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THE PRELIMINARY RESEARCH OF THE PHYSICO-MECHANICAL PROPERTIES OF AGGREGATES BASED ON THE COLLIERY SHALE, SUPPLEMENTED BY FLY ASH

BADANIA WSTĘPNE WŁAŚCIWOŚCI FIZYKOMECHANICZNYCH KRUSZYW NA BAZIE ŁUPKU PRZYWĘGLOWEGO Z DODATKIEM POPIOŁU LOTNEGO

The currently applicable legal provisions and also the economic concepts emphasize the importance of circular economy. In this aspect, it is very important to reduce the waste production respectively planning and running a business. Technical research is the key to finding a new applications for waste, in particular disposed on landfilling. Mining and energy industries belong to the biggest producers of waste in Poland. The total share of these two branches in waste production is up to 70% (mining and quarrying 53%; electricity, gas, steam and air conditioning supplay 17%). In environment, economy and social aspect, it is very important to develop this waste. The paper presents research on the physico-mechanical properties of the aggregates based on colliery shale supplemented by fly ash (20% - 40% supplement of fly ash). The following tests should be mentioned among performed: particle size distribution, the sand equivalent test, freeze resistance and direct shear tests. Also the chemical properties found in the literature was invoked. The research shows good physico-mechanical properties of the mixes, such as cohesion (44.62 kPa - 68.57 kPa) or internal firiction angle (34.74° - 40.52°). Though low resistance to weathering and a large susceptibility to frost heave (the mass loss after the freezing cycles is 76%) may limit its applicatin in road engineering. The sand equivalent tests were made only for aggregates. Tested materials shows usefulness for earthen structures. However, the research should be supplemented by chemical tests and also observations of the material properties changes as the effect of time. The research on the leachability of chemical pollutants, which will determine the acceptable share of ash in the mix, could be especially significant. The fact that fly ash contains a lot of sulphates and chlorides, which leach into the environment may pose a threat to living organisms.

Keywords: physico-mechanical properties, waste rock, fly ash from fluidized bed boiler, aggregate mixes

Aktualne przepisy prawa oraz koncepcje gospodarcze obowiązujące w Polsce kładą duży nacisk na gospodarkę o obiegu zamkniętym. W tym aspekcie bardzo ważne staje się ograniczanie liczby odpadów odpowiednio planując oraz prowadząc działalność gospodarczą. Dlatego, poprzez badania poszukuje się

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rozwiązań, które pozwoliłyby na znalezienie nowych zastosowań dla odpadów, w szczególności unieszkodliwianych poprzez składowanie. Energetyka i górnictwo to dwie gałęzie przemysłu, których udział w produkcji odpadów jest największy. W Polsce oba sektory wytwarzają łącznie około 70% odpadów (górnictwo 53%; energetyka 17%). Zagospodarowanie tych odpadów jest bardzo ważne w aspekcie środowiskowym, ekonomicznym jak i społecznym.W artykule przedstawiono badania właściwości fizyko-mechanicznych dla mieszanek kruszywowo-popiołowych bazujących na łupku przywęglowym oraz popiele lotnym (20%-40% dodatku popiołu lotnego). Pośród przeprowadzonych badań należy wymienić: badanie wskaźnika piaskowego, badanie składu ziarnowego, badania mrozoodporności czy test bezpośredniego ścinania. Przywołano także właściwości chemiczne popiołów lotnych, które znaleziono w literaturze.Przeprowadzone badania wskazują na dobre właściwości fizyko-mechaniczne mieszanek kruszywowo-popiołowych takie jak kąt tarcia wewnętrznego (34.74°-40.52°) i spójność (44.62 kPa-68.57 kPa). Jednak niska mrozoodporność łupku przywęglowego (utrata masy po cyklach mrożenia wynosi 76%) wprowadza pewne ograniczenia co do możliwości zastosowania niniejszego materiału, w szczególności np. w drogownictwie. Badania wskaźnika piaskowego wykonano jedynie dla kruszyw, nie uwzględniając mieszanek. Badany materiał wykazuje potencjał do zastosowania przy wznoszeniu budowli ziemnych. Należy jednak przedstawione badania uzupełnić o badania chemiczne, a także uwzględnić w nich zmianę właściwości materiału pod wpływem czasu. Szczególnie ważne mogą okazać się badania wymywalności zanieczyszczeń chemicznych, które określą dopuszczalny udział popiołu w mieszance. Jest to związane z tym, że popioły lotne zawierają dużo siarczanów i chlorków, które wymywane do środowiska mogą stanowić zagrożenie dla organizmów żywych.

