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Examinations of the Effect of Ashes from Coal and Biomass Co-combustion on the Effectiveness of Sewage Sludge Dewatering

Badania wpływu popiołów ze współspalania węgla i biomasy na efektywność procesu odwadniania osadów ściekowych

High water content and the associated large volume of waste represent a challenge to final disposal of sewage sludge. For this reason, dewatering is one of the most important stages in sewage sludge treatment. However, sewage sludge dewatering is also the most expensive and least explored process. The specific physical and chemical properties of raw sewage sludge make it impossible to obtain satisfactory dewatering effects without primary processing. Water removal efficiency can be improved with sludge conditioning by means of various technologies. Chemical conditioning, which consists in dosing organic flocculants, has been commonly used in wastewater treatment plants. Application of polyelectrolytes to sludge in order to improve its dewaterability generates high operating costs in sewage treatment plants, amounting even to several thousand PLN a month. The economic aspects have driven the development of the research on intensification of sewage sludge dewatering using various materials, including waste. Conditioning of sewage sludge with fuel combustion by-products represents an alternative to commonly used technologies. The paper presents the effect of by-products of co-combustion of hard coal and plant biomass on the efficiency of sewage sludge dewatering. The effect of ash on capillary suction time (CST), water content and specific resistance to filtration was discussed. Physical conditioning of sewage sludge led to the decrease in CST, specific resistance to filtration (SRF) and water content. An increase in filtrate volume after pressure filtration was also observed. The results obtained in the study showed that addition of waste can represent an alternative method of sewage sludge conditioning.

Keywords: **sewage sludge, ashes, conditioning, dewatering, sewage sludge management, recycling**

Introduction

Pursuant to the provisions of the Act of 14 December 2012 on waste [1], sewage sludge is defined as waste from fermentation chambers and other installations for treatment of municipal sewage and other types of sewage with a composition similar to that of municipal sewage. With intensification of land development and

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connecting new recipients to the system of collective sewage disposal, the volume of sewage sludge is gradually increasing year by year. According to the data contained in a report of the Central Statistical Office of Poland (Główny Urząd Statyczny, GUS) of 2017 [2], 568.3 thousand Mg d.m. (dry mass) of sewage sludge was generated in Poland in 2016. Furthermore, in 2017, this number was 584.45 thousand Mg d.m. of sewage sludge, of which the largest amount was observed in the Masovian Voivodeship (90.53 thousand Mg d.m.), Greater Poland Voivodeship (17.97 thousand Mg d.m.), and Silesian Voivodeship (64.03 thousand Mg d.m.) [3]. For comparison, in 2005 and 2010, these levels were 486.1 thousand and 526.7 thousand Mg d.m., respectively. The volume of sewage sludge generated in sewage treatment plants has been increasing every year and requires the implementation of both new and effective methods of its disposal, with consideration for legal, economic and ecological requirements.

According to Polish legislation [1, 4], sewage sludge requires modification before its final disposal to reduce health hazards. Nevertheless, sewage sludge treatment processes contribute to a significant increase in operating costs in sewage treatment plants. Wang and Wang [5] showed that annual financial expenditures for processing and final disposal of approximately 7 million m^3 of sewage sludge produced by over 13,000 treatment plants are estimated in the United States at nearly USD 2 billion. Furthermore, Wójtowicz [6, 7] found that the unit cost of processing and final management of dewatered sewage sludge amounts to ca. PLN 300÷500/Mg in the case of thermal treatment and ca. PLN 200-300/Mg for the biological treatment installations. According to Bień et al. [8], the cost of collection, transport and final disposal of municipal sewage sludge ranges from several dozen to several hundred zlotys per tonne of sludge. The economic reasons justify the need to reduce costs already at the stage of processing of waste generated during wastewater treatment.

An undesirable feature of sewage sludge in terms of their disposal is high water content, which directly translates into a significant volume of sewage sludge. A large content of water in sewage sludge significantly increases the costs of disposal, thus leading to problems with transport. For this reason, one of the most important, most expensive and least explored stages of sewage sludge treatment is dewatering [9]. Nevertheless, well-designed and properly operated drainage equipment such as presses and centrifuges does not ensure the required effectiveness of reducing water content without additional modification of sewage sludge. Poor dewaterability of raw sludge results from the specific structure and physicochemical characteristics of this type of sludge. According to Cyplik-Piotrowska and Czarnecki [10], sewage sludge forms a stable colloidal system in which the gelatinous aggregates of particles occur in the form of a gel with high elasticity. Sewage sludge dewatering results in its greater compressibility and, consequently, in lower capability of release of sludge liquor. Mowla et al. [11] enumerated the presence of extracellular polymeric substances (EPS) among the main causes of poor sewage sludge dewaterability. Extracellular polymeric substances, mainly composed of lipids and nucleic acids, are capable of absorbing organic matter from wastewater. The presence of EPSs in sewage sludge generates repulsive forces between particles, formation of a stable gel structure, and increased viscosity. Studies published by various researchers [11-13] have shown that the presence of extracellular polymeric substances in sewage sludge has a negative effect on sludge susceptibility to flocculation, thickening and dewatering. Another cause of poor dewaterability is the presence of water bound in the sewage sludge. Research by Wang et al. [14] and Chu et al. [15] also showed that in the sewage sludge characterized by high water content, binding forces are relatively low and, consequently, ca. 20% of water can be easily removed. The decrease in water content in sewage sludge to ca. 80% is associated with the supply of additional energy capable of destroying the binding forces that cannot be supplied by conventional dewatering equipment. The limiting factor is also the size of the sludge particles [16]. Fine sludge particles clog the channels through which water could be removed. The solution that determines intensification of sludge dewatering is offered by flocculation, which ensures the agglomeration of fine particles into larger flocks.

