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INFLUENCE OF LOADING ON THE CBR RATIO OF FUEL ASHES FROM THE "SKAWINA" POWER PLANT

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Abstract: The aim of this paper was to establish the influence of loading on the values of the CBR ratio of the ash–slag mixture and the fly ash from the "Skawina" Power Plant. The CBR ratio was determined at the loading of 22 and 44 N and without loading, both for the samples directly after compaction and after 4 days of soaking in water. The investigation was conducted to determine the usability of the wastes tested for the road engineering purposes.

In terms of geotechnics, the ash–slag mixture was classified as well-graded non-swelling clayey sands, and the fly ash as well-graded swelling silts. An increase in the loading of the samples directly after compaction led an the increase in the CBR ratio of the materials tested. Whereas after 4 days of soaking in water, as a result of an increase in the moisture content, a decrease in the CBR ratio occurred, but with an increase in the loading. It increased from 26 to 35% for the ash–slag mixture and from 1 to 11% for the fly ash.

The analysis of the usability of the fuel ashes tested for road engineering purposes makes possible the statement that only the ash–slag mixture meets the requirements of the pertinent standards and can be used for erecting embankments, provided that they are built in dry places or insulated from water.

1. INTRODUCTION

The production of thermal and electric power in Poland is based mainly on burning hard and brown coal. The side effect of this process is generation of huge quantities of solid combustion products, such as fly ashes and ash–slag mixtures. The estimated amount of fuel ash generated per every kilowatt-hour of energy ranges from 35 to 220 g, which is over 15% of the overall amount of the accumulated industrial wastes (HYCNAR [3], PISARCZYK [4]). Every year, there are produced in Poland about 4.5 mln tons of fly ashes and 6.8 mln tons of ash–slag mixtures, about 70% of which is commercially utilised (ZABIELSKA-ADAMSKA [5]). Therefore, the issue of utilizing fuel ashes without depositing them on damping sites becomes an essential problem. The range and ways of utilisation of these wastes depend on their chemical and physical properties, including geotechnical ones (GRUCHOT [1], [2], ZAWISZA et al. [7], ZAWISZA and ZYDROŃ [9], ZYDROŃ and ZAWISZA [10]).

Fuel ashes constitute valuable material, which is used for the production of building materials, in engineering works connected with, e.g., macrolevelling and reclamation of derelict lands as well as in road engineering as a material for building embankments or for the stabilisation of soils. Using fuel ashes as a substitute for mineral soils makes it possible to improve landscape values, to reduce the number and magnitude of dump sites, troublesome for the environment, as well as to diminish the exploitation of natural raw materials.

2. AIM AND SCOPE OF TESTS

Establishing the influence of loading on the values of the CBR ratio of fuel ashes from the "Skawina" Power Pant was the aim of our research. The materials tested were: the ash–slag mixture from the quarter C5 of the dumping site and fly ashes taken directly from under the power plant electrofilters.

Basic physical properties and compactibility parameters were determined in accordance with the standard (PN-B-04481:1988). Grain-size distribution was determined using sieve method for grains and particles whose diameters were larger than 0.053 mm and areometric method for the particles with the diameters smaller than 0.053 mm according to the standard [12]. Dry density of solid particles of the materials tested was determined in distilled water using volumetric flask method. Optimum moisture content and maximum dry density of solid particles were determined in Proctor apparatus equipped with the cylinders of the volume of 2.2 dm^3 for the ash–slag mixture and 1.0 dm^3 for the fly ashes, at the compaction energy of 0.59 Jcm^{-3}.

The tests of the CBR ratio were conducted using the samples of the ash–slag mixture of a granulation less than 20 mm and the samples of fly ashes of a full granulation in accordance with the standard [15]. An initial moisture content was determined also according to the standard [15] out of the compactibility curve for each material and it corresponded to 99% of the value of the maximum dry density of solid particles (table 1). The compaction index of the samples ranged from 0.97 to 0.99.

Table 1

Optimum moisture content and moisture content taken for the tests of the CBR ratio of the fuel ashes

Material	Moisture content (%)	
	Optimum W_{opt}	For the tests of the CBR ratio $W^{*}_{CBRtest}$
Ash–slag mixture	30.6	29.5
Fly ash	32.7	31.4

* On the basis of [15].

