. In the second stage, the amplitude of the ultrasonic field was changed: A = 30.5 μm. The time of sonication was the same as in the first stage, and the same chemical reagents were added.

Table 2 presents the references for samples used in charts.

A high power, microprocessor-based ultrasonic processor Sonics VC750 with automatic tuning and the frequency of 20 kHz was used to sonicate the digested sewage sludge. The sewage sludge was sonicated in static conditions, with a constant sample volume of 400 ml.

The scope of laboratory tests was: the measurement of CST, the determination of the dewatering parameters during

Table 1
Research stages

Series	Stage 1 (ultrasound: A = 15.25 μm, t = 30, 60, and 90 s)		Stage 2 (ultrasound: A = 30.5 μm, t = 30, 60, and 90 s)	
	PIX 113 (mg/$g_{d.o.m.}$)	Zetag 8180 (mg/$g_{d.o.m.}$)	PIX 113 (mg/$g_{d.o.m.}$)	Zetag 8180 (mg/$g_{d.o.m.}$)
I	1.0	4.0	1.0	4.0
II	1.0	5.0	1.0	5.0
III	1.0	6.0	1.0	6.0
IV	1.0	7.0	1.0	7.0

d.o.m. – dry organic mass

Table 2
References for sludge samples

Time of sonication of digested sludge with changing amplitude *A* = 15.25 and 30.5 μm	*t* = 30, 60, and 90 s
I	P1+Z4
II	P1+Z5
III	P1+Z6
IV	P1+Z7

P1 – PIX 113 in the dose of 1.0 mg/$g_{d.o.m.}$
Z4 – Zetag 8180 in the dose of 4.0 mg/$g_{d.o.m.}$

pressure filtration (final hydration and specific filtration resistance) and the analysis of the sludge liquid.

The sonicated sludge was mixed with selected chemicals using a magnetic stirrer MMS-3000N from Biosan. After adding PIX 113 to the digested sludge, first, it was stirred quickly for 60 s (200 rpm) to mix the whole volume thoroughly, and then slowly for 14 min (30 rpm), which ensured the formation of flocculi that made larger agglomerates. Then, a specific dose of Zetag 8180 polyelectrolyte was introduced, and after 2 min, the whole sample was stirred thoroughly again for 2 min (120 rpm).

The water removal capacity of the sludge was measured with the CST parameter, using the Baskerville and Galle methodology [47].

Pressure filtration was performed using a device made up of: a pressure filter with filtration felt inside (ET 18II polyester felt), a compressor, measurement cylinders for the filtrate, cut-off valves, a manometer and a stopwatch (Fig. 1). Compressed air with a pressure of 0.5 MPa was used in the filtration process. The data obtained during filtration was used to determine the specific filtration resistance and the final hydration of sludge [48].

3. Results and discussion

The physical-chemical characteristics of digested sludge are presented in Table 3. The sludge has neutral pH, greyish-black color, and sallow smell. The initial hydration of the sludge was around 98%, and the final hydration after pressure filtration was 72%. Digested sludge is a type of sludge that is hard to dewater, which is proved by CST measurement (1,859 s).

The results of CST measurement showed improved dewatering of sludge after the application of PIX 113 coagulant and Zetag 8180 polyelectrolyte (Figs. 2 and 3). It was found that CST of digested sludge decreases with the increase in the dose of Zetag 8180 combined with a constant dose of PIX 113. The CST of sonicated sludge (*A* = 15.25 μm) in time (*t*): 30, 60, and 90 s decreased by 94.7%; 97.8%, and 98.8%, respectively (Fig. 2). The shortest CST was obtained for sludge sonicated for 90 s prepared by PIX 113 in the dose of 1.0 mg/$g_{d.o.m.}$ plus Zetag in the dose of 7.0 mg/$g_{d.o.m.}$

As for sludge sonicated (*A* = 30.50 μm) for: 30, 60, and 90 s, CST was reduced by 97.4%, 99.2%, and 92.3%, respectively (Fig. 2). The greatest decrease in CST occurred for sludge sonicated for 60 s and with added PIX 113 in the dose of 1.0 mg/$g_{d.o.m.}$ and Zetag 8180 in the dose of 7.0 mg/$g_{d.o.m.}$

Fig. 1. Pressure filtration station.