Improved dewatering efficiency can be obtained by modification of the structure of sewage sludge using various conditioning substances. Extensive research has led to the development of sewage sludge conditioning methods. The introduction of the sludge conditioning process as a pre-dewatering stage helps separate sludge into the solid and liquid phases and reduces forces that bind water to the surfaces of solids, leading to higher efficiency of water removal [17]. Sewage sludge conditioning process is performed by means of various methods that determine final dewatering efficiency. Chemical conditioning using organic flocculants is commonly used in sewage treatment plants. Drawbacks of the method include high operating costs of the treatment plant associated with the purchase of polyelectrolyte and high doses of polyelectrolyte required to achieve the expected results [18].

To meet the demands of the circular economy, the initiatives have been started in recent years to replace chemical substances for conditioning of sewage sludge with other materials that would be beneficial from the standpoint of environmental protection. Examples include laboratory tests of the potential for improving sewage sludge dewaterability using different waste fractions. The substances that have been used at the stage of laboratory tests of the process of physical conditioning of sewage sludge include fly ash from combustion of various fuels, cement dust, gypsum, charcoal, wood chips, rice husks and bran, and sugar cane pulp [19-25]. The application of waste to sewage sludge results in improved permeability and increased strength of flocks. The opportunities for recycling of various materials during sludge treatment processes also reduces the amount of waste generated, thus contributing to the promotion of the principles of the circular economy.

Ashes represent a fuel combustion by-product, captured from the exhaust stream by means of the removal equipment (fly ash) or falling to the bottom of the combustion chamber and discharged to the outside (bottom ash). The interest in the application of ashes in the processes of intensification of sludge dewatering results mainly from their large specific surface area, substantial pore volume and high adsorption capacity [26, 27]. Furthermore, ashes are readily available, especially in industrial areas. According to Wójcik et al. [28], more than 15 million Mg of fuel combustion by-products are generated worldwide every year, of which only ca. 15% are recycled. The application of ashes to sewage sludge reduces the amount of sludge stored and represents an additional option of disposal, which ideally fits into the waste disposal hierarchy. The economic reasons resulting from the reduction of operating costs of sewage treatment plants related to the purchase of chemical reactants are also arguments for implementation of the method of physical conditioning of sewage sludge with fuel combustion by-products. According to Wang and Viraraghavan [29], replacing $FeCl_3$ with fly ash from coal combustion reduces the cost of sludge dewatering by over 70%. Furthermore, Stachowicz et al. [18] demonstrated that the replacement of cationic polyelectrolyte with ash from combustion of wood biomass in a combined heat and power plant resulted in a 90% reduction in financial expenditures for sewage sludge dewatering processes in a mechanical-biological wastewater treatment plant with capacity of ca. 2,000 m^3/d.

The economic and ecological aspects have caused that the opportunities for using ashes in sewage sludge dewatering technology attracted interest of many researchers. Kuglarz et al. [21] investigated the efficiency of dewatering of sewage sludge conditioned with ash from hard coal combustion. Furthermore, Chen et al. [20] analysed the methods to improve sewage sludge dewaterability using fly ash from combustion of coal modified with sulfuric(VI) acid. The potential of the use of fuel combustion by-products, including those from biomass combustion, is important to the sludge economy due to the fact that the amount of biomass consumed in the power industry is gradually increasing year by year. The literature review shows that the consumption of biomass in brown coal-fired and hard coal-fired power plants in 2013 was 3 751 612 and 42 917 011 GJ, respectively [30]. The purpose of the present study is to indicate the potential of the use of ashes from co-combustion of hard coal and biomass to intensify sewage sludge dewatering. The study also examined the effect of ash conditioning on the change of water content, the specific resistance to filtration and compressibility factor of sewage sludge. The use of ashes in dewatering fits perfectly into the idea of the circular economy, constituting an unconventional solution for sewage sludge management.

1. Material and methods

Laboratory tests of dewatering efficiency were performed using a stabilized and thickened secondary sludge collected from a gravity sludge thickener in the mechanical and biological wastewater treatment plant in Świlcza-Kamyszyn in the Podkarpackie Voivodship in Poland with a capacity of 1940 m^3/d. Parameters of sewage sludge are presented in Table 1.

The process of physical conditioning of sewage sludge was performed using ash from co-combustion of hard coal and wood biomass in a domestic central heating boiler at mass ratio of 70% coal and 30% biomass. The analysis of chemical composition of ash was made by means of X-ray fluorescence (XRF) analysis using the

Axios Max (Malvern Panalytical, USA) spectrometer according to ISO 29581-2:2010 [31] and ISO 12677:2011 [32]. The morphological analysis of ash from co-combustion of coal and biomass was conducted using scanning electron microscopy by means of a SEM scanning microscope (S-3400N, HITACHI, Japan).

Table 1. **Physico-chemical characteristics of sewage sludge used in laboratory tests**

Parameter	Unit	Mean value
colour	–	brown-grey
smell	–	earthy
pH	–	6.72 ±0.20
dry mass	%	2.06 ±0.72
DOM	% DM	41.16 ±1.94
water content	%	97.94 ±0.72
capillary suction time	s	146.82 ±10.01

The methodology of examinations of sewage sludge conditioning and dewatering was developed according to the generally accepted procedure. All the tests were performed in triplicate according to the following procedure. Five laboratory beakers with capacity of 1,000 cm^3 were filled with raw sewage sludge to the level of 500 cm^3. Ash from co-combustion of coal and biomass was applied to four samples with the following quantities: 5, 7.5, 15 and 30 g/dm^3. Material doses were determined based on a literature study [20, 24, 25] using the mass ratio of ash to dry matter content of sewage sludge, amounting to ca. 1:4, 1:3, 1:1 and 1,5:1. Sewage sludge with applied ashes and a sample of raw sewage sludge were quickly mixed in a flocculator (Flokulator SW6, Stuart, Great Britain) at a rate of 200 rpm (G = 20.94 1/s, F = 3.33 Hz) for one minute, and next slowly mixed for 15 minutes at 15 rpm (G = 5.24 1/s, F = 0.83 Hz). The effect of conditioning with ash from co-combustion of coal and biomass on the capability of sewage sludge to release water was measured by means of a qualitative method of capillary suction time test (CST) according to PN-EN 14701-1:2007 [33] using a ProLabTech (Poland) meter. The change in the pH value of sewage sludge after ash conditioning process was determined by means of the potentiometric method in accordance with PN-EN 15933: 2013-02 [34] by means of the HQ40d pH meter (HACH, Poland).