Słowa kluczowe: właściwości fizyko-mechaniczne, popiół lotny z kotła fluidalnego, mieszanki kruszywowo-popiołowe, skała płona

1. Introduction

The currently applicable legal provisions and also the concepts of product management emphasize the importance of planning, designing and managing any activities in such way as to "prevent waste production or to limit its amount and the impact on the human life, health and the environment both during manufacturing products and after their usage" (art. 18, par. 1, The Act on Waste, 24.11.2017; Gazette 2017, no 0 pl. 2422). According to the Act mentioned above, the next stage is the recovery (art. 18, par. 2) which obliges the owner to prepare the waste to be re-used or recycled (art. 18, par. 3). If the recovery is impossible, the owner has to dispose of the waste material (art. 18, par. 5). The disposal is only an option in the case of waste that had been deprived of any recoverable parts. According to article 18, it is only allowed to store waste when its disposal is impossible.

The foundations of the circular economy, established by the European Commission on the 2nd of December 2015, are also very important. This concept covers the 'whole life' of a product, starting with obtaining the raw materials, production, consumption and ending with waste management and the market for secondary raw materials (Jensen & Remmen, 2017; Korhonen et al., 2018; Ritzen & Sandstrom, 2017). The transformation of material management, and especially the circular economy, is strictly connected to the changing attitudes towards waste in general. There is a need for the knowledge of how and where waste can be used (Gomes et al., 2016; Kocianova et al., 2016; Park & Chetrow, 2014; Singh et al., 2015). Due to the lack of such knowledge, all the waste, regardless of its property, is stored at the landfills. Other materials are recovered at significant levels, thanks to the available experiences (Galos & Szlugaj, 2014; Gomes et al., 2016; Park & Chetrow, 2014). It can be assumed that the possibility of the economic use of waste demands extensive knowledge in order to find an innovative technology to process or recover waste. This is why the research on the economical use of waste or its modifications should be intensified to multiply the possibilities of its usage.

2. The characteristics of some waste produced by the mining and energy industries

The industries of mining and energy are the biggest producers of waste in Poland. According to the Polish Statistical Office (GUS, 2016) in 2015, the total amount of waste had reached 142 million tons – 53% of it was produced by the mining industry and 17% was produced by the energy industry (Fig. 1). The total share of these two branches in waste production – 70% – creates the need for an instant limitation or the re-management of waste, which should be beneficial for both the environment and the national economy.

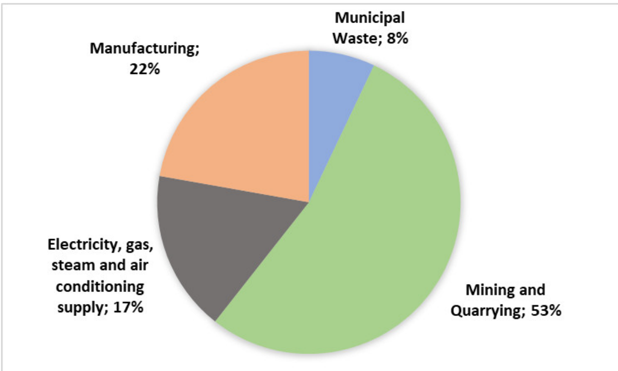

Fig. 1. The percentage share of waste production in different sectors of the economy in 2015 – compiled based on (GUS, 2016)

The massive amount of waste disposed of at the landfills had created the necessity to increase the effectiveness of its economic use. The share of the produced and stored waste is shown in Fig. 1. It should be pointed out that until 2015, a significant amount of waste was accumulated at the landfills – a total amount of about 1457.83 million tonnes (Fig. 2). Flotation dressing of nonferrous metal ores makes up for the biggest amount of waste (respectively 31.05 and 624.64 million tons). The second group, per the amount of produced and stored waste (33.61 and 434.94 million tons), is made up of rinsing and cleaning minerals. The ash-slag mixtures, resulting from the wet disposal of combustion waste (respectively 12.02 million tons of produced waste and 294.10 million tons of stored waste) take the next spot. The waste produced by the sectors mentioned above shows different physico-mechanical properties that determine its prospective use. The energy sector has almost no problems with the management of the coal fly ash (5.04 million tons produced and 0.05 million tons stored), as well as with the dust-slag compounds from the wet treatment of furnace waste (3.28 and 26.28 million tons). Their waste is successfully utilised by the cement industry (mixtures of fly ash and solid waste from lime wet scrubbing). There is still some potential in ash-slag mixtures from the wet discharge of furnace waste or fly ash from coal combustion. However, the waste from rinsing and cleaning excavated minerals still needs a consideration of its possible economic use. The research on mining and energy waste may discover a new direction of waste management and increase the amount of waste managed in the ways that are already known of.