The values of the CBR ratio were determined using the samples directly after compaction and after 4 days of soaking up water [15], without loading and at the loading with the force of 22 N (required by the standard [15]) and 44 N, and the penetration of the bolt, of the surface of 20 cm^2, to the depth of 2.5 and 5.0 mm with the velocity of 1.25 $mm \cdot min^{-1}$. The higher value of the CBR ratio was taken as a reliable value. During soaking, an increase of the sample height caused by its saturation with water was registered. The linear swelling was determined as the ratio of the height increase to the initial height of the sample and expressed as a percentage. The tests were carried out twice. An analysis of the results obtained was carried out based on the average values of the CBR ratio and the moisture content in the zone of bolt penetration.

3. RESULTS AND THEIR ANALYSIS

3.1. ASH–SLAG MIXTURE

Geotechnically, the ash–slag mixture corresponded to well-graded clayey sands (clSa) [[11], [12]. A sandy fraction prevailed in the grain-size distribution, its content was around 68%. The content of a cobble fraction did not exceed 16%, a silt fraction was 16% and a clay one – below 1% (table 2).

Table 2

Geotechnical characteristics of the ash–slag mixture

Parameter	Ash–slag mixture		
	Sample 1	Sample 2	Mean
Fraction content (%)			
gravel Gr: 63÷2 mm	17.2	14.6	15.9
sand Sa: 2÷0.063 mm	74.7	62.2	68.4
silt Si: 0.063÷0.002 mm	7.9	22.3	15.1
clay Cl: < 0.002 mm	0.2	0.9	0.6
Soil name according to [11], [12]	clSa	clSa	clSa
	Clayey sand		
Content of particles (%):			
≤ 0.075 mm	11.0	26.0	18.5
≤ 0.02 mm	3.0	9.0	6.0
Uniformity coefficient C_U (–)	4.6	10.4	7.5
Coefficient of curvature C_C (–)	0.7	1.2	0.9
Optimum 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
Density of solid particles ρ_s (g·cm^{-3})	2.47	2.49	2.48
Passive capillarity *Hkb* (m.)	0.46	0.42	0.44
Sand equivalent *WP* (–)	47.70	49.55	48.63

The content of the particles with diameters smaller than 0.075 mm was equal to 18.5% on average, and that of the particles whose diameters were smaller than

0.02 mm – 6.0%. The coefficient of the granulation curvature *C* equal to 0.92 testifies to good grading.

The maximum dry density of solid particles of the ash–slag mixture amounted, on average, to 1.263 g·cm^{-3} at the optimum moisture content close to 30.6%. The passive capillarity amounted to 0.44 m and the sand equivalent – to 48.6%.

Table 3

Values of CBR ratio and linear swelling for the ash–slag mixture

Load (N)	Time of soaking (days)	Moisture content in bolt penetration zone *w* (%)		CBR ratio $W_{noś}$ (%)		Linear swelling *p* (%)	
		For the sample	Mean	For the sample	Mean	For the sample	Mean
0	0	28.4	28.47	33.5	31.70	–	–
		28.5		29.9		–	
	4	36.9	36.77	29.8	26.20	0.08	0.08
		36.6		22.6		0.08	
22	0	29.1	29.22	44.5	43.90	–	–
		29.3		43.3		–	
	4	37.0	37.27	38.1	33.55	0.05	0.03
		37.5		29		0.00	
44	0	31.1	30.27	38.9	38.00	–	–
		29.5		37.1		–	
	4	37.0	36.94	34.1	35.20	0.02	0.02
		36.9		36.3		0.01	

The ash–slag mixture tested was characterised by high values of CBR ratio (table 3), depending on the changes of the moisture content caused by the soaking of samples (figure 1a) and their loading (figure 2a):

- for the samples without loading directly after compaction, the CBR ratio amounted, on average, to 32%, whereas after a 4-day soaking, at an increase in the moisture content by more than 8%, a decrease to 26% in the CBR ratio occurred,
- for the samples loaded with 22 N directly after compaction, the CBR ratio amounted, on average, to about 44%, an increase in the moisture content after a 4-days soaking amounted to 8%, and the CBR ratio diminished to 33.5%,
- for the samples loaded with 44 N, the CBR ratio directly after compaction amounted to 38%, whereas after a 4-day soaking it dropped to slightly above 35% at the rise in moisture content by less than 7%.