At the next stage of research, sewage sludge conditioned with ash from co-combustion of coal and biomass was filtrated in a vacuum at two vacuum pressure values, i.e. 0.01 and 0.02 MPa. This process allowed for determination of final water content of the sludge cake, specific resistance to filtration, and compressibility factor. After setting the desired vacuum pressure, 50 cm^3 of well mixed sludge was introduced into the Buchner funnel with the filter fabric. The process was performed until the sludge cake cracked. The samples were obtained from the post-filtration process and their water content was determined using the gravimetric method in accordance with PN-EN 15934:2013-02 [35]. The water content in the sludge cake was calculated from the formula (1):

$$U = \frac{m_s}{m_u} \cdot 100\% \qquad (1)$$

where:
m_s - sludge mass after drying, g,
m_u - mass of dewatered sludge, g.

Specific resistance to filtration (SRF) was determined based on PN-EN 14701-2: 2013-07 [36] and calculated from the formula (2). Compressibility factor (S) was determined from the formula (3):

$$SRF = \frac{2 \cdot p \cdot b_f \cdot A}{\mu \cdot c} \qquad (2)$$

where:
SRF - specific resistance to filtration, m/kg,
p - filtration pressure, Pa,
b_f - filtration constant, s/m^6,
A - filtration area, m^2,
μ - filtrate viscosity, Pa·s,
c - the amount of sludge per unit of filtrate volume, kg/m^3

$$c = \frac{1}{\frac{U_p}{(100 - U_k)} - \frac{U_k}{(100 - U_k)}}$$

where:
U_p - sludge water content before filtration, %,
U_k - sludge water content after filtration, %.

$$S = \frac{\log(SRF_1) - \log(SRF_2)}{\log(p_1) - \log(p_2)} \qquad (3)$$

where:
S - compressibility factor, –,
SRF_1 - specific resistance of the sludge at pressure p_1, m/kg,
SRF_2 - specific resistance of the sludge at pressure p_2, m/kg,
p_1 - negative pressure of 0.01 MPa,
p_2 - negative pressure of 0.02 MPa.

The dependence of filtrate volume on filtration time and final filtrate volume were also measured for sewage sludge after the vacuum filtration process. The evaluation of the effect of ash from co-combustion of coal and biomass on intensification of dewatering was performed by comparison of the results with the those obtained for non-conditioned sewage sludge.

2. Results and discussion

Chemical composition of ash from co-combustion of coal and biomass determined using the X-ray fluorescence (XRF) method is presented in Table 2. Studies have shown that the dominant components of ash calculated for oxides were: Al_2O_3, SiO_2 and CaO, which accounted for a total of ca. 79% of the total content of oxides contained in the material. The high content of aluminium and silicon(IV) oxides results from a significant content of carbon in the fuel burned. Furthermore, a high calcium content is caused by the presence of biomass in the fuel. Smaller contents in the ash were found for SO_3, Na_2O and MgO. The analysis of chemical composition of the waste reveals that it can be categorized as silicate-carbonate ashes with acid reaction (Ca:S ratio < 2.5).

Table 2. **Chemical composition of ash from coal and biomass co-combustion**

Oxide	Value, %
Al_2O_3	28.08
SiO_2	25.90
CaO	12.35
Fe_2O_3	11.86
SO_3	9.68
Na_2O	4.23
MgO	3.58
TiO_2	2.21
K_2O	1.04
MnO	0.44
P_2O_5	0.31
BaO	0.04
NiO	0.03
ZnO	0.03
PbO	0.03
CuO	0.02
other	< 0.02

SEM images of ash from co-combustion of coal and biomass at various magnifications are shown in Figure 1. Morphological analysis showed the differences in the material in terms of particle size and morphology. Co-combustion of coal and biomass was dominated by porous, multi-wall and irregular particles with sharp edges. The presence of grains with a spongy structure and particles with rounded edges was also found.

Capillary suction time (CST) was used as one of the indicators to evaluate the effectiveness of ash as a sludge conditioning agent. The effect of physical conditioning of sewage sludge using ash from co-combustion of coal and biomass on

CST is presented in Figure 2. Analysis of the results of the CST test showed that the application of ash from co-combustion of coal and biomass to sewage sludge improved its dewaterability. The sample of non-conditioned sewage sludge was characterized by mean CST value of 147 s, with the parameter showing a downward tendency for the increasing ash doses. The lowest content of ash had an insignificant effect on reducing the CST value. Addition of ash with the content of 5 g/dm^3 allowed for the reduction in this indicator by ca. 8% to 136 s. The most favourable result was obtained in the case of the ash dose of 30 g/dm^3, which reduced CST by over 75% to ca. 34 s.

