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Study of chemical and physical properties of ash derived from oxy-combustion of sewage sludge and coal blend

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ABSTRACT

Ash materials produced during combustion may create several technical and environmental problems. In this work, bottom and fly ashes obtained from lab-scale circulating fluidized bed oxy-fuel combustion of the mixture of sewage sludge and coal were characterized. The slagging and fouling tendency was determined; studies on the chemical composition, including heavy metals, were carried out; the environmental impact and their potential uses were also assessed. The findings showed that the lowest sintering temperature in the oxidizing atmosphere is mainly characterized by ashes from sewage sludge combustion: the higher the share of coal in the blend mixture, the higher the ash sintering temperature. A similar tendency occurs for the temperature of softening of the ash. The analysis of particle size distribution of fly ash showed that after the combustion of municipal sewage sludge alone, the volume fraction of <10 mm was 32%, while for fuel blends it was less than 10%. The shift of particle size distribution of ash from sludge combustion to fine particles results in significant activity of oxygen atoms and increased particle loading, as confirmed by the study of the amount of unburned char in ash. The fly ash after oxygen combustion was characterized by a low degree of crystallinity. The main crystalline phases were crystalline silica – SiO_2, diiron trioxide – Fe_2O_3 and calcium sulfate – $CaSO_4$. The main components of fly ash and bottom ash were aluminum and silicon compounds.

Keywords: Ash; Oxy-combustion; Sewage sludge

1. Introduction

In recent years, water and sewage management has seen dynamic changes in Poland. This resulted directly from the provisions of Council Directive 91/271/EEC of May 21, 1991 concerning urban waste treatment and Council Directive 86/278/EEC of June 12, 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. Actions taken to build and modernize the infrastructure and implement modern technologies of wastewater treatment lead to the generation of substantial amounts of municipal sewage sludge. According to the data of the National Waste Management Plan KPGO2022, the amount of municipal sewage sludge in 2016 was 568,000 tones of dry solid. The plan also assumes that, based on the tendency for generation of sewage sludge in 2011–2016, the amount of sewage sludge calculated per unit of dry matter will have been increasing until 2020 by 2%–3% annually. This amount of sludge causes problems with its management, especially because since January 2016, the storage of non-processed sewage sludge, which had been one of the most popular methods to manage sludge, has been forbidden due to non-compliance with the requirements specified in the Appendix to the Regulation of the Minister of Economy of 16 June 2015 on the acceptance of waste for storage in landfill sites [1].

Therefore, sludge management in wastewater treatment plants has to be implemented in a manner that ensures the proper selection of methods of sludge processing, while their final method of management should take into consideration

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legislative aspects, local conditions, technical specifications and economic and ecological conditions. As a consequence of the chemical composition of wastewater, sewage sludge is mainly the mixture of a number of hazardous inorganic compounds and elements, including heavy metals, and organic compounds, such as dioxins, furans, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, adsorbable organohalogens (AOX), phenols, phthalates, etc. These compounds represent the factor to limit the natural use of sewage sludge. For this reason, more restrictive methodologies have to be developed. Therefore, it is not surprising that a lot of research effort has been focused on the development of thermal methods [2–5]. Installations of thermal treatment that have been built in Poland in recent years can be divided into two groups of facilities. The first group includes drying plants, whereas the other group is installations for thermal transformation based on the process of initial drying and combustion, typically using the process of combustion in fluidized bed furnaces. Fluidized bed technology is the most available technology for thermal treatment of sewage sludge [6–9]. It should be noted that currently there are 11 such mono-incinerators of sewage sludge in Poland, with the total processing capability of 160.000 tons of dry mass per year.