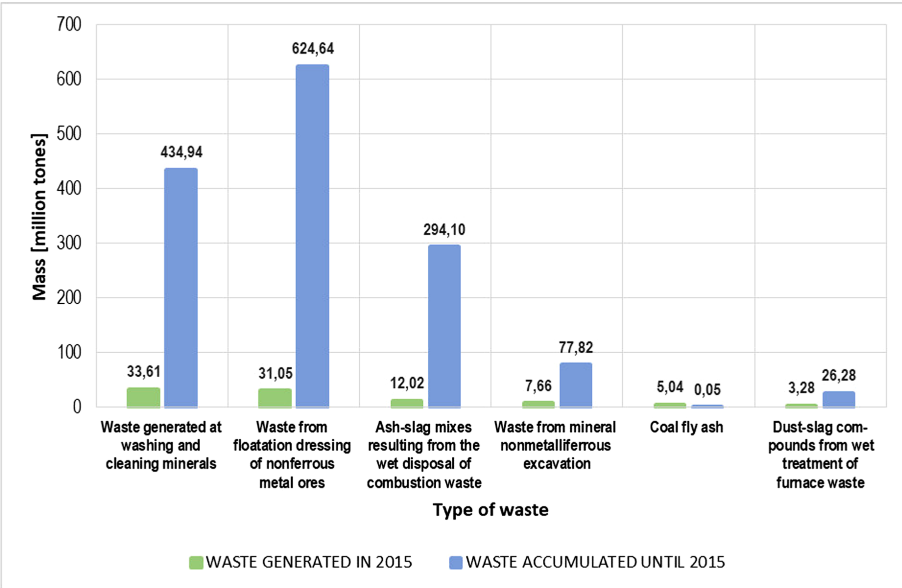

Fig. 2. The waste produced and stored in 2015 according to its type – compiled based on (GUS, 2016)

To estimate the potential of economic use of mining and energy waste, its general quantitative and qualitative characteristics ought to be taken into consideration.

Table 1 displays data from 2009, listing the producers of waste created during the coal combustion in a fluidized bed boiler. As it is shown, the fluidal fly ash makes up (on average) about 78% of the waste.

TABLE 1

The main producers of the fluidized coal combustion waste in 2009 in Poland (Zapotoczna-Sytek et al., 2013)

Plant name	Type and mass of the waste [thousands of tons]		
	Fluidized ash	Bottom ash from deposit	Total
Power plant „Turów”	1200	300	1500
Heat and power plant „Żerań”	120	40	160
Heat and power plant „Czechowice-Dziedzice”	40	10	50
Power plant „Jaworzno II”	100	50	150
Heat and power plant „Katowice”	100	30	130
Heat and power plant „Tychy”	20	5	25
Power plant „Siersza”	75	25	100
Pharmaceutical plant „Polpharma”	8	2	10
Power plant „Chorzów”	100	25	125
Power plant „Łagisza”	300	100	400
Total	**2063**	**587**	**2650**

The ash created by the fluidized bed boiler combustion reveals specific properties. It does not contain the glassy phase, is of great open porosity, and its granulation varies from 0 to 300 µm. All these characteristics influence its increased water demand, as compared to the ash from dust boilers. The fact that the temperature in fluidized bed boilers reaches 850°C, on one hand reduces pollutant emissions (Knapik, 2015), but on the other hand makes for the optimal conditions for the reaction of SO_2 with the product of the decarbonising of calcium carbonate $CaCO_3$. The chemical composition of the fly ash from fluidized bed combustion shows a reduced content of SiO_2 but an increased share of CaO and SO_3. Semi-morphic products of dehydration and dihydroxylation of clay minerals: anhydrite $CaSO_4$ (5-15%) and calcite $CaCO_3$ (4-10%) dominate in the composition phase. Because of the significant amount of dehydrated clay minerals, this material reveals pozzolanic activity that is twice as big as siliceous ash (Donnthuam et al., 2016; Łaskawiec et al., 2011; Shin et al., 2016; Zapotoczna-Sytek et al., 2013). This opens up the possibility of using this material for soil reinforcement, both – like an independent binder or as a component in binder mixtures, such as lime or cement (Knapik, 2015).