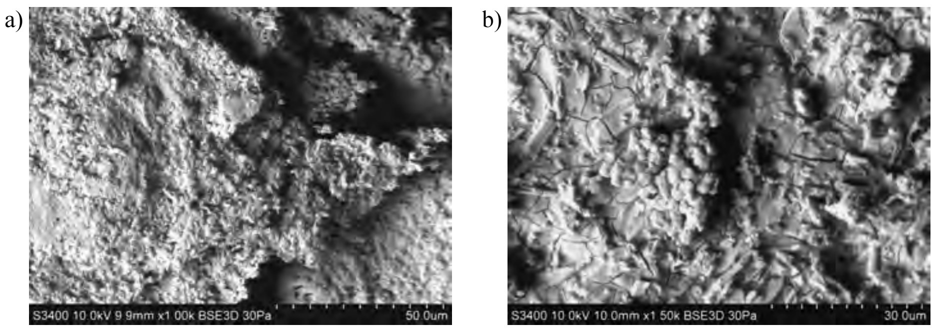

Fig. 1. SEM images of ash from coal and biomass co-combustion at two magnifications: 1000x (a) and 1500x (b)

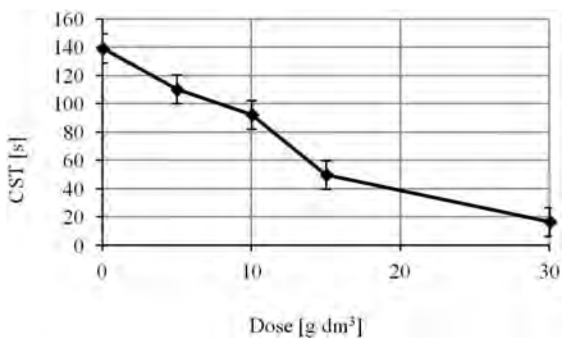

Fig. 2. Effect of sewage sludge conditioning with ash from coal and biomass co-combustion on CST

The effects of even small ash doses on CST of sewage sludge have been demonstrated in previous studies. Kuglarz et al. [21] documented over a 20% decrease in CST value for secondary sewage sludge conditioned with fly ash from hard coal combustion with the dose of ca. 1.7 g/dm^3. These results confirm the effectiveness of even low doses of ashes as structure-forming substances. Furthermore, Wójcik et al. [24, 25] found a nearly 90% decline in the CST value for sewage sludge conditioned with ash from combustion of various types of biomass. The decrease in CST values of conditioned sewage sludge results from changes in sludge structure. Zall et al. [37] and Benitez et al. [38] showed that the addition of fly ash as a structure-forming substance in the sewage sludge conditioning process improves the permeability and strength of the flocks.

Addition of combustion by-products due to intervention in the sewage sludge structure led to changes in water content in sewage sludge as early as at the conditioning stage (Fig. 3). Raw sewage sludge used in laboratory tests was characterized by mean water content of ca. 98%, with application of ashes resulting in reduction of water content in sewage sludge with increasing ash dose. For the highest dose of ash applied, the decrease in water content following the the conditioning stage slightly exceeded 3%. According to Grąz et al. [39], the reduction in water content in sewage sludge may have been caused by ash hydration capacity. However, no proportionality was found between the ash dose and the decrease in water content in sewage sludge after the conditioning process.

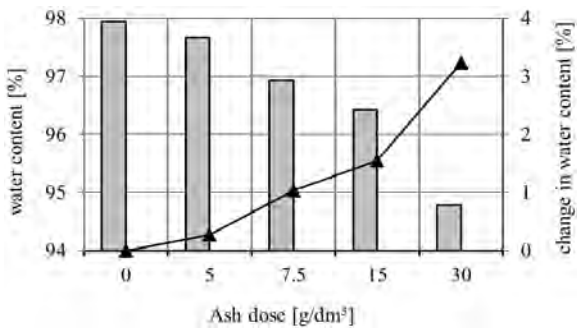

Fig. 3. Effect of ash from coal and biomass co-combustion on water content in sewage sludge after conditioning with ash

The results obtained at the stage of laboratory tests showed that the application of ashes from co-combustion of coal and biomass as a conditioning method improved efficiency of the vacuum filtration process. Addition of ashes as conditioning agents to sewage sludge leads to changes in final water content compared to non-conditioned sludge. Raw sewage sludge used for laboratory tests was characterized by a mean value of water content of ca. 88%, while addition of ash from co-combustion of coal and biomass caused a reduction in water content in sewage sludge. Depending on the dose of ash used and the value of vacuum pressure, different values were obtained for water content and, consequently, dry matter of sewage sludge (Fig. 4). The smallest dose of ash used (5 g/dm^3) led to the reduction in water content in sewage sludge after vacuum filtration by ca. 15% (0.01 MPa) and 17% (0.02 MPa). However, the best results of vacuum filtration were achieved by applying an ash dose of 30 g/dm^3. Consequently, the mean decrease in water content was 26 and 34% for the vacuum pressures of 0.01 and 0.02 MPa, respectively. Similar results in terms of the reduction in water content in sewage sludge were obtained in the research by Chen et al. [20], who used fly ash from coal combustion. Wójcik et al. [24] demonstrated that by applying ash from combustion of Salix viminalis willow to sewage sludge, water content in sewage sludge after vacuum filtration can be reduced by ca. 23%. Furthermore, in other studies by

Wójcik et al. [25], the researchers obtained a 25% decrease in water content after vacuum filtration after prior conditioning with ash from combustion of wood biomass generated in the combined heat and power plant. Compared to the application of ash from the combustion of pure biomass, by-products of co-combustion of coal and wood biomass allowed for intensification of sludge dewatering to a greater extent.

