Environment Protection Engineering

Vol. 45 2019 No. 4

DOI: 10.37190/epe190405

KAROL KRÓL[1], KRZYSZTOF ISKRA[2], WIESŁAW FERENS[1], JAN M. MIODOŃSKI[2]

TESTING PROPERTIES OF SEWAGE SLUDGE FOR ENERGY USE

The properties of sewage sludge in the context of their further energy use have been examined. For this purpose, 34 samples of sewage sludge from municipal sewage treatment plants from the area of Lower Silesia with a capacity higher than the 2000 population equivalent (PE) with separate sludge management were tested. As part of the study, tests were made to determine the technological usefulness of fuels and their elemental composition, i.e., technical analyses and elemental analyses. The obtained results show a large diversity of basic physicochemical properties of the tested sewage sludge. The share of volatile components important for energetic use ranged from 38.4 to 59.8 wt. %. The content of carbon (C) in the mass of tested sewage sludge ranged from 22.4 to 39.2 wt. %, which means that they have a lower content of elemental carbon compared to solid fuels. The higher heating value (*HHV*) of sewage sludge ranged from 9.3 to 17.4 MJ/kg dry mass.

1. INTRODUCTION

With ever-increasing water consumption, and therefore, the necessity to protect essential for life water resources, wastewater treatment plants (WWTP) have been progressively established to eliminate negative impacts of industrial and municipal wastewater (especially sewage from urban agglomerations) on the natural environment. Consequently, water reusing is achievable as a result of a series of treatments and uncomplicated processes [1, 2].

Consistent with the requirements of the European Union, on 1 January 2016, Poland introduced a legal standard [3] which imposed a ban on depositing on landfills for non-hazardous waste the substances which contain more than 8% of dry matter (DM) of organic materials, determined as 5% DM losses during calcination of total organic carbon as well as with the combustion heat above 6 MJ/kg DM. In practice, this excludes

[1]Wrocław University of Science and Technology, Chair of Energy Technologies, Turbines and Modelling of Thermal and Fluid Flow Processes, corresponding author K. Król, e-mail address: karol.krol@pwr.edu.pl

[2]The Institute of Environmental Protection, National Research Institute (IEP-NRI), Department of Wastewater Technology in Wrocław.

depositing on landfills all the wastes generated during wastewater treatment processes, even if they have been put through washing or biologically stabilized.

Currently, numerous activities are carried out to use WWTPs generated waste again [4]. The methods of sludge reuse include, among others, recovery in composting or biogas plants and waste thermal treatment. Taking into account restrictions in landfilling [3], the most advantageous method of WWTP waste disposal is burning. Thermal drying is a widely used method to evaporate water from wastewater residual solids with the use of heat. The method involves an uncomplicated technological process and is economically justified [5]. Among 27 EU Member States, sludge thermal drying is the most common method used in two countries, quite often used – in 12 countries, and hardly ever – in one country [6].

In most cases, the risks due to wastewater processing have been well recognized. The chemical factors include: heavy metals [7], volatile organic substances [8] and other organic compounds such as: polychlorinated biphenyls (PCBs) [9], dioxins – polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) [10], as well as polycyclic aromatic hydrocarbons (PAHs) [11]. As far as biological factors are concerned, there have been distinguished: bacteria, fungi, viruses, protozoa [7] and suspended in the air aerosols containing endotoxins [12]. In the case of thermal drying, i.e., removing water from a sample by drying at elevated temperature under normal or reduced pressure, there occurs a risk of forming explosive atmospheres (ATEX) by dust, which may lead to explosions [13]. All industrial plants where dust is present are exposed to this hazard, thus specific risk control activities should be undertaken to avoid accidents [14]. Dust generated during thermal drying of sewage sludge is a fuel product [15] and can cause an explosion as a result of a chemical reaction with oxygen [16].

Physical and chemical properties of sewage sludge differ depending on sampling points. A number of factors affect sewage sludge composition, including the city's urbanization level, the intensity and character of local industry and services, the presence/absence of agro-food processing or animal husbandry and the wastewater treatment technology used. For the most part, sewage sludge consists of organic matter and mineral substances [17]. About 75% of suspended solids and 40% of dissolved substances are of organic nature [18]. The characteristics of the examined sewage sludge sample depends on sludge type, and some parameters are contingent on seasonal/temporal variability and the collection site. Up to date studies [19, 20] have shown significant physical and chemical differences between the sewage sludge types and resultant effects on their combustion heat.

According to relevant guidelines [21], in order to fully determine sewage sludge properties and suitability for various processes, about 150 tests should be carried out, with different levels of validity and accuracy. However, not all chemical determinations are needed for a particular treatment process. The regulation of the Minister of the Environment [22] specifies a scope of research necessary to evaluate municipal sewage sludge and defines reference test methods. However, the chemical determinations listed in the regulation have no practical meaning for the preparation of thermal utilization of given sewage sludge and do not ensure trouble-free and high-efficiency operation of the power unit.