Colliery shale is one of the several types of waste rock. The excavated output contains a significant amount of it. In some mines, it could even reach 20-40% of the output (Baic et al., 2016; Gomes et al. 2016). The waste rock belongs to the so-called mineral waste materials, which occur during the output, enrichment and processing of minerals. Mineral waste materials are divided into four groups:

- accompanying minerals,
- mining waste or extractive waste,
- processing waste,
- secondary processing waste (Góralczyk, 2009).

A brief petrographic description of the waste rock is shown in Table 2. However, Table 3 displays the results of laboratory tests on three basic types of waste rock. Analysing the content of Table 2, it can be assumed that the colliery sandstone reveals the best parameters of mechanical resistance. Available sources (Gomes et al., 2016; Góralczyk & Baic, 2009; Góralczyk, 2009) confirm that colliery shale show low mechanical properties, so their usefulness as an aggregate is rather limited. Currently, the main direction of colliery shale reuse is road and hydrotechnical

TABLE 2

A brief description of the colliery spoil (Góralczyk, 2009)

Rock	Description	Comments
Colliery shale	Sedimentary rock, detrital; mainly of black, rarely of dark grey hue; layer structure (slate), aleurytio-pelital, different thickness of layers	Low mechanical resistance, slate separateness
Colliery siltstone	Sedimentary rock, detrital of dark grey to black hue, solid, non-directional and compact aleuryt texture; occasional appearance of sidereid bladders in the rock (spherosidereid – sedimentary carbonate rock, grey-russet or russet – yellow in hue; high thickness; solid, compact, non-directional texture)	Varied mechanical resistance, depending on the coal content
Colliery sandstone	Sedimentary, detrital rock; light to dark grey in hue; solid, non-directional, sometimes stratified, psamite texture;	High mechanical resistance, depending on the sandstone binder (the loamier the lower the resistance)

embankments, where it plays the role of the artificial aggregate. However, this requires the proper geotechnical recognition of these materials due to the complex petrographic composition and thus the variability of their geotechnical properties (Gruchot, 2014). To improve the possibilities of shale application, research and tests need to be conducted to enhance its physico-mechanical properties.

TABLE 3

The results of the laboratory tests on different colliery spoil (Góralczyk, 2009)

Type of the dominant rock material	**Type of the test**				
	LA	**M_{DE}**	**Absorbability WA_{24} [%]**	**Freeze resistance [%]**	**Density ρ_a [g/cm^3]**
Colliery sandstone	17-19	32-38	1.4-1.6	4-12	2.6-2.7
Colliery claystone and siltstone	18-20	66-72	1.7-2.0	12-18	2.4-2.6
Colliery shale	31-45	76-80	2.7-5.0	47-75	2.2-2.3

LA – grinding resistance, MDE – abrasion resistance

Colliery spoils investigations have been conducted since the second half of the twentieth century. One of the first extensive studies connected to mining waste was published in the 1990s (Skarżyńska, 1995). In the following years, the study of colliery spoil became more and more popular. Currently, a lot of mines have technical approvals, on the basis of which colliery shale gains the name of an aggregate and a specific application indicated for it. In the recent years, further possibilities of mining waste utilization in the form of aggregate mixtures with other types of UPS waste, coal sludge, etc. or with additives to improve the aggregate properties, have been sought. So far, many studies have been conducted (Zawisza, 2006; Gruchot & Zawisza, 2007; Cholewa, 2008; Borys et al., 2008; Zawisza & Micor, 2012; Zawisza & Organ, 2012; Gruchot & Ligas, 2012; Gruchot, 2014; Zabielska-Adamska et al., 2015), which show the results of the industrial waste research, taking into the account the high variability of the properties of these materials, the type of the exploited seam, sometimes seasoning, etc. There is a constant need to control their composition and to look for new possibilities to apply them.

3. Materials and methods

The aim of this research was to indicate the basic properties (grain composition, sand index, frost resistance) for the components of mixtures (fresh wrought aggregate and fly ash) and to perform the shear strength tests for the mixtures and their components.

The tests measuring the physico-mechanical properties had been conducted on the aggregates of granulations 0-31.5 mm and 0-2 mm, obtained from the mining plant ZG Sobieski in Jaworzno, and their mixtures with the fly ash from a fluidized bed boiler in the power plant 'Jaworzno' as a modifier. The aggregate was mixed with the ash in the following proportions of weight ratio: 20% of ash with 80% of the aggregate, and 40% of ash with 60% of the aggregate. The particle size distribution had been conducted for both the ash and the aggregate. The next step was to determine such parameters as the sand equivalent and the freeze resistance. Then, the optimum moisture content for the tested aggregate and its mixtures was established and direct shear tests were conducted. The results of the tests are discussed later in this article.