The process of incineration of municipal sewage sludge in these facilities occurs through conventional combustion under conditions of air atmosphere which (assuming that from the standpoint of combustion, sewage sludge is not a typical fuel but rather a by-product of wastewater treatment characterized by unfavorable hydration, high content of mineral matter, high content of volatile compounds and low density and fusibility of ashes) can lead to certain disturbances [10,11]. The change in combustion atmosphere involving the replacement of air with the mixture of oxygen and carbon dioxide may be an interesting alternative, since an elevated oxygen concentration in the oxidizing mixture offers opportunities for the utilization of fuels with worse quality, including municipal sewage sludge, and for management of waste through co-combustion. This technology, termed oxy-fuel combustion, is currently regarded as one of the key clean coal technologies. Substantial interest in this technology mainly results from elevated energy conversion and opportunities for direct sequestration of carbon dioxide [12–15]. As mentioned before, unlike combustion in air, oxy-fuel combustion occurs in the mixture of oxygen, whose concentration is higher than in the case of air and carbon dioxide. Consequently, the composition of flue gas that leaves the combustion chamber is basically CO_2, which after minor purification can be recycled and geologically sequestrated. Therefore, this technology has attracted much attention in the industrial energy sector. The combination of oxy-fuel combustion with conditions of fluidized bed circulation offers opportunities for utilizing sludge and coal mixtures in power-generating facilities. Coal and sewage sludge are two different fuels in terms of carbon, oxygen, hydrogen, nitrogen and sulfur content, which represent the main fuel elements. Therefore, mass content of sewage sludge in the fuel mixture should determine the opportunities for its incineration and effect on the environment [16,17]. Sewage sludge also has an effect on the obtained by-products. Ash from sewage sludge contains substantial amounts of alkali metals, with particular focus on potassium and sodium, and is characterized by higher content of calcium compared with the ash from coal [18–20]. This may lead to substantial functional problems that result from the behaviors of the mineral substance contained in the fuel. Therefore, the character of ashes will be different from the ashes generated through coal combustion.

The aim of this study was to compare ashes obtained from circulating fluidized bed oxy-fuel combustion under conditions of variable oxygen concentration in the gas mixture. The objectives were to determine the slagging and fouling tendency of these ashes with the fusibility test and to characterize them by chemical and particle size distribution (PSD) in order to assess their environmental impact and potential uses.

2. Experimental section

2.1. Raw materials

The sewage sludge used in the experiment was collected from a wastewater treatment plant located in a medium-sized agglomeration with approximately 250,000 inhabitants. The character of the sludge is typical for mixed municipal–industrial sewage. The presence of heavy metals makes the usage of the sludge for agricultural purposes impossible; therefore, combustion is preferred. The sludge is collected in the form of dry granulate with the diameter up to about 8 mm. Furthermore, the initial material for obtaining the sludge and coal mixtures was hard coal from the Janina mine in Poland. Different fuel mixtures were prepared using the initial materials, with different sewage sludge mass percentages. However, in this publication, only the results obtained with 30% sewage sludge mass in the fuel blend are presented. Further, this mixture is referred to as FSC30. The properties of FSC30 are presented in Table 1.

2.2. Combustion experiments

The proper tests of combustion of municipal sewage sludge and sludge and coal mixtures were conducted in an industrial laboratory environment, that is, at a test stand with a circulating fluidized bed with the power of 0.1 MWth. It should be noted that this is one of few laboratory installations of this scale used in Poland. An atmospheric lab-scale circulating fluidized bed is described in detail in a study by Czakiert et al. [21]. The combustion tests were conducted in O_2/CO_2 with the following contents of mixture components: 21% O_2/79% CO_2, 25% O_2/75% CO_2, 30% O_2/70% CO_2 and 35% O_2/65% CO_2, thus simulating flue gas recirculation. Emissions of pollutants (CO_2, CO, SO_2, SO_3, NO_2, NO, N_2O, NH_3, HCN, H_2O, HCl, HF) from combustion were measured using a measurement system based on the Gasmet DX-4000 analyzer, with the measurements based on the FTIR methodology. The results presenting emissions from sewage sludge and coal combustion in such conditions have been reported in previous articles [22,23]. This study aimed at evaluating fly and bed ashes through various analyses.

