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Geotechnical and chemical characteristics of ash and slag mixture of Skawina Power Plant (Poland)

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Fuel ashes are mainly utilised in civil engineering and earth structures, road engineering in particular. Tests have also been performed to evaluate them for hydraulic engineering purposes, e. g. for sealing coarse-grained materials. However, there is a high risk of exposing proximal ecosystems to emission of substances, such as heavy and alkaline metals contained in the fly ashes and the ash-slag mixtures. The wastes may also cause water mineralization, soil salinification of water and soil alkalisation as well as secondary air pollution with dust.

The research described in the paper aims at determination of basic geotechnical characteristics of the ash-slag mixture taken from the dumping site of the Skawina Power Station that has a potential for earth engineering. Moreover, there was determined the leachability of basic (Ca, Na, K, Mg) and trace (Cd, Pb, Cr, Zn, Cu) elements that could negatively influence the ecosystems in the adjacent areas.

The obtained results of the geotechnical tests of the ash-slag mixture suggest a high potential for earthworks. The requirements of the relevant standards concerning utilising fuel ashes are met; only frost-heave of the mixture is questionable. Assuming that the soil will be used for the embankment construction, i. e. above the ground water surface, the above mentioned standard requirements should not matter.

The analysis of the basic and trace elements contents as well as pH value and conductance also confirms the high potential of this material for the construction sites. The tests of leachability show that the effluent coming into existence as a result of soaking or filtration through the tested mixture should not negatively influence the ecosystems surrounding the site. There may be some doubts in this research area related to leached potassium which could pollute groundwater (water quality classes IV or V). However, assuming that the above mentioned technical requirements (Standard: PN-S-02205:1998) are met, i. e. the mixture will be placed without direct contact with groundwater and the first "biological barrier" which adopts potassium is the surface water, the tested material should be considered as suitable for building earth structures.

Key words: power plant, ash, slag, environment, leaching

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INTRODUCTION

In the year 2009 over 9.8 million tons of ash-slag mixtures from wet treatment of furnace waste were produced in Poland. In Małopolska province there were almost 390 thousand tons of these wastes. The total amount of furnace waste that is accumulated on landfills at the national level is 253.5 million tons. At the same time, in recent years there has been a very strong pressure for reusing it. In 2009 almost 18% of produced waste and in the years 2004–2007 from about 47 to 23% were used (GUS 2005, 2008, 2010). It is mainly used in civil engineering and earthworks, especially in road engineering. There are also tests on possibilities of their usage in hydrotechnical engineering, for example, for sealing coarse-grained materials. However, there is a risk that adjacent ecosystems will be exposed to emission of substances that are in fly ashes and ash-slag mixtures. These types of substances are, among other things, heavy and alkali metals, additionally this waste can be the cause of salinity and alkalinity of water and soil, as well as secondary dusting of air.

The type of burnt coal, co-burnt additions, for example, biomass, burning technology and technical parameters of appliances used in energy production processes have direct impact on the chemical composition of furnace waste. The chemical composition also depends on the way of transport and storing (Rosik-Dulewska and Karwaczyńska, 2008).

PURPOSE AND SCOPE OF TESTS

The purpose of the tests was to evaluate the basic geotechnical characteristics of the ash-slag mixture taken from the landfill of the Skavina Power Plant, that can determine its usage for earthworks, as well as leaching from its basic elements (Ca, Na, K, Mg) and trace elements (Cd, Pb, Cr, Zn, Cu), that can have a negative impact on the ecosystem that surrounds the earthwork structure.

Basic physical characteristics and compaction parameters were evaluated using standard methods. Graining was determined using the combined method – sieve (for $d \geq 0.063$ mm) and aerometric (for $d < 0.063$ mm), whereas specific density of solid particles was defined using the volumetric flask method with distilled water. Optimum moisture content and maximum dry density of solid particles were determined in the Proctor apparatus in the cylinder that has the capacity of 2.2 dm^3, at the compaction energy of 0.59 J/cm^{-3}.

Shear strength tests were carried out in a standard direct shear box apparatus in boxes that were 12 × 12 cm in cross section and 7.7 cm high, with transitional frames that created the shearing zone that was 10 mm high. Graining of the tested material was below 10 mm, it was assumed that the maximum grain size will correspond with the shearing zone's height. Samples were formed at the optimal moisture content and at the compaction indexes I_S = 0.90, 0.95 and 1.00. Earlier tests on the material from the same landfill carried out using the mentioned methods but on samples that were saturated before shearing were also taken into consideration in result analysis (Gruchot and Resiuła, 2011).