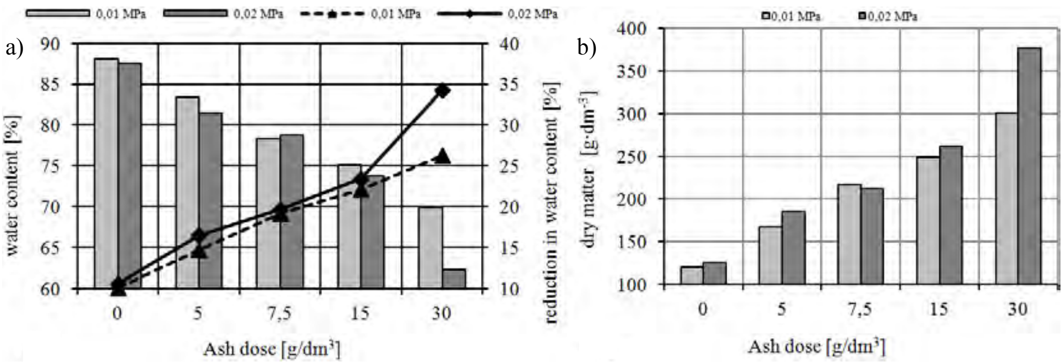

Fig. 4. Effect of ash from coal and biomass co-combustion on water content (a) and dry matter (b) in sewage sludge after vacuum filtration at the vacuum pressure of 0.01 and 0.02 MPa

In order to fully evaluate the effects of ashes from co-combustion of coal and biomass on intensification of the dewatering process, specific resistance to filtration and compressibility factor were also analysed (Fig. 5). Physical conditioning of sewage sludge with ash led to the reduction of specific resistance to filtration (SRF) compared to raw sewage sludge. Non-conditioned sewage sludge showed poor filtration properties, as evidenced by the high SRF values. With the increasing doses of ash, this parameter was reducing, and the largest changes in specific resistance to filtration were recorded for sewage sludge conditioned with the highest doses. The application of 30 g/dm^3 of ash resulted in a reduction of the specific resistance to filtration by approximately 80% (0.01 MPa) and 83% (0.02 MPa) compared to SRF for raw sludge. The impact of sewage sludge conditioning on the improvement of sludge dewaterability measured by the drop in SRF has been also documented in previous studies. Chen et al. [20] analysed sewage sludge conditioned with fly ash from hard coal combustion, and, for the dose of about 100 g/dm^3, obtained over a 75% reduction in specific resistance to filtration. Furthermore, Wu et al. [40] added ash from combustion of rice husks with the dose of 7 g/dm^3 to sewage sludge and reached ca. 45% drop in SRF.

Analysis of the results obtained for the compressibility factor of sewage sludge revealed that the value of the above-mentioned sludge index showed a downward tendency as the dose of applied ash increased. Conditioning of sewage sludge using the lowest experimental ash doses (5 g/dm^3) resulted in a nearly 40% reduction in the compressibility factor. Further increasing the dose of ash applied to the sludge led to the decrease in the value of this indicator, with this decline no longer as significant as between raw sewage sludge and conditioned sewage sludge at the lowest dose. Conditioning with the highest ash dose, i.e. 30 g/dm^3, allowed for the reduction in the value of sludge compressibility ratio by about 44%. The effect of ash application on the value of compressibility factor for sewage sludge has also been demonstrated in previous studies. Kowalczyk and Kamizela [41], who added ash from hard coal combustion with the dose of 44 g/dm^3, obtained even a five-time reduction in compressibility factor. This confirms the effect of structure-forming additives on the reduction of compressibility of sewage sludge.

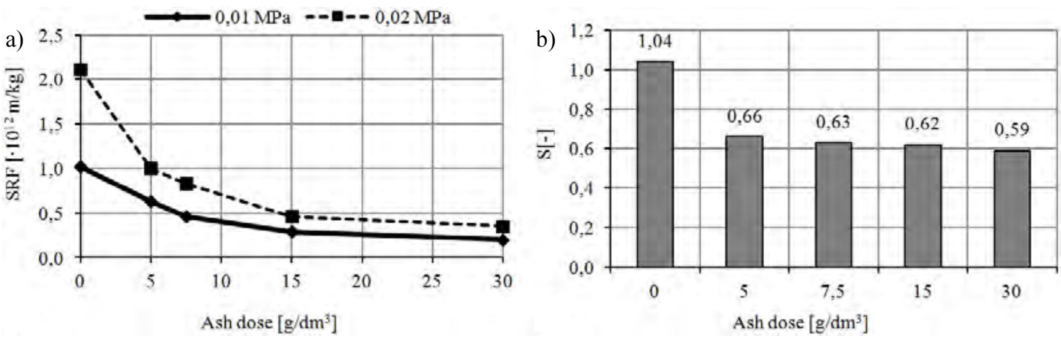

Fig. 5. Effect of ash from coal and biomass co-combustion on the specific resistance to filtration (a) and compressibility factor (b) of sewage sludge

The study analysed changes in filtrate volume (Fig. 6) over time and final amount of filtrate obtained after 15 minutes of filtration (Fig. 7). Despite the above effects of physical conditioning using ash from co-combustion of coal and biomass to reduce water content and specific resistance to filtration, no significant increase in the volume of the obtained filtrate was found. The amount of filtrate from vacuum filtration of raw sewage sludge was 41.5 and 42.0 cm^3 for the vacuum values of 0.01 and 0.02 MPa, respectively. Furthermore, the addition of ash with the highest test dose led to the increase in filtrate volume by only 1 to 3%, to the value of 45.5 cm^3 (0.01 MPa) and 48.0 cm^3 (0.02 MPa). A similar effect of waste application on the amount of sludge liquor was demonstrated in the study by Lee et al. [22, 23] and Lin et al. [42]. The above phenomenon is caused by binding of free water by ash particles. This is confirmed by the lack of significant proportionality between the increase in the dusty material dose and its effect on final filtrate volume.