2.3. Ash analysis

The fusibility test for the determination of characteristic temperatures was conducted according to PN-ISO 540:2001P. The other examinations involved:

Table 1
Proximate and ultimate analyses of FSC30, coal and sewage sludge

Fuel	Proximate analysis (db, wt%)			Heating values (db, kJ/kg)	
	Volatile matter	Ash	Fixed carbon	Higher heating value	Lower heating value
FSC30	35.17	20.27	35.66	19.483	18.116
Coal	29.24	10.33	49.10	22.531	21.118
Sludge	46.70	39.15	9.35	12.542	11.282
	Ultimate analysis (db, wt%)				
	Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen[a]
FSC30	57.46	5.64	2.39	1.63	12.61[a]
Coal	67.88	5.92	1.26	1.72	12.90[a]
Sludge	32.41	5.31	4.21	1.56	17.36[a]

db, dry basis.
[a]The oxygen content was calculated by difference.

- determination of the loss of ignition using the weight methodology according to the standards (PN-G-04516:1998) [24];
- determination of the content of carbon and sulfur by means of incineration elemental analysis using the Leco NHCS analyzer (PN-G-04571:1998) [25];
- determination of the characteristic melting points according to the standards (PN-G-04535:1982) [26];
- determination of the grain size distribution for bottom ashes using the sieve analysis methodology and for volatile ashes using laser diffraction methodology by means of the Mastersizer 2000 analyzer (Malvern Instruments, UK);
- determination of structural parameters and bulk and skeletal densities of volatile ashes by means of the AutoPore IV 9500 mercury porosimeter;
- analysis of the content of inorganic matter using the energy dispersive spectrometer PANalytical MiniPal QC;
- analysis of phase composition using XRPD powder diffractometry by means of the HXG-4 diffractometer (Carl Zeiss, Jena) with a copper lamp Cu ($\lambda K\alpha$) = 1.5418 Å with the spectral range of: 7–108 degrees of the 2Θ angle;
- determination of the characteristic indices of ashes (alkaline index, agglomeration index, growth index).

3. Results and discussion

3.1. Fuel blend characterization

From the proximate and ultimate analyses of the FSC30 shown in Table 1, it is clear that the fuel FSC30 was rich in volatile matter (35.17%), and the carbon content was 51.05%. The ash content in FSC30 was higher compared with the ash content in coal but lower than that in sewage sludge. As a result, the higher heating value (HHV) of FSC30 was lower compared with the HHV of coal. The sulfur content in FSC30 was quite high due to its high content in sewage sludge. The chlorine content was low. The fusion temperatures of the ashes are shown in Table 2.

It can be seen that initial deformation temperature for FSC30 is higher than for sewage sludge alone. However, these temperatures are still low for most combustion processes, resulting in slagging problems, except fluidized bed systems, where operating temperature is usually below 900°C. It is also clear that FSC30 ash softens at much higher temperatures then the ash from sewage sludge. The fluid temperature is nearly the same for both types of fuel. Differences in fusibility behavior reflect the variability in chemical composition between sewage sludge and coal.

3.2. Unburned carbon

The combustion efficiency can be determined by means of the content of unburned carbon. The effectiveness of combustion is influenced by many factors, including type of fuel, method of fuel preparation and combustion parameters, particularly humidity, which is important for biomass co-incineration (including sewage sludge), has a significant effect on the combustion process resulting in a shift of the flame nucleus and shorter residence of the particles, and directly contributes to the increase of unburned carbon in the ash. This situation is quite common when co-firing biomass with coal. The mass fraction of unburned carbon in fly ash and bottom ash after the combustion of FSC30 in modified O_2/CO_2 atmospheres is presented in Fig. 1.

The proportion of unburned carbon in fly ash was significantly higher than in bottom ash. A similar relationship was also observed in studies conducted by Wu et al. [27]. The effect of the oxygen content in the inlet gas on incomplete combustion losses is clear. The difference in unburned carbon content between the extreme conditions under which combustion tests were carried out, that is, 21% vol. and 35% vol. oxygen concentration in O_2/CO_2, indicates that combustion efficiency was continuously improving with higher oxygen concentration in the gas mixture. However, the high value of unburned carbon in 21% O_2/79% CO_2 atmosphere results from combustion conditions – the temperature in the reactor was about 750°C. For other atmospheres, the temperature in the reactor was typical for fluidized combustion. For bottom ash, there is also a noticeable effect of the oxygen content on the mass fraction of unburned carbon. The difference in the ash content in bottom ash was also strongly unfavorable for 21% O_2/79% CO_2 atmosphere. The properties of such unburned carbon are significant, because they are directly related to the potential use of ash. It is known that pozzolanic properties are more intense when carbon content is below 6% [28].