Table 3
Physical-chemical characteristics of sewage sludge

Parameter	Value
Color	Greyish black
Smell	Sallow
pH	7.3
Initial hydration, %	98
Final hydration, %	72
Dry remains, g/L	20.8
Mineral compounds content, %	28
Organic compounds content, %	72
CST, s	1,859

The final hydration rate was used to determine the susceptibility of sewage sludge to dewatering during pressure filtration (Figs. 4 and 5). Final hydration of sludge treated with ultrasonic field with *A* = 15.25 μm for 30, 60, and 90 s was 72%, 71%, and 70%, respectively. Changes in final hydration obtained for sonicated sludge prepared with PIX 113 in a constant dose and Zetag 8160 polyelectrolyte were in the range 68%–78% (Fig. 4). The analysis of charts (Fig. 4) shows that the values of final hydration of sludge that was sonicated (30 and 60 s) and chemically conditioned were higher than the hydration values of sludge that was only sonicated. For sludge sonicated for 90 s, the final hydration was reduced in the case of chemical preparation but only from the dose of Zetag 8180 of 4.0 mg/$g_{d.o.m.}$ The lowest value of final hydration (68%) was obtained for sludge sonicated for 90 s and prepared with PIX 113 in the dose 1.0 mg/$g_{d.o.m.}$ plus Zetag 8180 in the dose 7.0 mg/$g_{d.o.m.}$

The final hydration of sludge treated with ultrasonic field with amplitude 30.5 μm for 30, 60, and 90 s was 74%,

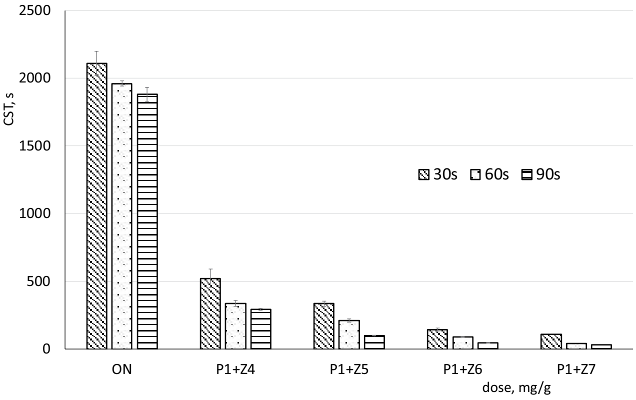

Fig. 2. Influence of selected reagents on capillary suction time (CST) of digested, sonicated sludge (A = 15.25 µm, t = 30, 60, and 90 s), ON – sonicated sludge.

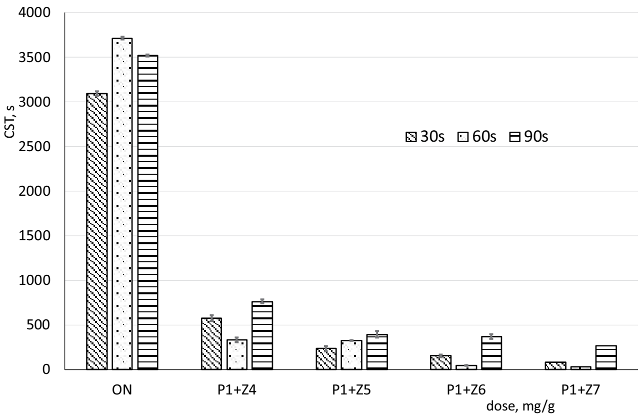

Fig. 3. Influence of selected reagents on capillary suction time (CST) of digested, sonicated sludge (A = 30.5 µm, t = 30, 60, and 90 s), ON – sonicated sludge.

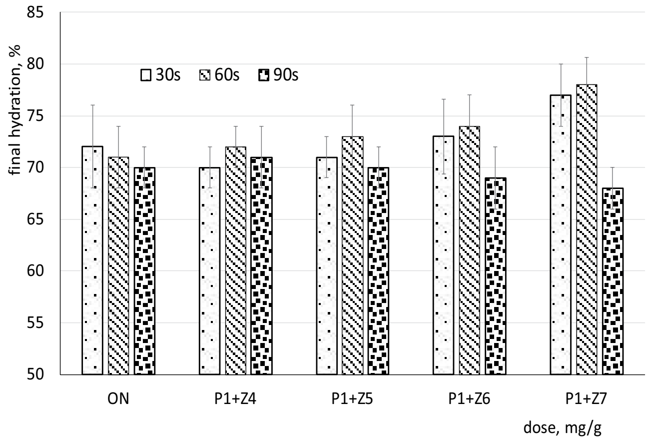

Fig. 4. Changes in final hydration of sonicated sludge (A = 15.25 µm, t = 30, 60, and 90 s) prepared with selected reagents in the process of pressure filtration, ON – sonicated sludge.