Tests on leaching of soluble substances from the ash-slag mixture were carried out using the water extract method (Journal of Laws, No. 110, Item 1263, 1999). This method consists of taking representative 1 kg samples from the ash-slag mixture landfill, then after their drying in 105 °C temperature and sieving through net sieve No. 10, taking 100 g samples and pouring them in flasks with 1 dm^3 of distilled water. Material that was prepared in this way was shaken in a laboratory shaker for 4 hours, then left for 12 hours and shaken again for 2 hours. After 6 hours the mixture was filtered through a medium filter to get water extract, for which pH, specific electrolytic conductance and some basic and trace elements content using the atomic absorption spectroscopy method (FAAS) in a UNICAM Solaar M6 spectrometer were determined.

TESTS RESULTS AND THEIR ANALYSIS

Physical and mechanical characteristics

According to the geotechnical nomenclature (PN-EN ISO 14688-2:2006), the ash-slag mixture was classified as silty sand (siSa). In graining sand fraction dominated in the amount of 64%, there were 21% of silt fraction and about 2% of clay fraction (Table 1). The gravel fraction content did not exceed 14%.

Table 1. **Geotechnical characteristics of the ash-slug mixture**

1 lentelė. **Pelenų ir šlako mišinio geotechninės charakteristikos**

Parameter	Value		
	Sample		Average
	1	2	
Fraction content, %:			
– gravel Gr: 63 ÷ 2 mm	13.7	13.7	13.7
– sand Sa: 2 ÷ 0.063 mm	62.8	64.3	63.5
– silt Si: 0.063 ÷ 0.002 mm	21.9	20.3	21.1
– clay Cl: <0.002 mm	1.6	1.7	1.7
Name acc. to PN-EN ISO 14688-2:2006	siSa	siSa	siSa
		silty sand	
Content of particles, %:			
– ≤0.075 mm	24.5	24.5	24.5
– ≤0.02 mm	12.0	12.0	12.0
Uniformity coefficient C_U (–)	13.5	13.5	13.5
Specific density ρ_s, g/cm^{-3}	2.53	2.54	2.54
Optimal moisture content w_{opt}, %*	30.0	31.2	30.6
Maximum dry density of solid particles ρ_{ds}, g/cm^{-3}*	1.258	1.268	1.263
Passive capillary h_{cp}, m	0.46	0.42	0.44
Sand equivalent SE (–)	47.70	49.55	48.63

* acc. to Gruchot and Resiuła, 2011

Specific density was on an average 2.54 g/cm^{-3}. Maximum dry density of solid particles was on an average 1.26 g/cm^{-3} with the optimal moisture content about 31% (Gruchot, Resiuła, 2011). The passive capillary was 0.4 m and the sand equivalent was 49%.

Tests on the shear strength of the ash-slag mixture showed high values of an angle of internal friction and cohesion, which depended on compaction and saturation. In case of the mixture at the optimal moisture content increase in the compaction index from I_S = 0.90 to 1.00 caused the increase in the angle of internal friction from 39 to 43° and in cohesion from about 15 to 2 kPa (Table 2). Saturation of the mixture caused the increase in the moisture content of 6 to 8% and – as an effect – significant decrease in shear strength parameters, in case of the angle of internal friction it was up to about 20° and cohesion up to about 6 kPa, for each compaction index.

The tested ash-slag mixture also had high values of the bearing ratio (Table 3). For samples loaded with the force of 22 N directly after compaction, the bearing ratio was 44% and after four days of soaking and increase in the moisture content of 8%, the bearing ratio decreased to about 33%. Values of linear swelling were negligibly small and did not exceed 0.1%.

Table 2. **Values of the angle of internal friction (ϕ) and cohesion (*c*) of the ash-slag mixture**

2 lentelė. **Pelenų ir šlako mišinio vidinės trinties kampas (ϕ) ir sankiba (*c*)**

Compaction index I_S (–)	Unsaturated samples		Saturated samples	
	ϕ, °	C, kPa	ϕ, °	C, kPa
0.90	39.1	14.8	18.0	2.4
0.95	40.1	21.5	17.5	5.6
1.00	43.4	25.3	21.4	5.4

Table 3. **Values of the bearing ratio and linear swelling for the ash-slug mixture**

3 lentelė. **Pelenų ir šlako mišinio tvaros santykis ir brinkimas**

Time of soaking, days	Moisture content in piston penetration zone w, %	Bearing ratio BR, %	Linear swelling p, %
0	29.2	43.9	–
4	37.3	33.6	0.03

Evaluation of mixture usability for road engineering

In case of using materials that have limited usability, all objections concerning technology and place of building for these materials should be taken into consideration. The Polish norm PN-S-02205:1998 classifies ash-slag mixtures as materials suitable for earthworks under certain conditions and allows their usage in the following cases:

- for bottom layers of embankments below the frost penetration zone if they are in dry places or they are isolated from water,
- for top layers of embankments within the frost penetration zone if they are improved with hydraulic binding agents, like cement, lime.