Table 2
Fusibility analysis of ashes

Sample	Initial deformation temperature (IDT)	Softening temperature (ST)	Hemispherical temperature (HT)	Fluid temperature (FT)
FSC30	960°C	1,200°C	1,270°C	1,290°C
Sewage sludge	920°C	1,120°C	1,270°C	1,300°C

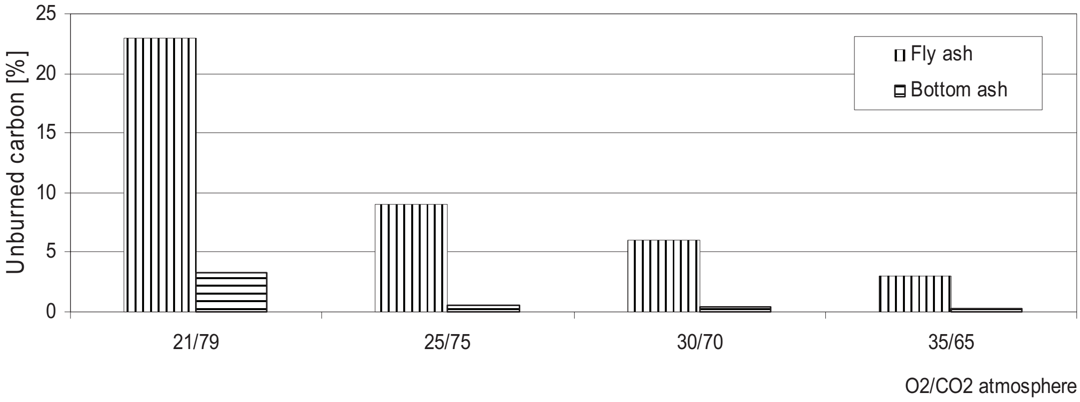

Fig. 1. Mass fraction of unburned carbon in fly and bottom ash.

3.3. Particle size distribution

The weight percentages of the PSD of FSC30 fly and bottom ash received from oxy-combustion in different atmospheres are illustrated in Figs. 2 and 3 respectively. The results show that fly ash constituted of particles up to 140 mm, where approximately 95% of particles were below 100 mm. The higher the oxygen concentration in gas mixture, the higher the percentage of fine grain fraction. This reflects the higher combustion efficiency of FSC30. The median particle size of FSC30 ash received in 21% O_2/79% CO_2 was about 11.15 mm, whereas the median particle size of ash received in 35% O_2/65% CO_2 was 9.67 mm. Obviously, the coarser particles were found in the bottom ash. The fraction over 315 mm comprised around 90% of the weight in the case when ash was received after combustion in 21% O_2/79% CO_2 atmosphere. In such conditions, the proportion of unburned carbon was also the highest, and the median particle size was 611.22 mm. The higher the oxygen concentration in the gas mixture, the lower the weight percentage of ash particles greater than 315 mm. For FSC30 bottom ash after oxy-combustion in 35% O_2/65% CO_2 atmosphere, the particle size fraction over 315 mm was about 52% of the weight. In this case, the median particle size of bottom ash was 332.68 mm. The properties of PSD are also significant in potential use of ash. Pozzolanic properties are more intense when particles are finer. However, such particles tend to concentrate heavy metals and their leachability is potentially greater [28].

3.4. Porosimetric analysis

Based on the structural parameters and according to the IUPAC classification, FSC30 fly ashes are classified as macroporous materials with dominant macropore fraction. Pore volume distribution of FSC30 fly ashes in different atmospheres is illustrated in Fig. 4. Fly ash in 21% O_2/79% CO_2 had a very well developed porous structure ranging from 4,000 to 12,000 mm in diameter. The ash displayed wide pore distribution and the area of ash particles varied with the depth of the porous structure. The increase of oxygen concentration in the gas mixture up to 25% O_2 led to pore sizes in FSC30 fly ash ranging from 2,500 to 6,000 mm.