This paper presents the results of the study carried out with the aim to: (1) identify physical and chemical as well as fuel properties of sewage sludge materials, (2) determine correlations between sewage sludge various parameters (the content of elements, ash, organic matter and moisture), (3) examine the effects of individual components on the heat of combustion, and to (4) specify the possibility of the use of sewage sludge for energy purposes.

2. MATERIALS AND METHODS

The study was carried out on selected and then collected diversified research material, which comprised 34 sewage sludge samples. The material was collected from municipal WWTPs which adopted the solutions most commonly used in sewage sludge management in Poland. These include the sequence of sludge treatment processes: thickening + biological stabilization (aerobic or anaerobic) + mechanical dewatering. The present study focused on sludge material just from municipal WWTPs, like that from industrial facilities is subject to different legal requirements and usually utilized in company heat plants or incinerators.

Sewage sludge is a non-homogeneous material, showing differences in properties between individual samples taken from different locations. For the purpose of this study, the mean (representative) sample was prepared according to the Polish Standard PN-EN ISO 5667-15:2009 from wastewater treatment plants of Lower Silesia area. Once under laboratory conditions, the content of the containers with the samples collected were spread over a large area so as to obtain a thin layer of sewage sludge material for further analyses, which was afterwards dried out in a well-ventilated and well-lit room. After reaching the humidity equilibrium with the environment, the materials tested were ground using a Retsch laboratory mill intended for grinding fuels of different origin, to the size of grains below 200 μm. Then the tested material was stored in tightly closed containers.

The technical analysis comprised the determination of the content of moisture, ash, volatile matter and solid combustible parts. The elemental analysis (using an analizator LECO TruSpec Micro) was carried out to assess the content of the following elements: C, H, O, S, N. Additionally, the heat of combustion was determined. The technical analyses were carried out in accordance with the Polish Standards for solid fuels: PN-EN ISO 18134-3:2015-11 (determination of moisture content by gravimetric method), PN-EN ISO 18122:2016-01 (determination of ash content by gravimetric method), PN-ISO 1928:2002 (higher heating value and calculation of calorific value by calorimetric methods) and PN-EN ISO 18123:2016-01 (volatile matter content by the gravimetric method). The results refer to the analytical state, i.e., the state of fuel with moisture and ash content equivalent to that in a sample brought to the level of equilibrium with the surrounding atmosphere. Fixed carbon (FC) is the solid combustible residue that remains in fuel after volatile materials and ash are expelled. There were tested 200 μm fraction, i.e., polydispersed dust from sewage sludge processed in agreement with generally applied principles used for hard and brown coals, according to the norm PN-G-04502: 2014-11. FC contents was calculated with the use of the following the formula:

$$[\mathrm{FC}] = 100 - ([\mathrm{A}] + [\mathrm{M}] + [\mathrm{VM}]) \quad (1)$$

where: [FC] – fixed carbon content, wt. %, [A] – ash content, wt. %, [M] – moisture content, wt. %, [VM] – volatile matter content, wt. %.

The quotient of [FC] and [VM] is called the fuel ratio (*FR*). For the purpose of the present study, the *FR* value was calculated with the use of the following the formula:

$$FR = \frac{[\mathrm{FC}]}{[\mathrm{VM}]} \quad (2)$$

FR is used to classify coal varieties: anthracite – *FR* at least 10, semi-anthracite – *FR* 6–10, semi-bituminous – *FR* 3–6, bituminous – *FR* 3, and alternative fuels – *FR* 1 or less.

3. RESULTS AND DISCUSSION

The results of the technical and elemental analyses along with data on the higher heating value (*HHV*) of the studied 34 sludge samples (SS) are presented in Table 1. For comparison, Table 2 shows parameters for solid fuels. As shown in the tables, sewage sludge materials differ from other solid fuels in terms of the content of moisture [M], volatiles [VM] and ash [A]. They also have a different elementary composition when compared with solid fuels.

The results presented in Table 1 show large diversification in the basic physical and chemical properties of the examined materials. Analytical moisture content ranges from 7.2 wt. % (SS19) to 18.2 wt. % (SS22). The water content in sludge accumulated in the wastewater treatment process can considerably vary and reach up to 95%, which is important as the level of moisture can considerably affect combustion. Increased moisture content results in an additional amount of water vapor in the exhaust. This leads to an increase in the volume of exhaust gas per energy unit, which in turn, in the case of high water content, is associated with the need to build devices with appropriately larger volumes. The results obtained show that the higher heating value of sewage sludge decreases with increasing moisture content (Table 1). Too high moisture content in sewage sludge can, among others, impede ignition and decrease combustion temperature due to heat demand for water evaporation. Reduced combustion temperature affects the composition of combustion products and, as a result, hazardous emission levels [24].