Ash-slag mixture which is allowed for using in road embankments should have graining as coarse as possible as well as fulfil the norm requirements (PN-S-02205:1998). The sand-gravel fraction content was about 77% and there were about 25% of grains below 0.075 mm, which was 2 times over and 3 times below the required values, respectively. The bearing ratio was 3 times higher and the angle of internal friction 1.5 to 2 times higher than the required values. Also values of the maximum dry density (higher than the required values by 0.3 g/cm^{-3}), passive capillary (lower than the values by 1.5 m) and linear swelling (negligibly small) are in concert with the requirements of the aforementioned norms. Therefore it can be stated that the ash-slag mixture at the optimal moisture content fulfils all norm requirements (Table 4). In case of saturated mixture values of the angle of internal friction are below or on the edge of the norm requirements, which is a confirmation of isolating mixture from water. Excess of water causes reducing of contact strength and, as a result, a significant decrease of the shear strength. Therefore when using the ash-slag mixture for earthworks, protection from water should be used.

It should be emphasized that after 4 days of soaking the mixture had high values of the bearing ratio, which exceeded the norm requirements by 3 times.

The sand equivalent of the tested ash-slag mixture was about 49% and the passive capillary was 0.4 m, therefore, according to PN-S-02205:1998, it was classified as non-frost-susceptible soils (Table 4).

Test on leaching of soluble substances from ash-slag mixture

Analysis of the results of leaching tests of the ash-slag mixture taken from the landfill after it was delivered there using hydraulic transport raises questions about its previous washing. The proportion of water to waste during hydraulic transport in the form pulp is 1:5–1:20 and most often 1:10 (Rosik-Dulewska, Karwaczyńska, 2008). Another factor that has an impact on potential changes of deposited waste chemistry is a possibility of their wash-

Table 4. **Ash-slag mixture characteristics in comparison to norm requirements**

4 lentelė. **Su norminėmis reikšmėmis palygintos pelenų ir šlako mišinio charakteristikos**

No.	Parameter	Symbol	Unit	Value	
				Determined	Required by PN-S-02205
1	Graining:				
	• Sand-gravel fraction content	–	%	77.2	≥35
	• Grains below 0.075 mm content			24.5	≤75
2	Maximum dry density	ρ_{ds}	g/cm^3	1.263	≥1.0
3	Bearing ratio after 4 days of soaking	BR	%	33.6	≥10
	Linear swelling:				
	• without load			0.08	≤2
	• with load 3 kN/m^2		%	0.04	≤0.5
	• with load 7 kN/m^2			0.03	no value
4	Angle of internal friction:				
	• unsaturated samples	ϕ	°	39.1–43.4	
	• saturated samples			17.5–21.4	≥20
5	Passive capillary	h_{cp}	M	0.44	≤2.0

ing by rainwater and by re-pumped supernatant water, changes in this range can also be caused by the influence of different climatic factors (Woźniak, Żygadło, 2002). Trace elements that occur in furnace waste are in general hard to leach, their content in eluate obtained during tests is usually on the detection limit and only in some cases exceeds limits that are acceptable for drinking and surface water (Rosik-Dulewska, Karwaczyńska, 2008; Kapuściński, Strzałkowska, 2005; Kucowski et al., 1993). Low solubility of heavy metals is usually caused by a strong alkaline reaction of water extract from ashes (pH = 9.0 ÷ 12.0) (Kapuściński et al., 2005). In case of tested furnace waste reaction of eluate was relatively low and equaled 6.5 (Table 5). Low content of the analyzed elements was also stated. It is especially noticeable in case of Cd, Pb, Cu, Zn content, the concentrations of which were a few times lower than in case of ash tests results (both static and dynamic), presented by Rosik Dulewska and Karwaczyńska (2008) and Woźniak and Żygadło (2002). A typical feature of ash filtrate is high salt content, in its composition there are mainly sulphates, calcium, magnesium and, in lower quantity, sodium, potassium and others. These salts are easily and quickly leached, but they are not a threat to humans, they can only have negative influence on soil and water environment (Woźniak, Żygadło, 2002). Analysis of the results was carried out in the aspect of evaluation of ash-slag influence on the surrounding ecosystem. Considering lack of guidelines, evaluation was carried out with regard to surface and underground water pollution, assuming that water percolating through mixture layers can get to these waters (Journal of Laws, No. 257, Item 1545, 2011; Journal of Laws, No. 143, Item 896, 2008). In the evaluation there were two documents used: the Regulation of Minister of Economy and Labour on procedures of allowing waste for given type of landfill (Journal of Laws, No. 186, Item 1553, 2005) and the Regulation of Minister of Environment on conditions, which have to be fulfilled when introducing sewage to water and soil, as well as on substances which are particularly harmful to water environment (Journal of Laws, No. 137, Item 984, 2006).