The pores were characterized by smaller diameters and smaller volume. They were developing intensively and they covered the entire surface, forming a compact structure. Fly ash obtained after oxy-combustion in 30% O_2/70% CO_2 atmosphere showed no significant change in pore size distribution (2,000–6,000 mm), but the specific surface area of ash was half the original size. It proves a decrease in the number of pores, which do not form such a compact structure on the surface area. In the case of fly ash obtained in 35% O_2/65% CO_2 atmosphere, the pores were developing in the range of 3,000–7,000 mm. The tested material was characterized by a small number of pores with little variation in shape. Table 3 presents the basic parameters of the porous structure of FSC30 fly ash.

The porosimetric analyses demonstrated that the porous structure of fly ash is affected by the type of combustion atmosphere. It affects the development of the ash specific surface area and the distribution of pore diameters, and the dynamics of changes in these parameters varies depending on oxygen content in the gas mixture. The ashes generated from combustion with low oxygen content in the gas mixture have pores with a compact structure, greater volume and better development of specific surface area.

3.5. Mineralogical analysis

Table 4 presents the crystalline mineral phases of FSC30 fly ash which were identified by XRD. FSC30 fly ash after oxy-fuel combustion displays a low degree of crystallinity.

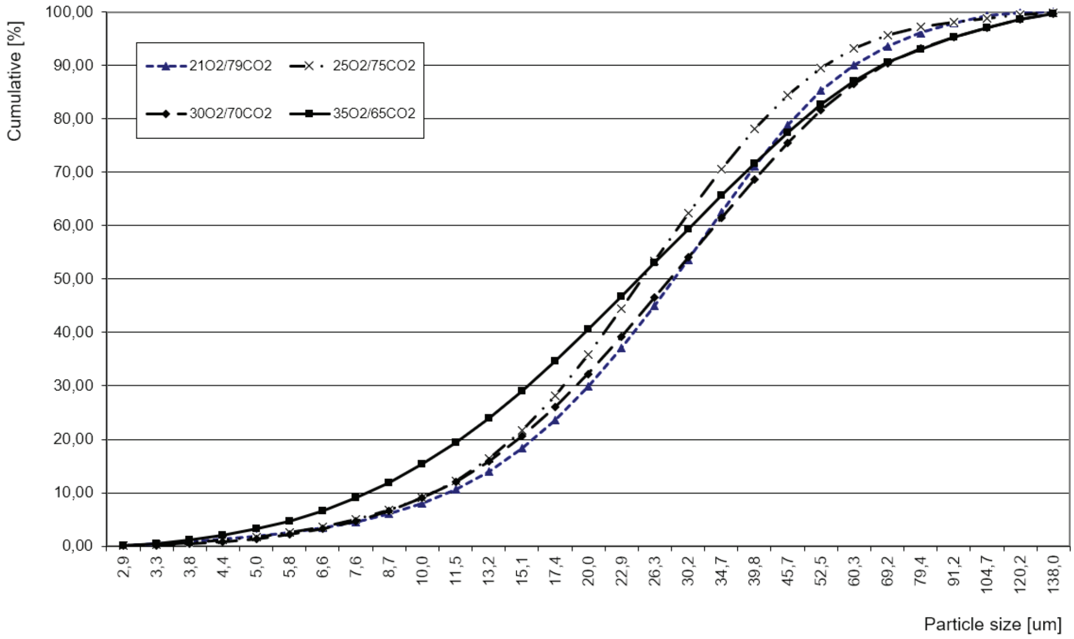

Fig. 2. Particle size distribution of FSC30 fly ash obtained in different atmospheres.