Table 1

The results of analyses of sewage sludge samples

Sample	Technical analysis				*FR*	Elemental analysis					*HHV* [MJ/kg]
	[M]	[A]	[VM]	[FC]		[C]	[H]	[N]	[S]	[O]	
	[wt. %]					[wt. %]					
SS1	9.8	28.4	51.0	10.8	0.21	32.7	4.0	4.6	1.0	19.5	14.1
SS2	10.7	32.7	46.9	9.8	0.21	30.7	3.8	3.8	1.0	17.4	13.2
SS3	10.0	27.2	52.4	10.4	0.20	32.2	4.2	4.4	1.4	20.7	14.0
SS4	10.3	30.8	49.8	9.1	0.18	30.4	3.9	4.1	1.8	18.7	13.1
SS5	10.2	25.1	54.1	10.6	0.20	34.4	4.1	4.5	1.2	20.4	15.3
SS6	11.7	29.6	48.4	10.3	0.21	30.5	3.8	3.8	1.1	19.5	12.8
SS7	9.2	31.4	50.9	8.6	0.17	30.1	3.8	4.2	1.2	20.1	12.9
SS8	8.9	46.5	38.4	6.2	0.16	22.4	3.0	2.8	2.0	14.4	9.3
SS9	9.4	25.3	54.1	11.1	0.21	35.1	4.2	5.0	0.9	20.1	15.1
SS10	10.6	25.4	53.5	10.6	0.20	35.5	4.3	4.6	1.1	18.6	15.0
SS11	9.1	32.5	50.5	7.9	0.16	32.0	3.9	2.9	1.1	18.6	13.5
SS12	9.8	35.5	46.1	8.5	0.19	30.2	3.6	3.2	1.5	16.3	12.7
SS13	9.9	24.7	55.5	10.0	0.18	36.4	4.5	4.6	1.4	18.6	15.4
SS14	9.6	38.4	45.5	6.5	0.14	27.6	3.6	3.4	1.8	15.8	11.6
SS15	10.1	26.7	52.1	11.2	0.21	34.4	4.2	4.6	0.9	19.2	14.4
SS16	11.3	28.3	49.6	10.8	0.22	31.4	3.7	4.0	0.8	20.5	13.5
SS17	9.0	31.1	49.3	10.5	0.21	31.0	4.0	4.4	0.9	19.5	13.2
SS18	9.1	31.2	49.4	10.3	0.21	30.4	3.8	4.4	1.0	20.2	13.4
SS19	7.2	31.1	53.2	8.5	0.16	36.2	4.5	3.1	1.1	16.8	16.0
SS20	10.9	31.9	47.4	9.8	0.21	29.7	3.7	3.6	1.4	18.9	12.9
SS21	12.1	23.6	53.2	11.0	0.21	33.5	4.0	4.8	1.4	20.5	14.6
SS22	18.2	25.2	46.4	10.3	0.22	28.7	3.4	3.6	1.5	19.4	12.4
SS23	9.8	19.7	59.8	10.6	0.18	39.2	4.7	4.0	1.8	20.8	17.4
SS24	10.0	34.4	46.7	9.0	0.19	27.2	3.5	3.7	2.7	18.5	11.8
SS25	11.9	29.4	48.8	9.9	0.20	31.5	3.9	4.0	1.6	17.7	13.1
SS26	8.5	35.0	46.2	10.3	0.22	29.1	3.6	3.4	1.7	18.7	12.8
SS27	10.7	24.1	53.6	11.6	0.22	32.7	4.0	4.2	1.4	23.0	14.9
SS28	10.1	34.9	45.1	10.0	0.22	27.2	3.5	3.6	2.1	18.6	12.0
SS29	12.0	27.6	49.1	11.3	0.23	29.9	3.7	4.0	1.2	21.6	13.2
SS30	8.5	31.9	50.9	8.8	0.17	32.8	4.2	3.1	1.3	18.4	14.7
SS31	12.7	21.8	52.6	12.9	0.24	34.5	4.0	4.6	0.9	21.5	15.0
SS32	13.3	23.6	50.0	13.1	0.26	33.0	3.6	4.2	1.0	21.4	14.2
SS33	12.2	23.3	53.0	11.6	0.22	33.1	3.9	4.4	0.9	22.2	14.7
SS34	12.6	25.5	52.0	9.9	0.19	31.8	3.7	4.3	1.7	20.4	13.8
Min	7.2	19.7	38.4	6.2	0.14	22.4	3.0	2.8	0.8	14.4	9.3
Avg	10.6	29.2	50.2	10.1	0.20	31.7	3.9	4.0	1.3	19.3	13.7
Max	18.2	46.5	59.8	13.1	0.26	39.2	4.7	5.0	2.7	23	17.4