However, analysis of the change in filtrate output over time revealed that ash conditioning intensifies the process of sludge dewatering. For sludge modified with ash, filtration occurred faster and with higher intensity. For example, a time of ca. 10 s was needed to obtain 10 cm^3 of filtrate for raw sewage sludge. For sewage sludge conditioned with ashes at a dose of 30 g/dm^3, this time was reduced to ca. 1 s. This results from increased sludge permeability after using structure-forming agents.

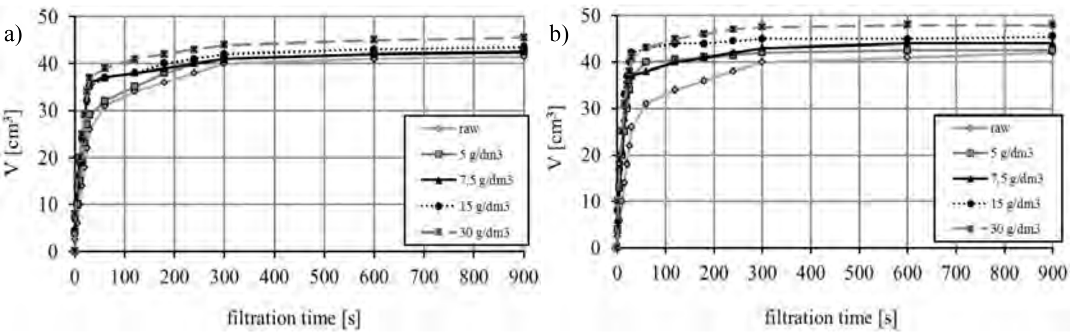

Fig. 6. Effect of ash from coal and biomass co-combustion on the change of filtrate volume for a vacuum pressures of 0.01 (a) and 0.02 (b) MPa

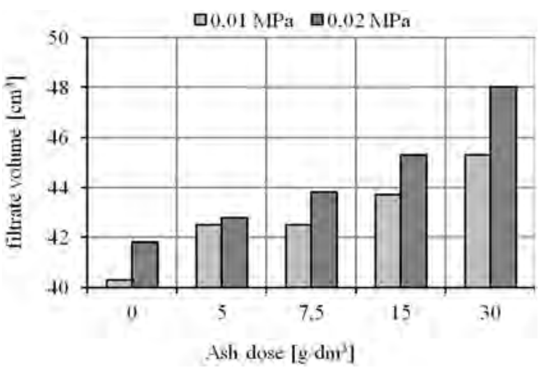

Fig. 7. Effect of ash from coal and biomass co-combustion on filtrate volume after 15 minutes of vacuum filtration

The results confirmed the effectiveness of sewage sludge conditioning with ash from co-combustion of coal and biomass. However, the achievement of satisfactory dehydration effects requires in most cases the use of high doses of conditioning substances, which results in an increase in the mass of generated sewage sludge [43]. The increase in sewage sludge mass after physical conditioning with high ash doses results in increased costs of transport and final sludge disposal. For this reason, the choice of an optimal method of sewage sludge conditioning should be made based on a previous detailed profitability analysis.

Conclusions

With specific physicochemical properties, ashes from co-combustion of coal and biomass can be used in sewage sludge management, which was demonstrated and discussed in the present paper. The examinations showed that the application of by-products of coal and biomass combustion leads to intensification of sewage sludge dewatering, as evidenced by the decrease in capillary suction time and specific resistance to filtration.

The results of laboratory tests performed in the study lead to the following conclusions:

1. Conditioning of sewage sludge with ash from co-combustion of coal and biomass contributes to the improvement of sewage sludge dewaterability expressed by the CST value. As the dose of the material applied increased, the value of this indicator declined. The best effects were achieved for the highest amount of ash, i.e. 30 g/dm^3, which yielded a value by ca. 75% lower compared to CST for the non-conditioned sewage sludge.
2. With addition of ash from co-combustion of coal and biomass, initial water content of conditioned sewage sludge was reduced. In the case of application of ash with the dose of 30 g/dm^3, water content in sewage sludge decreased by ca. 3% on average. This resulted from ash capacity to bind water.
3. After vacuum filtration, addition of ash from co-combustion of coal and biomass to sewage sludge results in a reduction of water content compared to raw sewage sludge. Increased reduction in water content in sewage sludge was observed for higher contents of the dusty material. For the highest ash dose, the lowest final water content was reached, equal to ca. 70% for the vacuum pressure of 0.01 MPa and about 62% for 0.02 MPa. These values were by ca. 26 and 34% lower compared to raw sewage sludge.
4. Physical conditioning with ashes reduced the specific resistance to filtration and compressibility factor. As the dose of applied ash increased, sewage sludge indicators showed a downward tendency. For sewage sludge conditioned with the highest ash dose, specific resistance to filtration and compressibility factor decreased by ca. 84 and 40%, respectively.
5. Conditioning of sewage sludge with ash from co-combustion of coal and biomass resulted in an increase in volume of filtrate after vacuum filtration. With initial conditioning, sludge filtration process was also faster and characterized by higher intensity. However, there were no noticeable relationships between the decrease in water content and the amount of released filtrate, which resulted from the capacity of ash particles to bind part of free water contained in sewage sludge.
6. However, the use of high ash doses during the conditioning process is likely to increase the mass of generated sludge. This results in higher costs of transport and disposal of sewage sludge. Implementation of physical conditioning methods as a pre-dewatering stage requires a preliminary profitability analysis.
7. Application of sewage sludge conditioning using ash from co-combustion of coal and biomass on an industrial scale requires taking into consideration the likely practical problems. The dewatering devices (presses, centrifuges) which are currently in use in wastewater treatment plants are not adapted to process sewage sludge conditioned with ash. Furthermore, ash dosing may accelerate wear of moving parts in pumps. For this reason, implementation of the method of physical conditioning sewage sludge with ash in a sewage treatment plant requires a detailed analysis of potential problems related to sewage sludge dewatering operation.