Laboratory tests were carried out in order to determine the basic physico-mechanical properties of aggregates based on coal shale and its mixtures with fly ash. These included:

- particle size distribution,
- sand-equivalent,
- freeze resistance,
- shear strength parameters.

The determination of the grain size distribution is a fundamental method, which allows for characterizing the structure of the material and predicting its physical and mechanical properties. These tests are crucial for planning further research. The grain size distribution curve of the aggregates from ZG Sobieski 0-31.5 mm and 0-2 mm had been determined with the use of sieves in sizes: 0.063; 0.125; 0.2; 0.4; 0.63; 0.8; 1.0; 2.0; 4.0; 8; 10; 15; 25; 31.5; 40; 60 [mm], according to the Polish Standards (PN-EN 12620). The particle size distribution of fly ash had been determined through the laser diffraction method, with the use of Analysette camera by Fritsch.

The sand equivalent tests were conducted based on the Polish Standard (BN-8931-01:1964). The test consists of segregating the tested material in a standardized cylinder after having mixed in a certain chemical solution. The tests were conducted after having separated the fractions of sizes 0-4 mm from the tested aggregates. The tests aimed to determine the percentage ratio of sand and partly gravel fractions' capacity to the capacity of the whole sample together with the particles in the suspension.

Large differences in the values of SE_4 and SE (10) obtained in the sand equivalent tests for the aggregates with a silt content below 10% (m / m) in the 0-2 mm fraction do not allow for the assessment of the frost sensitivity of these aggregates based on the value of SE (10), because the SE (10) index is always a sand index for aggregates with a silt content of ≤10%, regardless of their actual content (Piech et al., 2015). Thus, the research determined the WP sand index based on the industry standard BN-8931-01: 1964, because the value obtained is comparable to the value of the SE_4 index determined on the basis of PN-EN 933-8: 2012.

The freeze resistance was tested on the aggregate's (0-31.5 mm), in accordance with the Polish Standard (PN-EN 1367-1). For testing purposes, a single-fraction, analytical sample of the aggregate had been chosen. The sample was soaked in water, with normal air pressure present. Next, it was frozen and unfrozen repeatedly in 10 cycles. One cycle covers freezing underwater in a temperature of minus 17, 5°C, and then unfreezing in a water bath in a temperature of about 20°C. Upon finishing the whole program, the mass loss of the sample is measured. During the freeze resistance tests the aggregate of grains 0-2 mm was skipped, because the size of the grains was too small.

The optimal moisture content (w_{opt}) in accordance with PN-B-04481-1988 standard means the water content for which the soil compacted by punning (according to the standard 8.2) obtains the maximum value of the soil volume density (ρ_{ds}). The values of w_{opt} and ρ_{ds} depend on the compaction method used. The PN-B-04481-1988 standard provides four soil compaction methods, two of them have been applied in this study, depending on the grain size of the aggregate being tested.

The method II was used for the aggregate and its mixtures with fly ash with a fraction range of 0 to 20 mm. It consists of compacting the soil in a large cylinder in three layers, compacting each of them with 55 strokes of a light compactor – a large one, lowered from the height of 320 ± 1 mm. However, for the aggregate and its mixtures in the fraction range from 0 to 6.3 mm (fly ash sample), the method used was one in which a small cylinder is utilized, compacting the soil in three layers using a light compactor, making 25 strokes for each layer. Similarly to the method II, the rammer is lowered from a height of 320 ± 1 mm, which corresponds to the work of compacting 0.59 [J/cm^3]of soil. Due to the limitations associated with the maximum size of the fraction that is allowed in the given method II, tests were conducted for the fractions from 0 to 10 mm.

The shear strength parameters (the internal friction angle and cohesion) were defined in the direct shear tests, which were conducted under normal and consolidation stresses from the range of 100-400 kPa. The direct shear tests were done in a shear box sized 6 × 6 cm, and in the case of the sample S 0-20 in a shear box measuring 30 × 30 cm. Due to the limitations of the shear boxes sizes, the material was sieved (when needed), in such a way that the maximum granulation was not bigger than 10% of the shear box side.