Waters in the environment are enriched and impoverished in substances from the atmosphere, lithosphere, and biosphere. These substances have a natural or anthropogenic origin. For evaluation

Table 5. **Results of tests on leaching of soluble substances from the ash-slag mixture**

5 lentelė. **Pelenų ir šlako mišinio išplovimo eksperimento rezultatai**

No.	Determined index	Unit	Content in eluate
1	pH	–	6.5
2	Conductance	$\mu S/cm^{-1}$	450
Basic and trace elements content			
3	Cd	$\mu g/dm^{-3}$	<0.4
4	Pb		1.0–1.2
5	Zn		6.2–6.3
6	Cu		2.3–2.9
7	Cr		6.3–8.3
8	Na	Mg/dm^{-3}	12.2–13.1
9	K		16.8–20.3
10	Ca		55.4–64.2
11	Mg		27.9–37.8

of surface water quality the Regulation (Journal of Laws, No. 257, Item 1545, 2011) is used, which is based on the fact that water is a place for organisms to live. The basis of the water quality classification is the evaluation of the quality of lives of organisms chosen as indicators. In water eluate of the analyzed mixture there is no life, nevertheless, in case of its introducing to the environment (usage in earthworks) it can have influence on chemistry and quality of waters. Therefore it can be assumed that the tested water extract (eluate) is a sample of surface or underground water. Determined values of pH at the level of 6.5 and conductance at the level of 450 $\mu S/cm^{-1}$ (Table 5) allow classifying the tested sample for water purity Class I. The Regulation used for evaluation does not determine limit values for sodium and potassium, therefore their content was not evaluated. The magnesium and calcium content in the eluate, similarly to pH and conductance, allowed to classify it for water purity Class I. Determined heavy metals contents (Cd, Pb, Zn, Cu and Cr) are much lower than allowable values (limit?) and have no influence on potential water pollution.

Water eluate evaluation as a sample of underground water was carried out according to the Regulation (Journal of Laws, No. 143, Item 896, 2008) on criteria and methods for ground water quality evaluation. Similarly to surface water values of pH, conductance and heavy metals contents did not exceed limit values and matched water purity Class I.

The sodium content also classified the tested sample for water purity Class I, only magnesium and calcium contents classified it for Class II. A significant problem appeared in case of the potassium content – the sample was classified for Class IV and Class V. Therefore, it should be remembered (which was pointed out when discussing mixture's physical and mechanical characteristics) that when using it for earthworks protective layers against water should be used. Technologies used nowadays in earthworks fulfil this condition.

Another Regulation (Journal of Laws, No. 186, Item 1553, 2005) presents allowable values of trace elements concentrations for three types of landfills: neutral, dangerous and different than dangerous or neutral. In the evaluation that was carried out the most strict allowable values for neutral waste were used (Table 6). Analysis of the results of the leaching tests allowed to state that cadmium, chromium, cooper, lead and zinc contents were many times lower than the allowable values, for example, the total chromium content was 8 times lower and zinc 64 times lower than the allowable value. Alkaline metals contents, values of salinity or reaction are not taken into consideration in this Regulation. From its point of view the mixture can be safely deposited, so it should not have a negative influence on natural environment.

The tested eluate can also be treated as a kind of sewage that is introduced to the environment. The Regulation of Ministry of Environment on quality of sewage that is introduced into water or soil from 2006 was used for water extract evaluation in the mentioned aspect. This Regulation does not standardise the conductance and magnesium and calcium content. Comparing the test results with the allowable values presents them in a very good way. The evaluated values in relation to the allowable ones are one, two or even three orders lower. Comparing allowable 2 000 mg Zn/l with determined 6 mg/l is the most extreme example. On the other hand, for the most problematic potassium the difference between the determined and allowable values is almost four times lower.