References

[1] Ustawa z dnia 14 grudnia 2012 r. o odpadach, Dz.U. 2013, poz. 21.

[2] Raport Głównego Urzędu Statystycznego Ochrona Środowiska 2017.

[3] Bank Danych Lokalnych. www.bdl.stat.gov.pl

[4] Rozporządzenie Ministra Środowiska z dnia 6 lutego 2015 r. w sprawie komunalnych osadów ściekowych, Dz.U. 2015, poz. 257.

[5] Wang J., Wang J., Application of radiation technology to sewage sludge processing: A review, Journal of Hazardous Materials 2007, 143, 2-7.

[6] Wójtowicz A., Modelowe rozwiązania w gospodarce osadowej. Izba Gospodarcza „Wodociągi Polskie", Bydgoski Dom Wydawniczy, Bydgoszcz 2013.

[7] Wójtowicz A., Kierunki rozwoju gospodarki osadowej. Gaz, Woda i Technika Sanitarna 2014, 4, 148-153.

[8] Bień J., Górski M., Gromiec M., Kacprzak M., Kamizela T., Kowalczyk M., Neczaj E., Pająk T., Wystalska K., Ekspertyza, która będzie stanowić materiał bazowy do opracowania strategii postępowania z komunalnymi osadami ściekowymi na lata 2014-2020, Częstochowa 2014.

[9] Bruus J.H., Nielsen P.H., Keiding K., On the stability of activated sludge flocs with implications to dewatering, Water Resources 1992, 26, 1597-1604.

[10] Cyplik-Piotrowska A., Czarnecki Z., Pomiar czasu ssania kapilarnego (CSK) jako metoda wyznaczania optymalnej dawki flokulantów do wspomagania procesu odwadniania komunalnego osadu ściekowego, Journal of Research and Applications in Agricultural Engineering 2005, 50(1), 21-23.

[11] Mowla D., Tran N.H., Allen D.G., A review of properties of biosludge and its revelance to enhanced dewatering processes, Biomass and Bioenergy 2013, 58, 365-378.

[12] Li X.Y., Yang S.F., Influence of loosely bound extracellular polymeric substances (EPS) on the flocculation, sedimentation and dewaterability of activated sludge, Water Research 2007, 41(5), 1022-1030.

[13] Zhang H., Lu X., Song L., Zhang L., Effects of loosely bound EPS release and floc reconstruction on sludge dewaterability, Water, Air & Soil Pollution 2018, 2229, 27. http://doi.org/10.1007/s11270-017-3683-z.

[14] Wang W., Lud Y., Qiao W., Possible solution for sludge dewatering in China, Frontiers of Environmental Science & Engineering in China 2010, 4(1), 102-107.

[15] Chu P.C., Lee D.J., Moisture distribution in sludge: effects of polymer conditioning, Journal of Environmental Engineering 1999, 125(14), 340-345.

[16] Skinner S.J., Studer L.J., Dixon D.R., Hillis P., Rees C., Wall R.C., Cavalida R.G., Usher S.P., Stickland A.D., Scales P.J., Quantification of wastewater sludge dewatering, Water Research 2015, 82(1), 2-13.

[17] Tuán P.A., Sewage sludge electro-dewatering, Acta Universitatis Lappeenrantaensis - Diss. Lappeenranta University of Technology, Lappeenranta 2011.

[18] Stachowicz F., Wójcik M., Trzepieciński T., The cost-effectiveness analysis of biomass ashes application in sewage sludge management, International Multidisciplinary Conference, 12^{th} edition, Bessenyei Publishing House, Nyiregyhaza 2017, 87-92.

[19] Albertson O.E., Kopper M., Fine-coal-aided centrifugal dewatering of waste activated sludge, Journal of Water Pollution Control Federation 1983, 55, 145-156.

[20] Chen C., Zhang P., Zeng G., Deng J., Zhou Y., Lu H., Sewage sludge conditioning with coal fly ash modified by sulfuric acid, Chemical Engineering Journal 2010, 158, 616-622.

[21] Kuglarz M., Bohdziewicz J., Przywara L., The influence of dual conditioning methods on sludge dewatering properties, Architecture Civil Engineering Environment 2008, 1 (3), 103-106.

[22] Lee D.Y., Jing S.R., Lin Y.F., Using seafood waste as sludge conditioners, Water Science Technology 2001, 44, 301-307.

[23] Lee D.Y., Lin Y.F., Jing S.R., Xu Z.J., Effects of agricultural waste on the sludge conditioning, Journal of the Chinese Institute of Engineers 2001, 11, 209-214.

[24] Wójcik M., Stachowicz F., Masłoń A., The application of biomass ashes for improvement of sewage sludge dewatering, E3S Web of Conferences 2017, 17, 1-8.

[25] Wójcik M., Stachowicz F., Masłoń A., The possibility of sewage sludge conditioning with the use of biomass ashes, Inżynieria i Ochrona Środowiska 2017, 20(2), 153-164.

[26] Vassilev S.V., Baxter D., Andersen L.K., Vassileva C.G., An overview of the composition and application of biomass ash. Part 1. Phase-mineral and chemical composition and classification, Fuel 2013, 105, 40-76.

[27] Vassilev S.V., Baxter D., Andersen L.K., Vassileva C.G., An overview of the composition and application of biomass ash. Part 2. Potential utilization, technological and ecological advantages and challenges, Fuel 2013, 105, 19-39.

[28] Wójcik M., Stachowicz F., Masłoń A., Możliwość wykorzystania popiołów lotnych w celu poprawy odwadniania osadów ściekowych, Czasopismo Inżynierii Lądowej, Środowiska i Architektury JCEEA 2017, 64(1), 377-393.