Table 2

The parameters of solid fuels [25, 31]

Fuel	Technical analysis				*FR*	Elemental analysis					*HHV* [MJ/kg]
	[M]	[A]	[VM]	[FC]		[C]	[H]	[N]	[S]	[O]	
	[wt. %]					[wt. %]					
Bituminous coal	2.0	17.3	26.9	53.8	2.00	65.4	3.7	1.3	1.2	9.1	27.8
Lignite	10.7	19.5	41.6	28.2	0.68	43.5	4.9	0.7	2.6	19.4	16.6
Biomass	2.8	2.9	76.2	18.0	0.24	47.7	5.7	0.4	0.0	40.4	18.9

The sewage sludge materials tested showed a high share of volatile matter (Table 1), characterized by large variation: from 38.4 wt. % (SS8) to 59.8 wt. % (SS23). The gases formed as a result of sewage sludge degassing are, likewise in the case of other fuels, light hydrocarbons, carbon monoxide and dioxide, hydrogen and water vapor. The proportions of individual components depend on the temperature at which the reaction takes place and on the rate of heating of the combusted material. Due to the high content of volatiles, sewage sludge can ignite at relatively low temperatures, i.e., at 470–600 °C [25]. Therefore, sewage sludge combustion proceeds quickly, and consequently, the process should be adequately supervised [24]. Figure 1 shows the dependence of the fixed carbon (FC) on the volatile matter (VM) content. The FR value is between 0.26 and 0.14. A linear correlation between [FC] and [VM] was detected.

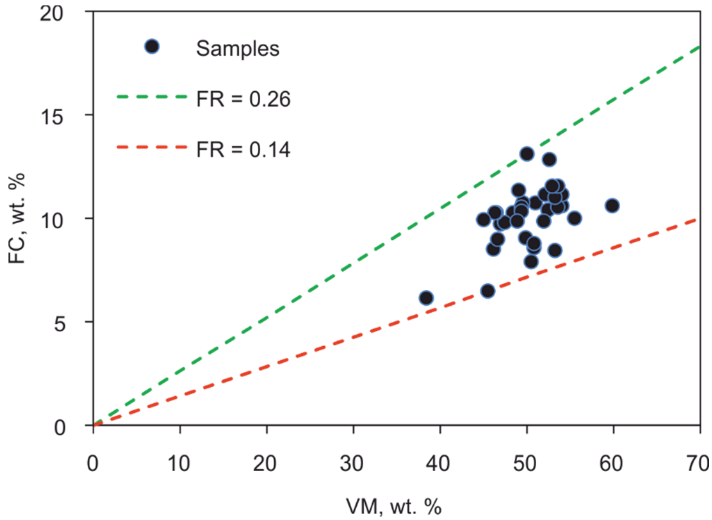

Fig. 1. Dependence of fixed carbon (FC) on the volatile matter (VM) content

The sewage sludge material tested was characterized by high and diversified ash content ranging from 19.7 wt. % (SS23) to 46.5 wt. % (SS8). Due to considerable mineral content, a sewage sludge burning installation should be equipped with an appropriately effective dust removal system. The high proportion of ash in fuel reduces its higher heating value. Ash has negative effects on the heating surfaces, as it increases their erosive wear and can cause the formation of slag and ash deposits [24, 26]. The analysis of the results obtained showed a linear correlation between the amount of volatile matter (VM) and ash (A) content. This correlation is shown in Fig. 2.