The analysis of the influence of moisture content on CBR ratio allows us to conclude that its increase by about 6 to 8% caused a decrease in the CBR ratio by around 3 to 10% compared to the samples directly after compaction. Whereas an increase in the load value from 0 to 22 N for the samples directly after compaction caused the rise in CBR ratio from about 32 to 44%. Further increase in loading to 44 N resulted in a decrease in CBR ratio to 38% (figure 2a). In the case of the tests after a 4-day soaking, the rise in CBR ratio occurred and ranged from 26.2% for the samples without loading to 35.2% for the samples loaded with 44 N.

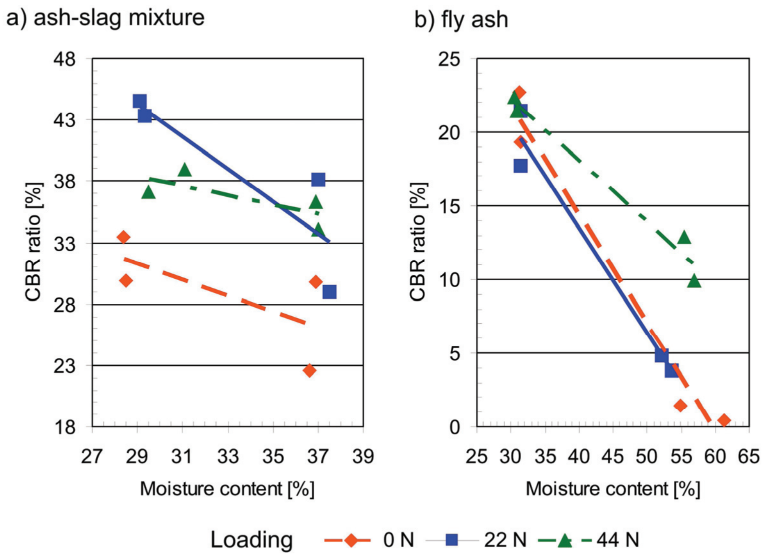

Fig. 1. Influence of moisture content on CBR ratio of fuel ashes

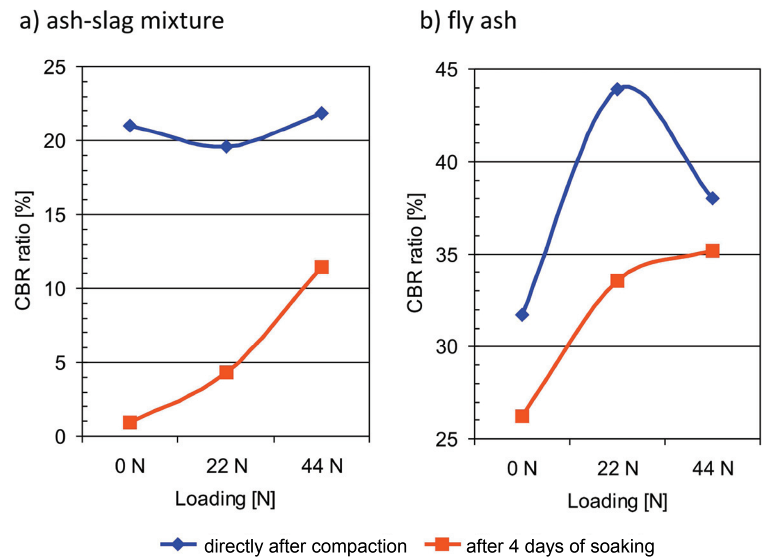

Fig. 2. Influence of loading on CBR ratio of fuel ashes

Summing up, one can forecast that while isolated from water, the weight of the road pavement structure will guarantee retaining the bearing capacity of the subsoil made of the ash–slag mixture.

The linear swelling of the ash–slag mixture was not marked and did not exceed 0.1% (table 3, figure 3a). The biggest increase in the linear swelling was observed after the first day of soaking, and then its stabilisation occurred. It should be stressed that an increase in loading caused a decrease in the linear swelling.