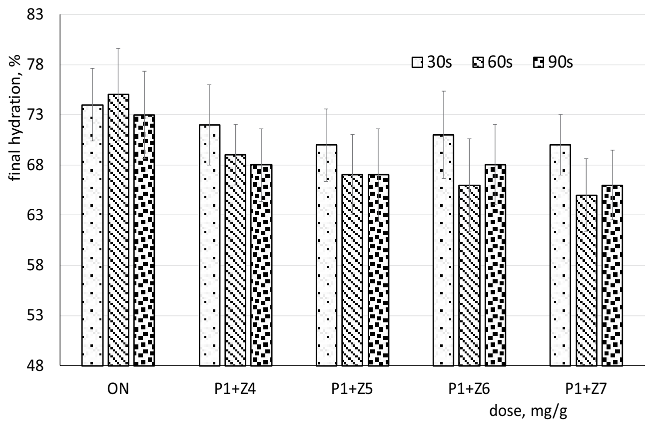

Fig. 5. Changes in final hydration of sonicated sludge (A = 30.5 µm, t = 30, 60, and 90 s) prepared with selected reagents in the process of pressure filtration, ON – sonicated sludge.

75%, and 73%, respectively (Fig. 5). The analysis of the final hydration obtained for sonicated sludge prepared with selected reagents showed that it was in the range of 65%–72% (Fig. 5). The data presented on the chart in Fig. 5 shows that the values of the final hydration of sonicated and chemically conditioned sludge were lower than the hydration values of sludge that was only sonicated. As the doses of chemicals added to the sludge grew, in most cases the value of final hydration decreased. The final hydration only grew for sonicated sludge (30 and 90 s) treated with PIX 113 and Zetag 8180 in the dose of 6.0 mg/$g_{d.o.m}$. The greatest decrease in final hydration was observed for sludge sonicated for 60 s and conditioned with PIX 113 in the dose 1.0 mg/$g_{d.o.m.}$ plus Zetag in the dose of 7.0 mg/$g_{d.o.m.}$: the hydration was 65%.

Lower values of final hydration were obtained for sludge that was sonicated with higher amplitude and with the addition of selected chemicals. The lower hydration value 65% was achieved at the following parameters: A = 30.5 µm, t = 60 s, dose of PIX 113 1.0 mg/$g_{d.o.m.}$ and a dose of Zetag 8180 7.0 mg/$g_{d.o.m.}$, where at A = 15.25 µm, t = 60 s, dose of PIX 113 1.0 mg/$g_{d.o.m.}$ and a dose of Zetag 8180 7.0 mg/$g_{d.o.m.}$ the lower hydration value was 68%. Treating sludge with ultrasonic field and then with a chemical substance led to changes in the final hydration as compared to the parameters of untreated sludge. Ultrasonic field as a physical method of modifying sewage sludge conditioned with a chemical substance was the factor that intensified the dewatering processes, as evidenced by the presented findings. Combining chemical conditioning with the physical method proved to be a satisfactory solution, reducing the volume of dewatered municipal sludge, especially for sludge sonicated with the amplitude A = 30.5 µm.

Analyzing changes in the values of specific filtration resistance (Figs. 6 and 7), we found out that filtration resistance increased in all the tested ways of conditioning the sludge in relation to sludge that was only sonicated, which did not have a negative influence on the obtained effects of final hydration. This relationship may have been the result of the applied chemicals that increased sludge

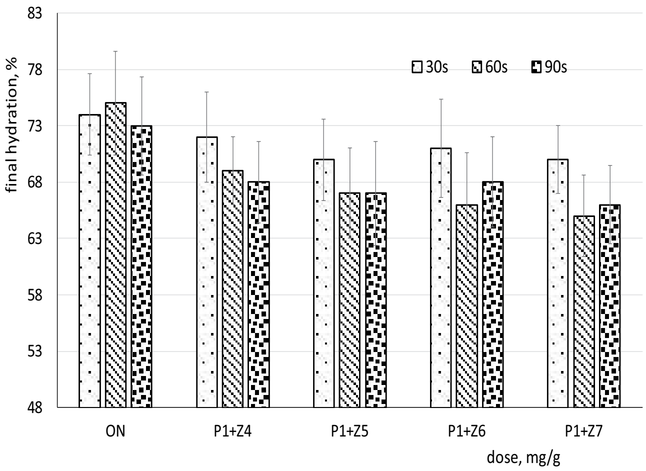

Fig. 6. Changes in specific filtration resistance of sonicated sludge (A = 15.25 µm, t = 30, 60, and 90 s) prepared with selected reagents in the process of pressure filtration, ON – sonicated sludge.