The maximum shear stress was assumed as the value corresponded to that when the horizontal strain had reached the level of 10%. For each of the materials, the four tests were done at a different vertical stress. To guarantee a proper density of the material, similar to this, obtained in the optimal moisture content conditions, each sample was dried to a constant mass, then was mixed with an amount of water, which corresponded to the water content in the optimal moisture state. In the next stage, the sample was compacted in the direct shear apparatus box in 4-5 layers, so as to obtain the maximum bulk density, similar to that with the optimal moisture content. Thus, the samples have been shearing not in a saturation state, but with the moisture close to the optimal one. When the proper density was reached, the sample was consolidated under the value of the consolidation stress which corresponded to the vertical stress at which the shear test was performed after the consolidation stage. The consolidation stage ended when the consolidation speed was stabilized at the level lower than 0.01 [mm / min]. After the consolidation stage, a shear test had been conducted. On the basis of the initial consolidation time, the maximum allowable shear displacement increment was determined. Thus, the speed of shearing was established on the level of 1 mm/min.

4. Physico-mechanical properties of selected materials

PARTICLE SIZE DISTRIBUTION

Figure 3 shows the grain size distribution curve of fly ash from the fluidized bed boiler from the power plant ‘Jaworzno’. Figure 4 depicts the grain size distribution for the aggregates 0-31.5 mm and 0-2 mm. The fly ash from the fluidized bed combustion can be divided into seven fractions: medium sand (0.2-0.63 mm – 1.35%), fine sand (0.063-0.2 mm – 28.29%), coarse silt (0.02-0.063 mm – 32.29%), medium silt (0.0063-0.02 mm – 18.57%), fine silt (0.002-0.0063 mm – 12.72%), clay (d ≤ 0.002 mm – 7.3%) (PN-EN ISO 14688-1:2006).

For the aggregate of grain size 0-2 mm, five fractions can be distinguished: fine gravel (oversized grain) (2.0-6.3 mm – 2.32%), coarse sand (0.63-2.0 mm – 27.51%), medium sand (0.2-0.63 mm – 38.28%), fine sand (0.063-0.2 mm – 31.04%), silt and clay (0.00-0.063 – 0.85%).The aggregate of grain size 0-31.5 mm consists of the following fractions: coarse gravel (20-63 mm – 2.4%), medium gravel (6.3-20.0 mm – 41.19%), fine gravel (2.0-6.3 mm – 25.17%), coarse sand (0.63-2.0 mm –12.53%), medium sand (0.2-0.63 mm – 11.34%), fine sand (0.063-0.2 mm – 6,95%), silt and clay (0.00-0.063 – 0.42%) (PN-EN ISO 14688-1:2006).

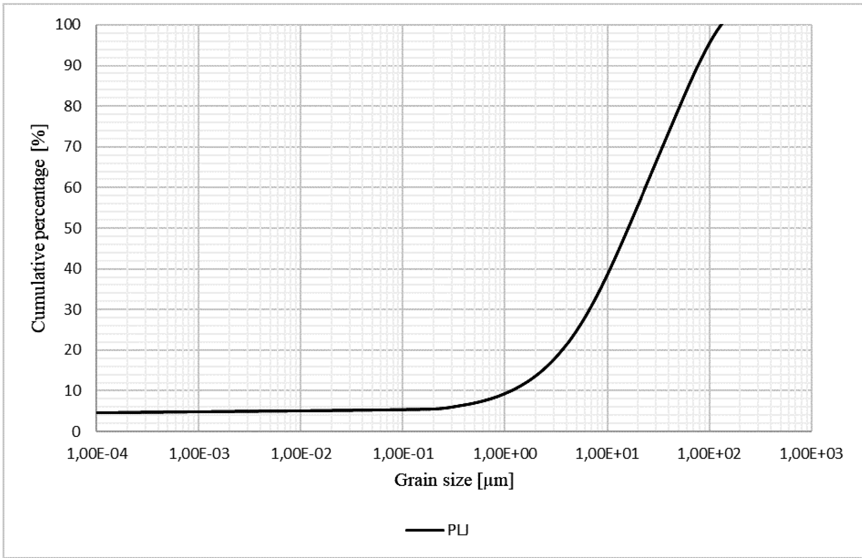

Fig. 3. The grain size distribution curve of the fly ash from the power plant 'Jaworzno' fluidized bed boiler