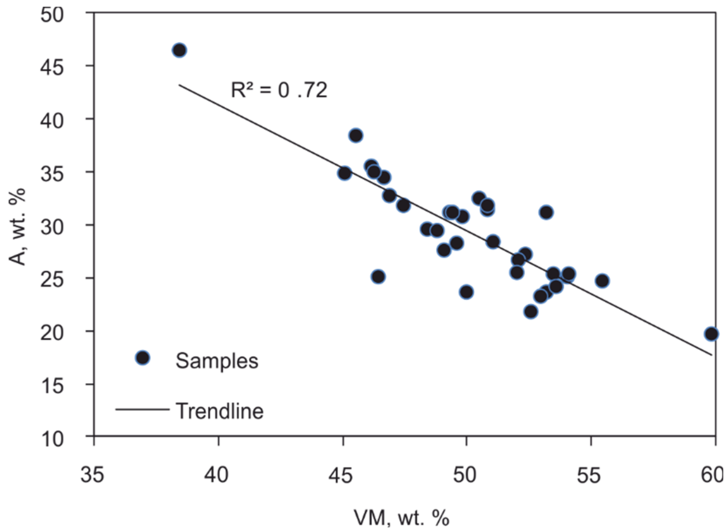

Fig. 2. Dependence of mineral substance (A) on volatile matter (VM) content

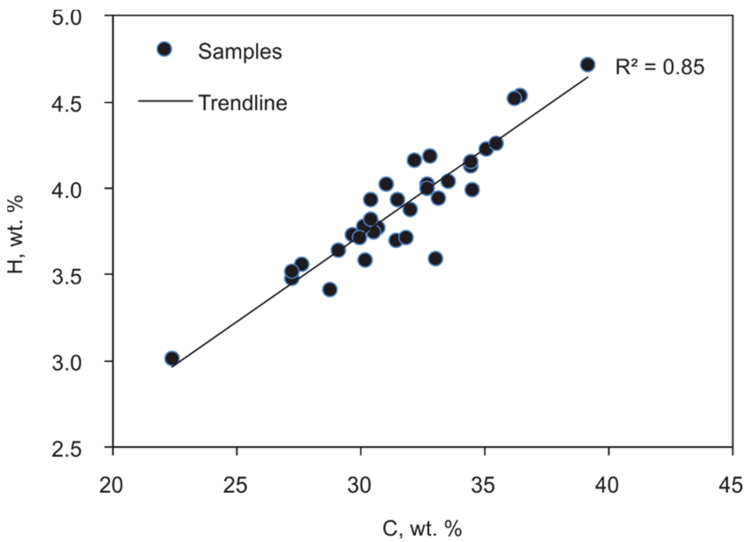

Fig. 3. Dependence of hydrogen (H) on elemental carbon (C) content

The elemental carbon (C) content in the material tested in the present study does not differ from the C content in sewage sludge reported in the literature [27]. In the examined sewage sludge, C content ranged from 22.4 wt. % (SS8) up to 39.2 wt. % (SS23). Figure 3 shows the linear correlation between hydrogen (H) and carbon (C) in content in the examined sludge.

The content of nitrogen and sulfur in the fuels determine their potential to pose risks related to emissions of nitrogen oxides and sulfur dioxide. The nitrogen content determined in the sewage sludge tested in the present study is comparable with the values given by other authors [28, 29]. The measured amount of nitrogen ranged from 2.8 wt. % (SS8) up to 5.0 wt. % (SS9). Sulfur content ranged from 0.8 wt. % (SS16) up to a maximum 2.8 wt. % (SS24, Table 1). Similar values for this type of waste are given in the available literature [28, 29].

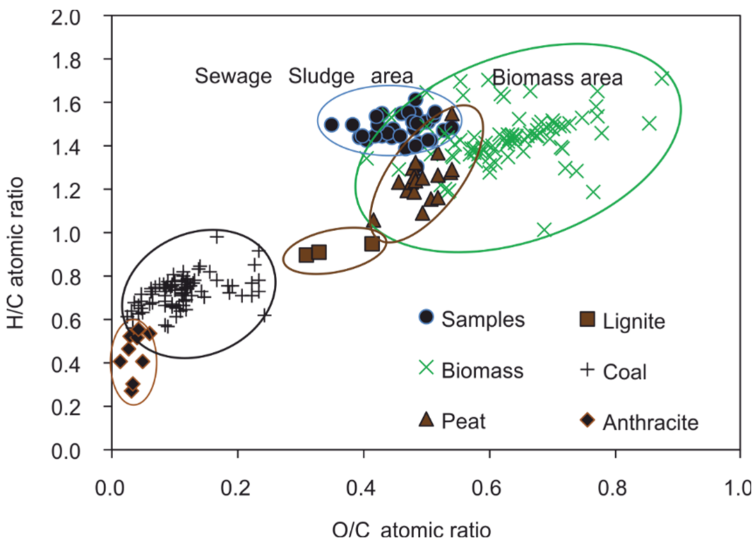

Fig. 4. van Krevelen diagram of various fuels based on [30] and tested sewage sludge

The properties of alternative fuels are very different from those of coals. The tested sewage sludge materials contained less elemental C when compared with anthracite and hard coals, thus H/C ratios in sewage sludge materials showed higher values. In addition, increased oxygen (O) content observed in sewage sludge examined led to higher O/C ratio and the lower heat of combustion when compared with carbon fuels (Fig. 4). The atomic ratio is a measure of the ratio of atoms of one kind to another kind. A closely related concept is the atomic per cent (or at.%), which gives the percentage of one kind of atom relative to the total number of atoms. The results presented in Fig. 4 confirm that the sewage sludge materials under investigation can be regarded biofuels, however, due to the increased content of mineral matter and moisture, this does not mean that sewage sludge has similar properties to those of biomass.

As part of the conducted study, there were compared sewage sludge fuel properties (inside a relevant fuel group). There was also attempted to systematize sewage sludge in search of the correlations (Figs. 1–3) between the properties characteristic of the sewage sludge materials tested. The content of elemental carbon constitutes a very important component of sewage sludge materials, decisive of their technological usefulness. Figure 5 shows the dependence of the higher heating value (*HHV*) on the content of elemental carbon (C). With increasing C content, there increases energy from fuel combustion caused by enlarged available chemical energy in fuel mass unit [27, 31].