[29] Wang S., Virraraghavan T., Wastewater sludge conditioning by fly ash, Waste Management 1997, 17(7), 443-450.

[30] Uliasz-Bocheńczyk A., Pawluk A., Pyzalski M., Charakterystyka popiołów ze spalania biomasy w kotłach fluidalnych, Gospodarka Surowcami Mineralnymi 2016, 32, 149-162.

[31] ISO 29581-2:2010 Cement - Test methods - Part 2: Chemical analysis by X-ray fluorescence.

[32] ISO 12677:2011 Chemical analysis of refractory products by X-ray fluorescence (XRF) - Fused cast-bead method.

[33] PN-EN 14701-1:2007 Charakterystyka osadów ściekowych - Właściwości filtracyjne - Część 1: Czas ssania kapilarnego (CST).

[34] PN-EN 15933:2013-02 Osady ściekowe, uzdatnione bioodpady oraz gleba - Oznaczanie pH.

[35] PN-EN 15934:2013-02 Osady ściekowe, uzdatnione bioodpady, gleba oraz odpady - Oznaczanie suchej masy poprzez oznaczanie zawartości suchej pozostałości lub zawartości wody.

[36] PN-EN 14701-2:2013-07 Charakterystyka osadów ściekowych - Właściwości filtracyjne - Część 2: Oznaczanie oporu właściwego filtracji.

[37] Zall J., Galil N., Rebhun M., Skeleton builders for conditioning oily sludge, Journal of the Water Pollution Control Federation 1987, 59, 699-706.

[38] Benitez J., Rodriguez A., Suarez A., Optimisation technique for sewage sludge conditioning with polymer and skeleton builders, Water Research 1994, 28(10), 2067-2073.

[39] Grąz K., Gronba A., Białopiotrowicz T., Nowak J., Zawół K., Zastosowanie popiołów lotnych ze spalania węgla kamiennego w budownictwie, Innowacyjne rozwiązania i technologie w gospodarce komunalnej, Stalowa Wola 2015, 159-177.

[40] Wu Y., Zhang P., Zeng G., Liu J., Ye J., Zhang H., Fang W., Liu Y., Fang Y., Combined sludge conditioning of micro-disintegration, floc reconstruction and skeleton building ($KMnO_4$/$FeCl_3$/biochar) for enhancement of waste activated sludge dewaterability, Journal of the Taiwan Institute of Chemical Engineering 2017, 74, 121-128.

[41] Kowalczyk M., Kamizela T., Zmiana ściśliwości osadów ściekowych a wzrost efektywności ich odwadniania w procesie filtracji, Materiały Konferencji Naukowo-Technicznej, Częstochowa 2017.

[42] Lin Y.F., Jing S.R., Lee D.Y., Recycling of wood chips and wheat dregs for sludge processing, Bioresource Technology 2001, 76, 161-163.

[43] Shi Y., Yang J., Yu W., Zhang S., Liang S., Song J., Xu Q., Ye N., He S., Yang S., Hu J., Synergic conditioning of sewage sludge via Fe^{2+}/persulfate and skeleton builder: Effect on sludge characteristics and dewaterability, Chemical Engineering Journal 2015, 270, 572-581.

Streszczenie

Mankamentem osadów ściekowych pod kątem ich ostatecznej utylizacji jest wysoki stopień uwodnienia i związana z tym duża objętość odpadu. Z tego względu jednym z najważniejszych, ale zarazem jednym z najdroższych i najmniej poznanych etapów przeróbki osadów ściekowych jest proces odwadniania. Specyficzne właściwości fizykochemiczne surowego osadu ściekowego uniemożliwiają uzyskanie zadowalających efektów odwadniania bez wstępnej obróbki osadów ściekowych. Poprawę efektywności usuwania wody z osadów można uzyskać poprzez kondycjonowanie z użyciem różnych dostępnych technik. Powszechnie w oczyszczalniach ścieków stosuje się kondycjonowanie chemiczne, polegające na dozowaniu organicznych flokulantów. Aplikacja polielektrolitów do osadów w aspekcie poprawy ich odwadnialności generuje wysokie koszty eksploatacyjne w oczyszczalniach ścieków, wynoszące nawet kilka tysięcy złotych miesięcznie. Aspekty ekonomiczne doprowadziły do rozwoju badań nad intensyfikacją odwadniania osadów ściekowych z zastosowaniem różnych materiałów, w tym również produktów odpadowych. Kondycjonowanie osadów ściekowych z użyciem ubocznych produktów spalania paliw stanowi alternatywę dla powszechnie stosowanych metod wspomagania odwadnialności osadów. W pracy przedstawiono wpływ popiołu ze współspalania węgla kamiennego i biomasy roślinnej na efektywność procesu odwadniania osadów ściekowych. Omówiono wpływ aplikacji popiołu na wartość CSK, uwodnienie oraz opór właściwy filtracji. Analizie poddano również ilość uzyskanego filtratu po procesie odwadniania. Fizyczne kondycjonowanie osadów ściekowych z użyciem popiołu ze współspalania węgla i biomasy skutkowało obniżeniem CSK oraz uwodnienia osadów. Uzyskane rezultaty potwierdziły spadek wartości ww. parametrów po procesie kondycjonowania osadów popiołami. Odnotowano również zwiększenie ilości filtratu uzyskanego po procesie odwadniania. Na podstawie otrzymanych wyników stwierdzono, że aplikacja popiołów do osadów może stanowić niekonwencjonalną metodę kondycjonowania osadów ściekowych.

Słowa kluczowe: osady ściekowe, popioły, odwadnianie, kondycjonowanie, recykling, gospodarka osadami ściekowymi