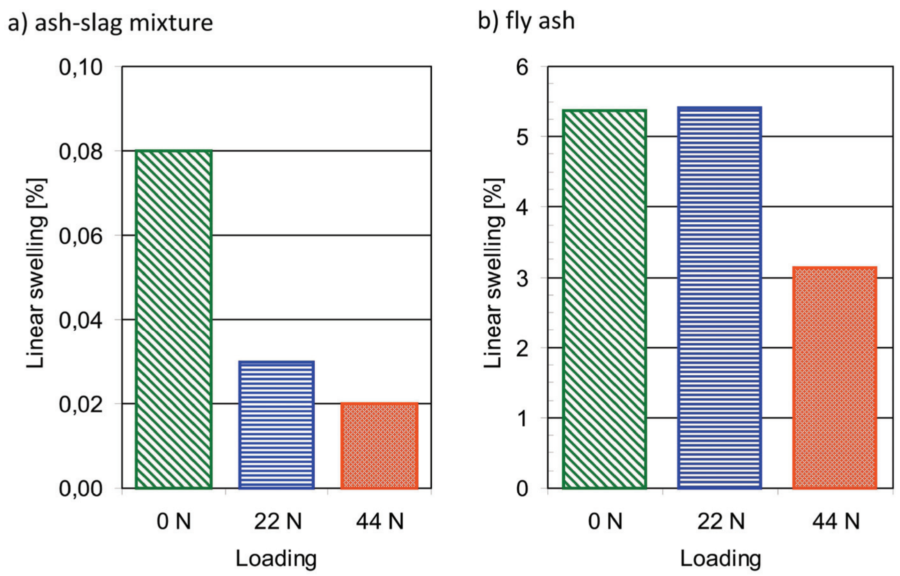

Fig. 3. Influence of loading on linear swelling of fuel ashes

3.2. FLY ASH

Geotechnically, fly ash corresponded to well-graded silts (Si) [11], [12]. Silt fraction prevailed in the grain-size distribution and its content amounted, on average, to 87%, sand fraction content reached 11%, and clay fraction was less than 2% (table 4). The coefficient of the granulation curvature *C* exceeded 3, which indicated non-uniform granulation of the material.

The content of particles whose diameters were smaller than 0.075 mm amounted, on average, to 94%, and that of the particles with diameters smaller than 0.02 mm – to 13.5%.

The maximum dry density of the solid particles of fly ash was equal, on average, to 1.17 g·cm^{-3} at the optimum moisture content of 32.7%. Passive capillarity was equal to 0.53 m.

Table 4

Geotechnical characteristics of fly ash

Parameter	Fly ash		
	Sample 1	Sample 2	Mean
Fraction content (%)			
sand Sa: 2÷0.063 mm	6.9	14.8	10.9
silt Si: 0.063÷0.002 mm	91.1	83.7	87.4
clay Cl: < 0.002 mm	2.0	1.5	1.7
Soil name according to [11], [12]	Si	Si	Si
	Silt		
Content of particles (%)			
≤ 0.075 mm	96.0	92.0	94.0
≤ 0.02 mm	14.0	13.0	13.5
Uniformity coefficient *U* (–)	7.5	5.9	6.7
Coefficient of curvature of the gradation curve *C* (–)	5.54	4.35	4.94
Optimum moisture content w_{opt} (%)	32.18	33.20	32.69
Maximum dry density of solid particles ρ_{ds} (g·cm^{-3})	1.178	1.165	1.171
Density of solid particles ρ_s (g·cm^{-3})	2.69	2.64	2.66
Passive capillarity *Hkb* (m)	0.55	0.52	0.53

The fly ash was characterised by smaller values of the CBR ratio (table 5) in comparison to the ash–slag mixture, but this radio also depended on the sample moisture content (figure 1b) and its loading (figure 2b):

- for the samples without loading directly after compaction, the CBR ratio amounted, on average, to 21%, whereas after a 4-day soaking, at an increase in the moisture content by more than 27%, a decrease in the CBR ratio to 0.9% occurred,
- for the samples loaded with 22 N directly after compaction, the CBR ratio was close to 20%, and after a 4-day soaking, at an increase in the moisture content by 21.4%, it decreased to 4.3%,
- for the samples loaded with 44 N, the CBR ratio directly after compaction amounted to about 22%, and after a 4-day soaking, it dropped to 11.4% at the rise in the moisture content by 26%.

Analysing the influence of a moisture content on the value of the CBR ratio one can state that its increase by about 21 to 27% causes a decrease in the CBR ratio to about 1% for the samples without loading and to about 11% for the samples loaded with 44 N. The influence of loading on the CBR ratio for the samples directly after compaction is little, the values of this ratio vary from 20 to 22% (figure 2b). Whereas an increase in the loading from 0 to 44 N in the test after a 4-day soaking is significant; the CBR ratio increase ranges from 0.9 to 11.4%.