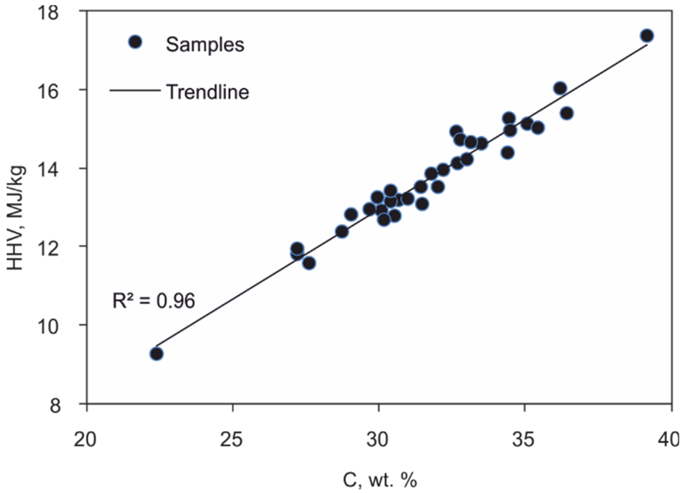

Fig. 5. Dependence of the higher heating value (*HHV*) on the elemental carbon (C) content

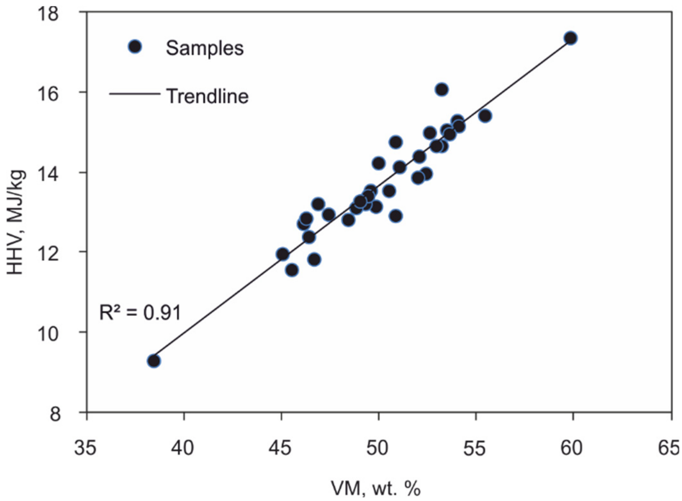

Fig. 6. Dependence of the higher heating value (*HHV*) of the volatile matter (VM) content

Figures 3 and 5 show that with increasing carbon (C) and hydrogen (H) content, there increases the higher heating value of the sewage sludge investigated. Due to the fact that the heat of combustion of fuels depends on the flammable components H and C, the increased content of these elements cause an increase in the energy released during combustion [31].

Figure 6 shows the correlation between the content of volatiles (VM) and the higher heating values (*HHV*). Sewage sludge *HHV*s increase proportionally with the increase of VM content. Consistent with Fig. 2, [VM] is inversely proportional to those of ash (A). At the same time, VM amounts are proportional to those of the solid combustible flammable residue (FC) (Fig. 1), therefore an increase in volatile content entails an increase in flammable residue amounts, which increases the heat of combustion [24–26].

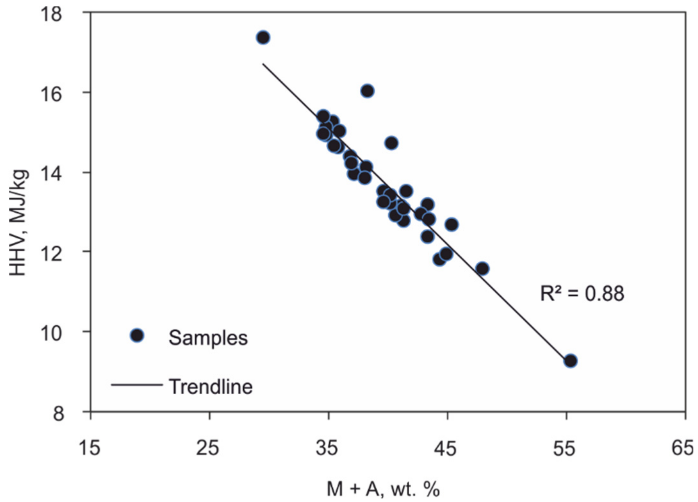

Fig. 7. Dependence of the higher heating value (*HHV*) on the moisture content with mineral substance content [M] +[A])

Figure 7 shows the correlation between the moisture and mineral content and the higher heating value. The increase in the amount of ballast in fuel (moisture M + ash A) reduces the share of combustible fraction, so the observed dependence is in line with expectations. Figures 6 and 7 show a strong dependence of higher heating value (*HHV*) on the available quantity of combustible parts. This indicates a similar composition (*HHV*) of the combustible substance of the tested sewage sludge samples. This is in line with the correlation shown in Figs. 2 and 6 because the increase in ballast in the form of M + A will result in a reduction of the available energy released during combustion [24, 26].