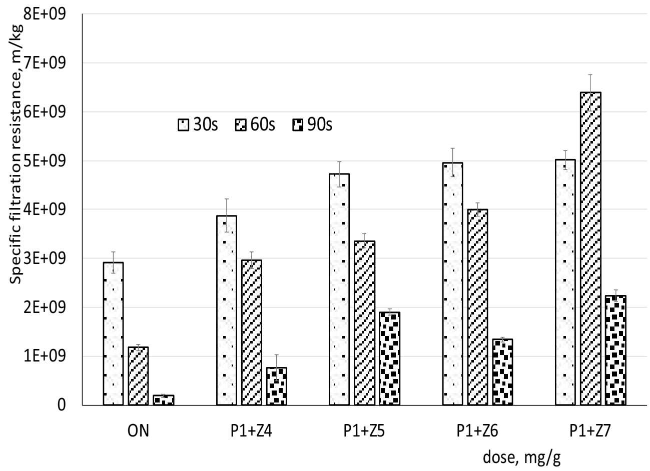

Fig. 7. Changes in specific filtration resistance of sonicated sludge (A = 30.5 µm, t = 30, 60, and 90 s) prepared with selected reagents in the process of pressure filtration, ON – sonicated sludge.

porosity. Producing a thicker structure of sludge, able to maintain high porosity under the influence of high pressure, contributed to the removal of a considerable amount of water.

During the dewatering process, we obtain a dry cake and filtrate, that is, sludge liquid. The quality of sludge liquids produced during mechanical dewatering of sludge depends on the stabilization technology and the kind of device, its proper operation, and an appropriate choice of conditioning chemicals [49]. Sludge liquids from sludge that was only sonicated had very high concentrations of ammonium nitrogen (760–1,430 mg $N–NH_4^+/dm^3$), phosphorus (0.42–58 mg P/dm^3) and organic compounds referred to as COD (2,146 – 3,756 mgO_2/dm^3). In samples of sludge liquid (Table 4) obtained from sonicated sludge (A = 15.25 µm, A = 30.5 µm) treated with PIX 113 and Zetag 8180, the pH values decreased. The value of pH decreased with the increasing dose of the coagulant. The content of phosphorus and nitrogen decreased in all samples. The lowest value of phosphorus, 0.43 mg $P–PO_4^{-3}/dm^3$ (a decrease by 99%) was found for the sample treated with PIX 113 and Zetag 8180 in the dose of 7.0 $mg/g_{d.o.m.}$ for sludge sonicated for 30 s (A = 30.5 µm). The lowest value of ammonium nitrogen was observed for samples of liquid separated from sludge sonicated for 30 s (A = 15.25 µm) and treated with PIX 113 and Zetag 8180 in the dose of 7.0 $mg/g_{d.o.m.}$ was 460 mg $N–NH_4^+/dm^3$ (reduction by 43.4%), and for sludge liquids from sludge sonicated with A = 30.5 µm: 670 mg $N–NH_4^+/dm^3$ when treating it with PIX 113 in the dose of 1.0 $mg/g_{d.o.m.}$ and Zetag 8180 in the dose of 7.0 $mg/g_{d.o.m.}$, the reduction was by 53.1%. Adding PIX 113 plus Zetag 8180 caused the reduction in total suspended solids n the liquids as compared to sludge liquids sampled from sludge that was only sonicated. We found that as the doses of reagents increased, the amount of suspended solids in the samples decreased. The number of organic compounds (chemical oxygen demand (COD)) in sludge liquid that was only sonicated decreased in the process of chemical sludge conditioning. However, the effectiveness of their removal decreased with the growing dose of Zetag 8180 and a constant dose of PIX 113.