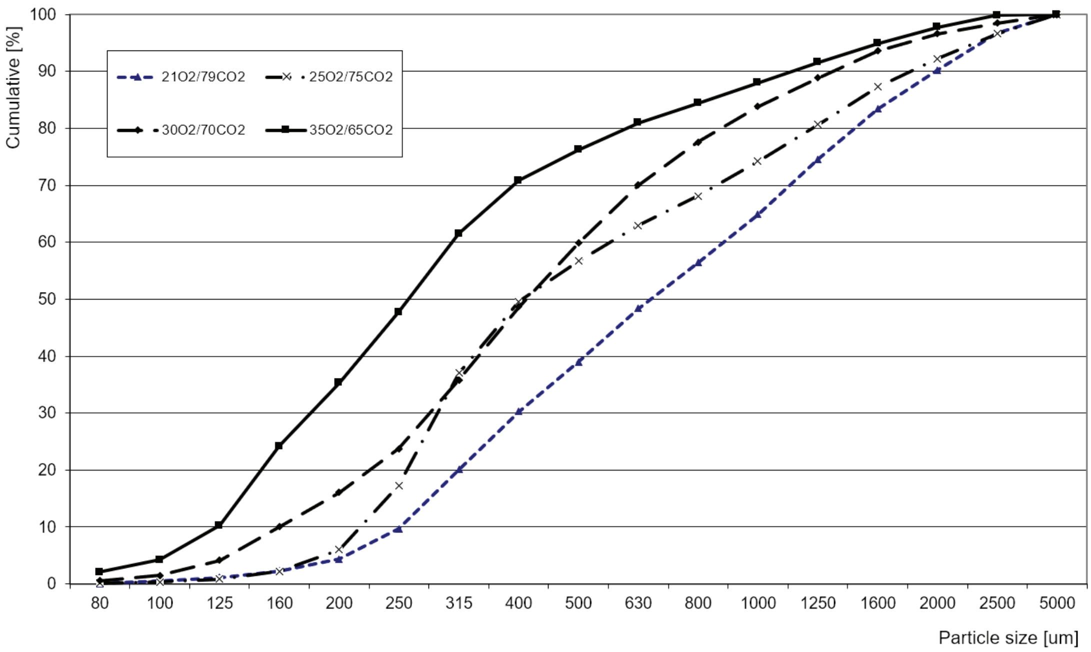

Fig. 3. Particle size distribution of FSC30 bottom ash obtained in different atmospheres.

Apparently, the principal mineral species in all ash samples were Si-based, followed by Fe and Ca-based minerals. The main crystalline phases were crystalline silica (SiO_2), diiron trioxide (Fe_2O_3) and calcium sulfate ($CaSO_4$).

The presence of complex aluminosilicates was observed in FSC30 fly ash obtained after oxy-combustion in 21% O_2/79% CO_2 atmosphere, while calcium-magnesium phosphates were observed in ash after combustion of FSC30 fuel in 35% O_2/65% CO_2 atmosphere. Most minerals of the present study have also been identified in other studies on biomass and coal blends ashes [20].

3.6. Chemical analyses

The contents of major elements in fly and bottom ash from FSC30 fuel expressed as oxides are shown in Table 5.

As we can see, fly ash is rich in Si, Al, Fe and Ca, whereas bottom ash is mostly rich in Si and Al. Therefore, the main components of both fly ashes and bottom ashes are aluminosilicates. The results show that SiO_2 varies from 23.5% to 36.3% for fly ash, and from 39.3% to 65.5% in for bottom ash. On the other hand, Al_2O_3 varies from 13.6% to 23% for fly ash, and from 13.1% to 18.7% for bottom ash. The domination of Fe in fly ash is typical for sewage sludge addition [29]. A considerable amount of P in FSC30 ash is also noticeable due to sewage sludge [29,30]. The higher oxygen content in the gas mixture, the higher aluminosilicates content observed in the ashes. This tendency is in conformity to literature [31].

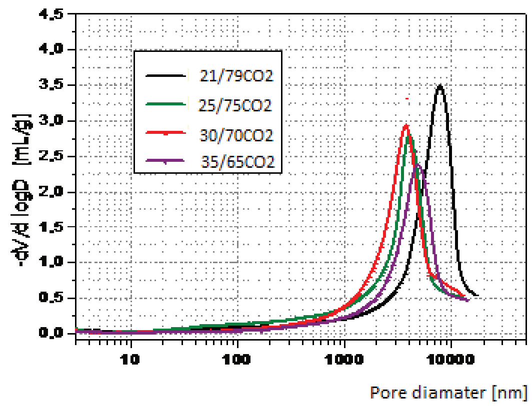

Fig. 4. Pore volume distribution of FSC30 fly ash.