To sum up, Figures 1, 3, 5 and 6 show that with increasing combustible residue (FC), carbon (C), hydrogen (H) and volatile matter (VM) contents, there still occurs an increase in the higher heating value, while with the increase of moisture (M) and mineral substance (A) contents (Figs. 7 and 2), the higher heating value decreases.

Sewage sludge tests showed similar content and a strong correlation between hydrogen and carbon content. To determine higher heating value, a formula was used that estimates the *HHV* value based on combustible elements such as C, H, S and fuel ballast in the form of elementary oxygen (O). For the purpose of the present study, Mendeelev formula was used (for solid fuels in the analytical state):

$$HHV = 339.15[\mathrm{C}] + 1255.9[\mathrm{H}] + 108.9[\mathrm{S}] - 108.9[\mathrm{O}] \qquad (3)$$

The above formula is mainly used for fossil fuels, and especially for hard coal. Figure 8 shows the *HHV* of samples, calculated on the basis of Mendeleev formula using data from Table 1 compared to the *HHV* determined in accordance with the Polish Standard PN-ISO 1928:2002.

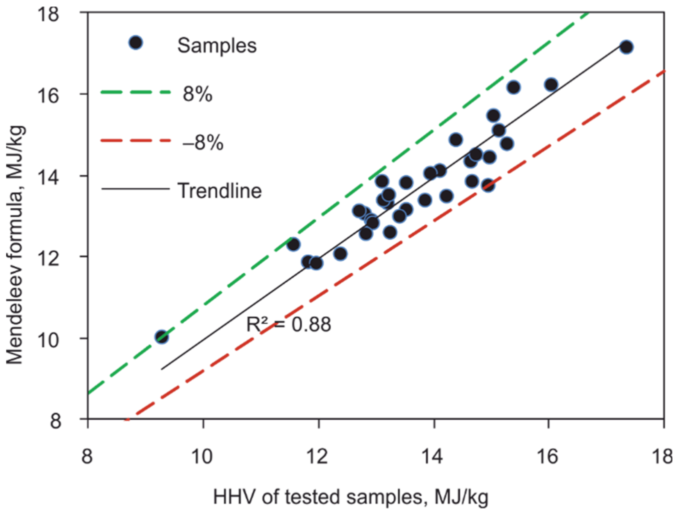

Fig. 8. *HHV* calculated with the use of Mendeleev formula
vs. *HHV* determined in accordance with the Standard PN-ISO 1928:2002

As a result of the simulation, it was found that in the case of the tested sewage sludge materials, the Mendeleev formula is applicable to calculate the *HHV*. It is, therefore, possible to determine the *HHV* just on the basis of the elemental analysis. The maximum uncertainty of determination is below 8% of the measurement value (Fig. 8).

4. CONCLUSIONS

The results of the analyses of municipal sewage sludge samples refer only to alternative fuels tested in the present study. Although the results of the simulation show high conformity, further research should be carried out to unambiguously answer the question on applicability of the Mendeleev formula to calculate the higher heating values of alternative fuels based on elemental analysis.

As shown in the present study, sewage sludge materials differ from other solid fuels in terms of the content of moisture, volatiles and ash. They also have a different elementary composition when compared with solid fuels, especially – with bituminous coal. However, sewage sludge can be a valuable complementary fuel that can be successfully co-combusted in the power industry. In the case of large and medium-sized cities, where the quality of sewage sludge is affected by industrial pollution, thus it may be insufficient when evaluated in line with agricultural or natural criteria, combustion or co-burning with energy recovery seems to be the best alternative among existing and allowed methods of sewage sludge utilization.