CONCLUSIONS

Results of the geotechnical characteristics tests on the ash-slag mixture allow to state its high potential for earthwork purposes. The norm requirements

Table 6. **Chosen limit values from the norms used in evaluation of the ash-slag mixture**

6 lentelė. **Pelenų ir šlako mišinio įvertinimo rodikliai**

Parameter or element		Geochemical background[1]	Surface water[2]	Underground water[3]	Landfills[4]	Sewage[5]
pH		6.5–8.5	6.0–8.5	6.5–9.0 I	Brak	6.5–9.0
Conductance uS/cm^{-1}		200–700	≤1 000	700 I	No value	No value
Cd	µg/dm^{-3}	1–5	≤0.45–1.5	1	4	50 (200)
Pb	µg/dm^{-3}	1–10	7.2	10	40	100 (500)
Zn	µg/dm^{-3}	5–50	≤1 000	50	400	2000
Cu	µg/dm^{-3}	1–20	≤50	10	200	100 (200)
Cr	µg/dm^{-3}	1–10	≤50	10	50	500
Na	Mg/dm^{-3}	1–60	No value	60 I. 200 II and III. 300 IV	No value	800
K	Mg/dm^{-3}	5–10	No value	10 I and II. 15 III. 20 IV	No value	80
Ca	Mg/dm^{-3}	2–200	≤100	50 I. 100 II. 200 III. 300 IV	No value	No value
Mg	Mg/dm^{-3}	5–30	≤50	30 I. 50 II. 100 III	No value	No value

[1] Kabata-Pendias and Pendias, 1999;

[2] Journal of Laws, No. 257, Item 1545, 2011;

[3] Journal of Laws, No. 143, Item 896, 2008;

[4] Journal of Laws, No. 186, Item 1553, 2005;

[5] Journal of Laws, No. 137, Item 984, 2006; I, II, III – purity classes

(PN-S-02205:1998) concerning application of power waste are fulfilled, only frost heaving classifies it as a questionable soil. Assuming that the tested mixture will be built in the embankment according to the mentioned norm recommendations – so above the water surface – it should not be a problem.

Analysis of the basic and trace elements as well as pH and conductance confirms high usability of this material for earthwork purposes. As the leaching tests showed, eluate from percolation or filtration through the tested mixture should not have a negative influence on the surrounding ecosystem. Doubts in this matter are raised only by potassium leaching in relation to potential underground water pollution (purity Class IV, V). On the other hand, assuming that the mentioned technical conditions will be fulfilled (PN-S-02205:1998 norm requirements), i.e. that the mixture will have no direct contact with ground water and the first "biological barrier" which will absorb potential eluate will be the surface water for which the quality standards are fulfilled, the tested material should be accepted as suitable for using in earthworks.

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SKAVINOS JĖGAINĖS (LENKIJA) PELENŲ IR ŠLAKO MIŠINIO GEOTECHNINĖS IR CHEMINĖS SAVYBĖS

S a n t r a u k a

Kuro pelenai dažnai naudojami civilinėje inžinerijoje, žemės darbuose ir kelių statyboje. Nemažas jų potencialas siejamas ir su hidraulinėmis savybėmis, ypač naudojant izoliavimo konstrukcijoms. Tačiau šių atliekų panaudojimas yra pavojingas aplinkiniams rajonams, ypač dėl taršos sunkiaisiais ir šarminiais metalais, kurių gausu minėtame mišinyje. Dėl to gali pakisti vandens ar dirvožemio mineralizacija, padidėti jų druskingumas, galima oro tarša pavojingomis dulkėmis. Straipsnyje apibūdinamos pagrindinės Skavinos jėgainės išmetamo pelenų ir šlamo mišinio, pasižyminčio nemažu praktinio panaudojimo potencialu, geotechninės savybės, analizuojamos pagrindinių (Ca, Na, K, Mg) ir retųjų elementų (Cd, Pb, Cr, Zn, Cu) išplovimo galimybės, galinčios paveikti gretimas ekosistemas.

Gauti rezultatai atskleidė didelį pelenų ir šlako mišinio praktinį panaudojimą žemės darbams, jo savybės atitinka normatyvus, išskyrus kriogeninius procesus. Mišinį siūloma naudoti dambų statyboms, t. y. statyboms virš gruntinio vandens lygio.

Raktažodžiai: jėgainė, pelenai, šlakas, aplinkosauga, išplovimas