Table 5

Values of CBR ratio and linear swelling of fly ash

Load (N)	Time of soaking (days)	Moisture content in bolt penetration zone w (%)		CBR ratio $w_{noś}$ (%)		Linear swelling p (%)	
		For the sample	Mean	For the sample	Mean	For the sample	Mean
0	0	31.4	31.3	19.30	21.00	–	–
		31.2		22.70		–	
	4	54.9	58.1	1.40	0.90	6.14	5.36
		61.3		0.40		4.58	
22	0	31.5	31.4	21.40	19.55	–	–
		31.4		17.70		–	
	4	52.1	52.8	4.80	4.30	5.98	5.41
		53.6		3.80		4.83	
44	0	30.5	30.4	22.40	21.90	–	–
		30.9		21.40		–	
	4	57.0	56.3	9.90	11.40	2.87	3.14
		55.5		12.90		3.40	

The fly ash was characterised by a considerably bigger linear swelling in comparison with the ash–slag mixture (figure 3b). A linear swelling of the samples without loading and loaded with 22 N equalled, on average 5.4%, and that of the samples loaded with 44 N – 3.1%. The fly ash, just as the ash–slag mixture, showed the biggest increase in a linear swelling after the first day of soaking up water.

3.3. COMPARISON OF THE RESULTS

Comparing the results of the tests carried out to establish the CBR ratio of both kinds of fuel ashes, one can state that the ash–slag mixture was characterised by higher values (figure 4). Directly after compaction, the CBR ratio of the ash–slag mixture was 1.5 times higher for the samples without loading and, on average, 2 times higher at the loading of 22 and 44 N.

After 4 days of soaking the samples, the CBR ratio decreased. In the case of ash–slag mixture, this decrease ranged from 3 to 10% compared to the ratio of the samples subjected to the test directly after compaction. For the samples of the fly ash without loading and loaded with 22 N, almost total loss of the bearing capacity took place. Only at the loading of 44 N, the values of CBR ratio of the fly ash amounted, on average, to 11%, but it was still a decrease in the value by over 3 times when compared to the ash–slag mixture.

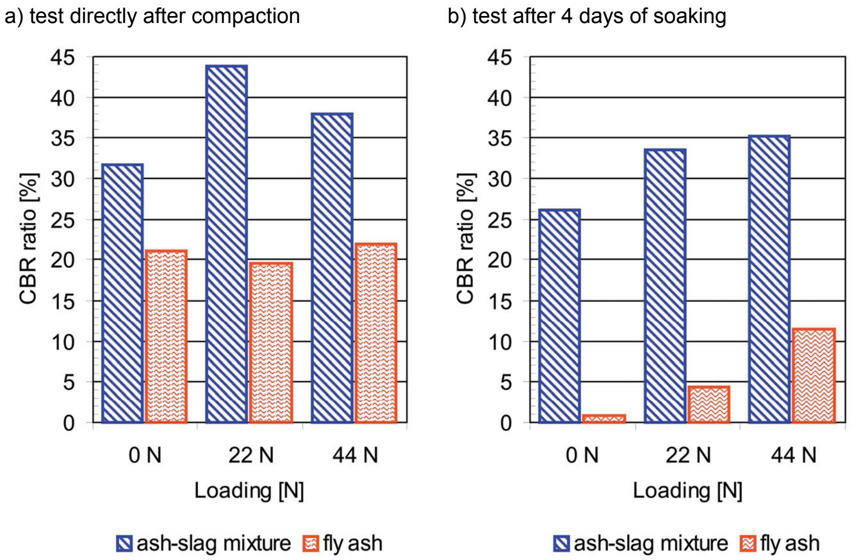

Fig. 4. Comparison of the results of tests determining CBR ratio of fuel ashes

While analysing a linear swelling, one can state that in the case of the ash–slag mixture it is negligibly small and does not exceed 0.1%. Whereas a linear swelling of the fly ash is big and together with an increase in the loading it decreases from over 5 to about 3%. The observations reveal that mainly the upper part of the sample of the height of 3–4 cm swells. In this layer, an intensive loosening of the material and an increase in the moisture content are observed, which is responsible for a significant decrease in the value of the CBR ratio.