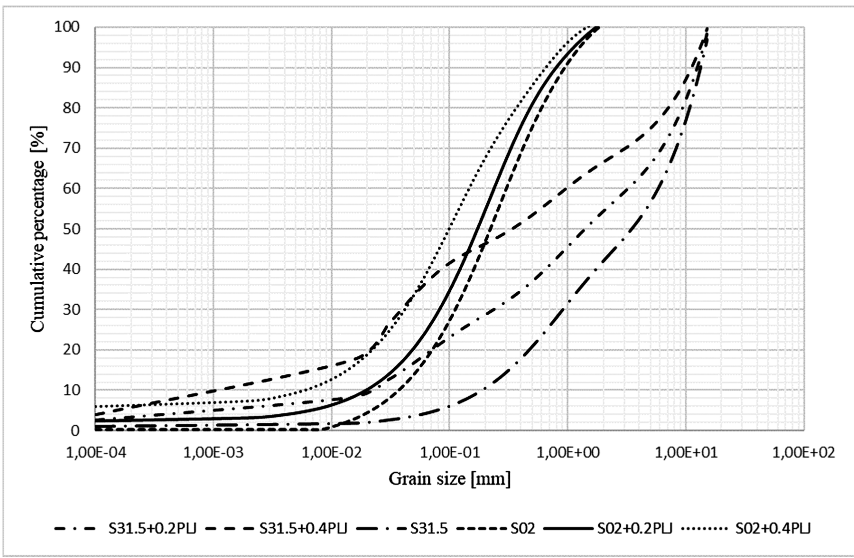

Fig. 4. The grain size distribution curves of the aggregates and their mixtures based on the colliery shale from ZG Sobieski (S31 – grain size 0-31.5 mm, SO2 – grain size 0-2 mm) and fly ash from the power plant 'Jaworzno' fluidized bed boiler

The tested aggregates differ significantly in the content of sand and stone fractions, which is visible in the curves of the particle size distribution (Fig. 4). This is reflected in the value of the sand equivalent, which determines the aggregate's frost susceptibility.

The aggregate of the grain sizes 0-2 mm consists in 82.5% with the sand fraction and its mixtures with fly ash (+0.2 PLJ; +0.4PLJ) reduce the proportion of the sand fraction to 75.5% and 62% respectively. The aggregate of the grain sizes 0-31.5 mm is a mix consists mainly of the sand (38%) and gravel fractions (58%) and its mixtures with fly ash (+0.2 PLJ; +0.4PLJ) reduce the proportion of the gravel fraction to 48% and 42% respectively.

THE SAND EQUIVALENT TEST

Few legal documents determining the requirements for the sand equivalent exist in Poland. Some of the few existing documents, however, provide conflicting information. A deeper discussion on the subject can be found in the work of Piech et al. (Piech et. al. 2015). Usually, a material is classified as non-heaving if the discussed index is larger than 35%. Therefore, the indexes would classify both kinds of the aggregates as heaving ones (the aggregate 0-2 mm: the sand equivalent – 28.8%, the aggregate 0-31.5 mm: the sand equivalent – 11.45%). This is why these aggregates are of a small usefulness for earthen structures without a modification of their properties.

FREEZE RESISTANCE

The results of the tests of the other grain sizes are shown in the Table 4.

TABLE 4

The results of freeze resistance tests on the aggregate from ZG Sobieski 0-31.5 mm

Test No.	Fraction [mm]	Sample mark	Aggregate weight before the test [g]	Weight of the aggregate after 10 cycles of freezing [g]	Loss of weight after 10 cycles of freezing [%]	Fraction share [%]
1	4.0-8.0	Z-22	480.1	148.1	69.2	5.1
2	8.0-16.0	Z-18	696.5	191.8	72.5	34.7
3	16.0-31.5	Z-21	1472.8	189.5	87.1	12.7
M_{xsr} = 75.7						

The analysis of Table 4 reveals that the tested aggregate shows a slight resistance to the changing environmental conditions. The colliery shale, which the aggregate consists of, becomes soft and muddy in the presence of water. This is why the mass loss after the freezing cycles is 76%. Because of this, the tested aggregates do not belong to any of the categories determined by the Polish Standard PN-EN 12620. The fly ash from the fluidized bed boiler shows binding properties after having been mixed with the tested aggregate, which can potentially limit its absorbability, as well as improve its freeze resistance. It seemed purposeful to carry out further tests on the ash-aggregate.

DIRECT SHEAR TESTS

Tables 5 and 6 show the obtained mechanical parameters, optimum moisture content, maximum bulk density and moisture content of the sheared samples. The aggregates S 0-31.5 were screened on the sieve 5 mm (tested fractions: 0-5 mm), because maximum grain size need to be lower than 10% of the shear box size.