Due to alkali species in biomass (sewage sludge), ash-related problems including alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion or ash utilization are still the most challenging problems. To assess the potential for the occurrence of this phenomenon, some characteristic indexes, such as alkali index (AI), bed agglomeration index (BAI), the ratio of base to acid (RBA) and sintering index for FSC30 fly ash were determined. The values of these indexes are compared in Table 6.

It could be noticed that the higher oxygen concentration in the gas mixture, the higher the temperature of combustion, and as a result, the lower the values of SI index. Fly ash has the tendency to build up unmanageable deposits on the fired surfaces. This is also confirmed by the RBA index, where the values below 0.75 are recognized as a potential tendency for deposits growth.

3.7. Ash utilization

Ashes should generally be recycled, but if this is impossible, they should be transported for treatment. However, legal regulations are much more complex than in the case of ashes of combustion of coal alone. Sewage sludge is the waste that is generated in the process of sewage treatment. Consequently, the ash is defined in legal regulations on waste management, that is, the Act of 14 December 2012 on waste, which stipulates that municipal sewage sludge is classified in the waste stream as the 19.08 group. Combustion or co-combustion of this type of waste is approached as a process of thermal treatment of waste, which leads to the necessity of proper management or

Table 3
Characteristics of structural parameters of FSC30 fly ash

FSC30 fly ash	Unit	Atmosphere			
		21% O_2/79% CO_2	25% O_2/75% CO_2	30% O_2/70% CO_2	35% O_2/65% CO_2
Total pore volume	cm^3/g	1.68	1.44	1.33	1.22
Specific surface area	m^2/g	16.86	16.84	8.99	7.04
Mean pore diameter	nm	398.5	342.3	681.7	691.5
Porosity	%	62.88	55.56	57.14	58.04

Table 4
Crystalline phases identified in FSC30 fly ash after oxy-combustion

	Ref. no.	Chemical formula	Name
21% O_2/79% CO_2			
*	01-085-0930	SiO_2	Crystalline silica
*	01-072-6225	Fe_2O_3	Diiron trioxide
*	01-074-2421	$CaSO_4$	Calcium sulfate
*	04-012-1065	$MgFe_2O_4$	Magnesioferrite
	00-007-0032	$KAl_2Si_3AlO_{10}(OH)_2$	Muscovite
$35O_2/65CO_2$			
*	01-073-3825	Fe_2O_3	Diiron trioxide
*	01-070-3755	SiO_2	Crystalline silica
*	04-007-6682	$CaSO_4$	Calcium sulfate
*	04-010-2972	$Ca_{2.71}Mg_{0.29}(PO_4)_2$	Magnesium-calcium phosphate

*Main phases.

Table 5
Chemical composition of FSC30 fly and bottom ash

Atmosphere	Al_2O_3 $\%_{mas.}$	CaO $\%_{mas.}$	Fe_2O_3 $\%_{mas.}$	MgO $\%_{mas.}$	P_2O_5 $\%_{mas.}$	K_2O $\%_{mas.}$	SiO_2 $\%_{mas.}$	Na_2O $\%_{mas.}$	TiO_2 $\%_{mas.}$	MnO $\%_{mas.}$
	Fly ash									
21% O_2/79% CO_2	13.62	7.21	17.08	1.94	5.17	1.45	23.48	0.37	0.67	0.07
25% O_2/75% CO_2	16.12	8.90	19.78	1.89	7.25	1.56	27.92	0.41	0.71	0.08
30% O_2/70% CO_2	23.07	4.98	14.60	1.73	1.79	2.01	36.34	0.35	0.63	0.03
35% O_2/65% CO_2	20.81	6.61	16.88	1.66	4.59	1.95	35.11	0.46	0.70	0.06
	Bottom ash									
21% O_2/79% CO_2	15.25	5.27	8.02	1.43	6.28	1.62	51.98	0.37	0.77	0.06
25% O_2/75% CO_2	13.11	8.86	1.80	2.08	10.89	1.51	39.35	0.39	0.64	0.09
30% O_2/70% CO_2	18.70	4.18	3.53	1.63	2.91	1.81	61.07	0.33	0.68	0.02
35% O_2/65% CO_2	17.32	3.59	4.46	1.36	4.21	1.91	65.55	0.35	0.55	0.03