REFERENCES

[1] DAIGGER G.T., *Wastewater management in the 21st century*, J. Environ. Eng. – ASCE, 2007, 133, 671.
[2] DAIGGER G.T., *Evolving urban water and residuals management paradigms: water reclamation and reuse, decentralization, and resource recovery*, Water Environ. Res., 2009, 81, 809.
[3] Regulation of the Minister of Economy of 15 July 2015 on the acceptance of waste for landfilling, Dz.U. 2015, poz. 1277 (in Polish).
[4] BIXIO D., THOEYE C., DE KONING J., JOKSIMOVIC D., SAVIC D., WINTGENS T., MELIN T., *Wastewater reuse in Europe, Desalination*, 2006, 187, 89.
[5] SPINOSA L., VESILIND P.A., *Sludge into biosolids, processing disposal and utilization*, IWA Publishing, London 2001.
[6] KELESSIDIS A., STASINAKIS A.S., *Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries*, Waste Manage., 2012, 32, 1186.
[7] MULLOY K.B., *Sewage workers. Toxic hazards and health effects*, Occup. Med., 2001, 16, 23.
[8] KUSZMIDER G., KOLONKO I., SUSCHKA J., *Volatile organic compounds in municipal wastewater*, Arch. Environ. Prot., 1997, 23, 91 (in Polish).
[9] *Organic contaminants in sewage sludge for agricultural use*, European Commission, 2001.
[10] *Pollutants in urban wastewater and sewage sludge*, Final report, ICON, IC Consultants, Ltd., London 2001.
[11] JANOSZKA B., BODZEK D., BODZEK M., *Occurrence and determination of polycyclic aromatic hydrocarbons and their derivatives in selected sewage*, Arch. Environ. Prot., 1997, 23, 55 (in Polish).
[12] THORN J., BEIJER L., JONSSON T., RYLANDER R., *Measurement strategies for the determination of airborne bacterial endotoxin in sewage treatment plants*, Ann. Occup. Hyg., 2002, 46 (6), 549.
[13] JOSEPH G., *Combustible dusts. A serious industrial hazard*, J. Hazard. Mater., 2007, 142, 589.
[14] American Institute of Chemical Engineers, *Is sugar an explosion hazard?*, J. Fail. Anal. Prev., 2008, 8, 311.
[15] FODOR Z., KLEMEŠ J.J., *Waste as alternative fuel. Minimising emissions and effluents by advanced design*, Proc. Saf. Environ., 2012, 90, 263.
[16] ECKHOFF R.K., *Dust explosions in the process industries*, Butterworth–Heinemann, Oxford 2003.
[17] HARRISON E.Z., OAKES S.R., HYSELL M., HAY A., *Organic chemicals in sewage sludges*, Sci. Total Environ., 2006, 367, 481.
[18] TCHOBANOGLOUS G., BURTON F.I., STENSEL H.D., *Wastewater engineering. Treatment and reuse*, 4th Ed., McGraw-Hill, 2003.

[19] FUENTES M.J., FONT R., GÓMEZ-RICO M.F., MOLTÓ J., *Multivariant statistical analysis of PCDD/FS in sewage sludges from different areas of the Valencian Community (Spain)*, Chemosphere, 2007, 67, 1423.
[20] GARCÍA-DELGADO M., RODRÍGUEZ-CRUZ M., LORENZO L., ARIENZO M., SÁNCHEZ-MARTÍN M., *Seasonal and time variability of heavy metal content and of its chemical forms in sewage sludges from different wastewater treatment plants*, Sci. Total Environ., 2007, 382, 82.
[21] BIEŃ J.B., *Sewage sludge*, *Theory and Practice*, Wydawnictwo Politechniki Częstochowskiej, Częstochowa 2002 (in Polish).
[22] Regulation of the Minister of Environment of 6 February 2015 r. on municipal sewage sludge, Dz.U., 2015, poz. 257 (in Polish).
[23] Environmental Protection Inspection, *Physicochemical and biological reference methods for testing municipal sewage sludge*, Warsaw 2003 (in Polish).
[24] KHAN A.A., DE JONG W., JANSENS P.J., SPLIETHOFF H., *Biomass combustion in fluidized bed boilers. Potential problems and remedies*, Fuel Proc. Techn., 2009, 90, 21.
[25] RYBAK W., MOROŃ W., FERENS W., *Dust ignition characteristics of different coal ranks, biomass and solid waste*, Fuel, 2019, 237, 606.
[26] STELMACH S., WASIELEWSKI R., *Co-combustion of dried sewage sludge and coal in a pulverized coal boiler*, J. Mater. Cycles Waste Manage., 2008, 10, 110.
[27] WANG C.X., WANG X.H., JIANG X.D., LI F.Y., LEI Y.Y., LIN Q.Z., *The thermal behavior and kinetics of co-combustion between sewage sludge and wheat straw*, Fuel Proc. Techn., 2019, 189, 1.
[28] ZHANGLIANG H., FEI Q., HUI W., RUOYU L., DEZHI S., *Odor assessment of NH_3 and volatile sulfide compounds in a full-scale municipal sludge aerobic composting plant*, Biores. Techn., 2019, 282, 447.
[29] HEIN K.R.G., BEMTGEN J.M., *EU clean coal technology. Co-combustion of coal and biomass*, Fuel Proc. Techn., 1998, 54, 159.
[30] *IFRF solid fuel database*, http://www.ifrf.net/page/ research/solid- fuel- characterization
[31] HUPA M., KARLSTRÖM O., VAINIO E., *Biomass combustion technology development. It is all about chemical details*, Proc. the Combustion Institute, 2017, 36, 113.