TABLE 5

Mechanical properties of the aggregate from ZG Sobieski 0-2 mm and its mixtures with fluidized fly ash

Material marking	Cohesion c [kPa]	Angle of internal friction φ [°]	Optimum moisture content w_{opt} [%]	Moisture content of the tested sample w [%]	Maximum bulk density ρ [g/cm^3]	Obtained bulk density ρ [g/cm^3]
S 0-2	14.69	30.77	—	—	—	—
S 0-2 +20%pl	68.57	34.74	14.70	12.40	1.91	1.80
S 0-2 +40%pl	44.62	37.75	17.98	15.52	1.92	1.85

Sample marking used in the Tables 5 and 6 refers to the granulation of the tested material and the addition of fly ash from the fluidized bed boiler.

TABLE 6

Mechanical properties of the aggregate from ZG Sobieski 0-31.5 mm and its mixtures with fluidized fly ash

Material marking	Cohesion c [kPa]	Angle of internal friction φ [°]	Optimum moisture content w_{opt} [%]	Moisture content of the tested sample w [%]	Maximum bulk density ρ [g/cm^3]	Obtained bulk density ρ [g/cm^3]
S 0-20	36.65	34.56	10.30	13.42	2.16	1.98
S 0-5 +20%pl	48.55	40.52	15.70	15.81	1.99	1.89
S 0-5 +40%pl	55.03	39.84	18.15	16.05	1.88	1.76

An analysis of the Tables 5 and 6 shows that the moisture content and the bulk density of the tested materials is similar to their optimum moisture content and the values vary from 0.11% to 3.12%.

For both kinds of the aggregates it can be observed that the addition of fly ash improves both cohesion and the angle of internal friction. With both types of aggregate, a 40% addition of fly ash had caused a decrease in either cohesion or the internal friction angle in comparison to the mixtures with a 20% share of ash. All of the obtained shear strength parameters allow the tested materials to be used in earth structures (lower layer construction of road embankments, improving the soil substrate).

5. Summary

Both mining and energy sectors have a substantial share in waste production. The massive amount of the produced and stored waste (Fig. 1 and 2) creates the need to search for effective methods of waste management. Despite the huge progress in this field, there is still a lot of work to do in order to find new ways of managing and utilising the produced waste. The mechanical and chemical properties of the waste product may limit the possible ways of its application. Modifying additives may be a good solution in this case. The research on the properties of the mixtures based on waste is completely justified, as it creates the possibility of finding a new product, which may present better parameters and better usage possibilities.

A low resistance to weathering and a large susceptibility to frost heave characterize the colliery shale tested in this study, which is why it is vital to find a modifier of its properties. The preliminary research of its shear strength properties shows a positive influence of fly ash additive on resistance properties of ash-aggregate mixtures, as compared to the aggregate itself. The research also reveals that there is a border share of additives, which may improve the tested properties.

Within the scope of the criterion regarding the properties of ash-slag mixtures for the construction of embankments (Generalna Dyrekcja Dróg Publicznych, 1998, PN-S-02205:1998) – the values of the internal friction angle of aggregates and its mixtures with fluidal fly ash are greater than 20°, hence they do fulfill the requirements for this geotechnical parameter. The similarity of the clay fraction and the sand-gravel fraction of the tested materials are within the range designated by the above criterion.

According to the internal friction angle requirements φ (36-40°) contained in the Technical Approval AT/1802014-0064-00 (Aprobata Techniczna ITP, 2014), the values of these parameters for the mixtures S 0-2 + 40% pl and S 0-20 + 40%pl also fit in the given range. In the case of the sand equivalent index, the requirements in the Technical Approval No AT /2010-03-2576/2 are fulfilled for the S 0-2 aggregate.

However, it cannot be said that the tested mixtures fully respond the requirements of the given approbation, because the entire spectrum of tests required for the approvals was not conducted. The research focused only on the determination of the grain composition, the freeze resistance and the sand equivalent index for mixture components and shear strength parameters (φ, c) for mixtures made of them.

It should be highlighted that the research is of initial character. This work, including the research on the chemical and other mechanical mixtures properties, will be continued. However, it has to be noted that there is a risk that with a big addition of ash, the border limits of harmful element leaching will be exceeded. Some other tests on the aggregate additives should also be conducted: freeze resistance, sand equivalent, bearing capacity index. Nevertheless, the initial research had revealed the beneficial properties of aggregate-ash mixtures. Further work on the elaboration of proper recipes of such mixtures may widen the possibilities of expanding the economic use of waste.

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