4. Conclusions

The conclusions from the experiments are as follows:

- Physical conditioning of sludge with the ultrasonic field increased its CST in relation to crude sludge (1,859 s). However, the use of a method combining the ultrasonic field and chemicals decreased the CST. The best effect of reducing CST (29.3 s) was obtained for sludge sonicated for 60 s, A = 30.5 µm, with the addition of PIX 113 in the dose of 1.0 $mg/g_{d.o.m.}$ and Zetag 8180 in the dose of 7.0 $mg/g_{d.o.m.}$
- Adding chemical substances to sludge sonicated with the amplitude of 30.5 µm produced better dewatering effects as compared to sludge sonicated with the amplitude of 15.25 µm.
- The greatest decrease in final hydration was observed for sludge sonicated for 60 s (A = 30.5 µm) conditioned with PIX 113 in the dose 1.0 $mg/g_{d.o.m.}$ plus Zetag in the dose of 7.0 $mg/g_{d.o.m.}$: the hydration was 65%. Final hydration proved to be a better parameter to evaluate the process of dewatering of sludge than specific filtration resistance.
- The use of the ultrasonic field and a method combining PIX 113 and Zetag 8180 allowed to reduce the amount of total suspended solids in sludge liquid obtained from sludge. The greatest reduction of suspended solids was obtained for sludge sonicated for 60 s (A = 15.25 µm) with the use of PIX 113 in the dose of 1.0 $mg/g_{d.o.m.}$ and Zetag 8180 in the dose of 7.0 $mg/g_{d.o.m.}$: it was 92.4%.
- In leachates from dewatering of sludge sonicated for 30 s (A = 30.5 µm) treated with selected reagents (PIX 113 in the dose of 1.0 $mg/g_{d.o.m.}$, Zetag 8180 in the dose of 7.0 $mg/g_{d.o.m.}$), the amount of phosphorus was decreased to 99%., the amount of ammonium nitrogen was reduced to 53.1%.

Table 4
Change of selected parameters of sludge liquids separated from sewage sludge

Parameters of sludge liquids	Dose	pH	Phosphorus	Ammonium nitrogen	COD	Suspended solids
Unit	$mg/g_{d.o.m.}$	–	mg P–PO_4^{-3}/dm^3	mg N–NH_4^+/dm^3	mg O_2/dm^3	mg/dm^3
Sludge liquids separated from sludge treated with ultrasonic field with the amplitude of 15.25 μm and the combination of PIX 113 and Zetag 8168						
Sludge liquids from sludge sonicated for 30 s	–	7.34	47	760	2,146	516
PIX 113 (1.0) + Zetag 8180	4.0	6.89	8.6	770	1,169	196
	5.0	6.84	5.5	750	1,435	164
	6.0	6.82	5.4	450	1,494	127
	7.0	6.80	1.9	430	1,650	64
Sludge liquids from sludge sonicated for 60 s	–	7.37	58	1,160	3,244	709
PIX 113 (1.0) + Zetag 8180	4.0	7.08	6.0	890	1,216	236
	5.0	7.04	3.4	770	1,263	200
	6.0	6.98	3.1	750	1,630	164
	7.0	6.95	2.0	730	1,684	54
Sludge liquids from sludge sonicated for 90 s	–	7.41	43.5	1,060	3,146	527
PIX 113 (1.0) + Zetag 8180	4.0	6.96	6.6	730	1,080	345
	5.0	6.93	2.6	690	1,125	310
	6.0	6.90	2.0	550	1,206	182
	7.0	6.86	1.9	450	1,314	127
Sludge liquids separated from sludge treated with ultrasonic field with the amplitude of 30.50 μm and the combination of PIX 113 and Zetag 1868						
Sludge liquids from sludge sonicated for 30 s	–	7.47	43.60	1,430	3,385	600
PIX 113 (1.0) + Zetag 8180	4.0	7.00	1.96	1,240	1,242	309
	5.0	6.95	0.98	1,000	1,297	254
	6.0	6.93	0.85	730	1,370	200
	7.0	6.91	0.42	670	1,518	72
Sludge liquids from sludge sonicated for 60 s	–	7.62	46.60	1,210	3,698	836
PIX 113 (1.0) + Zetag 8180	4.0	7.36	3.86	1,140	1,407	364
	5.0	7.31	1.96	1,070	1,499	273
	6.0	7.28	1.11	1,050	1,610	290
	7.0	7.24	1.11	880	1,674	236
Sludge liquids from sludge sonicated for 90 s	–	7.36	30.10	1,070	3,756	582
PIX 113 (1.0) + Zetag 8180	4.0	7.03	2.48	940	1,527	454
	5.0	6.94	1.76	870	1,619	400
	6.0	6.87	1.11	740	1,692	345
	7.0	6.84	0.98	830	1,757	272

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