Table 6
Characteristic indexes of FSC30 fly ash

Atmosphere	AI	RBA	SI	BAI
21% O_2/79% CO_2	0.76	0.74	5.00	9.32
25% O_2/75% CO_2	0.74	0.73	5.46	10.00
30% O_2/70% CO_2	0.40	0.39	2.83	6.14
35% O_2/65% CO_2	0.49	0.49	3.42	6.98

treatment of ash. Based on the properties of the ashes and the process in which the waste is generated, this type of waste is classified under waste code 19 01 12 or 19 01 14. Nevertheless, it is remarkable that municipal waste is a derivative of the quality of sewage and processes observed in the sludge facilities, which leads to varied characteristics of the sludge, with particular focus on inorganic and organic pollutants. This may also lead to classifying the sludge as hazardous waste. The recycling of ash is possible only toward the use of the ash for the preparation of concrete mixtures. However, ash cannot be used for buildings designed for permanent residence or keeping animals or buildings for the production and storage of foods. Furthermore, three conditions have to be met, including total carbon content in ashes below 3% or the content of combustible fractions below 5%. The content of combustible fractions in the analyzed ashes obtained in the study met the criteria of acceptance for ash recycling.

4. Conclusions

In view of the growing awareness of climate warming, caused by, inter alia, the burning of fossil fuels, greater emphasis is being placed on methods applied to reduce carbon dioxide emissions. In that regard, oxygen combustion is considered as one of the technologies that can significantly reduce carbon dioxide emissions into the atmosphere, but it also can be used to recover energy from the combustion of poorer quality fuels, for example, sewage sludge. However, ash materials produced during combustion may create several technical and environmental problems. In this work, bottom and fly ashes obtained from lab-scale circulating fluidized bed oxy-fuel combustion of sewage sludge and coal (referred to as FSC30) were characterized. The mineral substances contained in fuel undergo transformation in the combustion process. Ash fusion temperatures of FSC30, which in the case of fluid technology is of great importance, were considerably higher than for ashes from sewage sludge only, suggesting that the combustion of FSC30 fuel in fluidized bed systems is possible. The PSD analysis of FSC30 fly ash showed that it mainly constituted of particles up to 140 mm, while the size of approximately 95% of particles was below 100 mm. The higher oxygen concentration in the gas mixture, the higher percentage of fine particles fraction in fly ash was observed. The median particle size of FSC30 ash obtained in 21% O_2/79% CO_2 was about 11.15 mm, whereas the median particle size of ash obtained in 35% O_2/65% CO_2 was 9.67 mm. Coarser particles were found in the case of bottom ash. It was around 90% of the ash weight with the fraction over 315 mm in 21% O_2/79% CO_2 atmosphere (the median particle size was 611.22 mm), while in 35% O_2/65% CO_2 it was only 52% (the median particle size was 332.68 mm). Based on the structural parameters and according to the IUPAC classification, FSC30 fly ashes were classified as macroporous materials with the dominant macropore fraction. The porosimetric analyses demonstrated that the porous structure of fly ash was affected by the type of combustion atmosphere, which affected the development of ash specific surface area and distribution of pore diameters. Ashes obtained from combustion with low oxygen content in the gas mixture were characterized by pores with compact structure, greater volume and better development of specific surface area. The obtained ash was rich in Si, Al, Fe, Ca and P. The domination of Fe and P is typical for fuel where sewage sludge is part of the blend. The ash displayed a low degree of crystallinity. The main crystalline phases were crystalline silica – SiO_2, diiron trioxide – Fe_2O_3 and calcium sulfate – $CaSO_4$.

The obtained parameters showed potential possibilities of utilization of ash in grading and leveling. The problem, however, lies in its classification. In accordance with the regulation on the waste catalog applicable in Poland, generated ash is classified in group 19, and waste from this group may not be utilized in any way out of the installations. Hence, regarding ashes obtained in the co-combustion process, a more flexible approach to the issues of potential utilization would be worthwhile, not strictly following the classification but rather taking into consideration their physical–chemical characteristics.

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