4. THE ANALYSIS OF THE RESULTS OF TESTS IN THE ASPECT OF USABILITY OF FUEL ASHES FOR BUILDING ROAD EMBANKMENTS

The analysis of the usability of fuel ashes from the "Skawina" Power Pant for road engineering purposes was conducted based on the standard [15], taking into consideration the factors influencing the swelling properties of the wastes, the ash grain-size distribution, maximum dry density of solid particles, CBR ratio after 4 days of soaking and linear swelling.

The ash–slag mixture. Its grain-size distribution corresponds to clayey sands, the passive capillarity amounts to 0.44 m, so it is less than 1 m, and the sand equivalent equals 49, so it is greater than 35. These features allows us to qualify this mixture as a non-swelling soil (table 6).

Table 6

Evaluation of usability of the ash–slag mixture for road engineering purposes

Parameter	Unit	Standard requirements	The value obtained	Assessment
Grain-size distribution:				
sand–gravel fraction content	%	≥ 35	87.9	+
content of grains with diameters smaller than 0.075 mm	%	≥75	18.5	+
Maximum dry density of solid particles ρ_{ds}	g·cm^{-3}	≥ 1.0	1.263	+
CBR ratio after 4 days of soaking	%	≥ 10	34.85	+
Linear swelling of material	%	≤ 0.2	0.03	+
(+) – usable for road engineering purposes				

Sand–gravel fraction content is as high to as 87.9%, which exceeds the standard minimum requirements over 2 times, whereas the content of the particles finer than 0.075 mm equals 18.5%, which is over 4 times less than the permissible standard maximum. Similarly, the mixture fulfils the requirements for the maximum dry density of solid particles, which should be greater than 1 g cm^{-3} and equals 1.26 g·cm^{-3}.

The CBR ratio of the samples loaded with 22 N after 4 days of soaking was close to 35%, so over 3.5 times higher than the required minimum. Linear swelling was also much below the required maximum value and equalled 0.03%.

Summing up, it can be concluded that the ash–slag mixture meets the requirements of usability for road engineering purposes.

The fly ash. Its grain-size distribution corresponds to that of silts and the value of its passive capillarity amounts to 0.53 m, which allows the fly ash to be qualified as a swelling soil (table 7). The content of sand–gravel fraction is more than twice lower than the minimum required and equals about 14.5%, and the content of grains finer than 0.075 mm reaches 94%, which is by 19% higher than the maximum required. The CBR ratio determined after 4 days of soaking is more than twice lower than the minimum required and equals 4.3%, whereas the linear swelling reaches 5.4%, which exceeds many times the maximum value of 0.2%.

The fly ash fulfils only the criterion of the maximum dry density, which should be greater than 1 g·cm^{-3}, and amounts to 1.17 g·cm^{-3}.

Considering the above criteria it should be inferred that fly ash does not meet the requirements allowing its use for road engineering purposes. Nonetheless it should be noticed that, as revealed the tests (ZAWISZA et. al. [6], ZAWISZA and KŁĘK [7], ZAWISZA and SOBULA [8]), it can be used for the above purposes after stabilisation with hydraulic binders.

Table 7

Assessment of usefulness of fly ash for road engineering purposes

Parameter	Unit	Standard requirements	The value obtained	Assessment
Grain-size distribution				
sand–gravel fraction content	%	≥ 35	14.55	–
content of grains < 0.075 mm	%	≤ 75	94	–
Maximum dry density of solid particles ρ_{ds}	$g \cdot cm^{-3}$	≥ 1,0	1.171	+
CBR ratio after 4 days of soaking	%	≥ 10	4.30	–
Linear swelling	%	≤ 0.2	5.41	–
(+) – usable for road engineering purposes (–) – unusable for road engineering purposes				

5. CONCLUSIONS

The analysis of the results of testing the fuel ashes from the "Skawina" Power Plant enables the following conclusions to be drawn:

1. CBR ratio of the wastes tested depended on their moisture content and the loading. Its highest values were obtained for the samples directly after their compaction. An increase in the moisture content of the wastes as a result of their 4-day soaking up water led to an insignificant decrease in CBR ratio of the ash–slag mixture and almost complete loss of bearing capacity of the fly ash.

2. An increase in the loading from 0 to 44 N resulted in an insignificant rise in CBR ratio while testing the samples directly after compaction, whereas after 4 days of soaking, this influence was significant. Hence, it can be stated that the weight of a road pavement structure will be a factor increasing the CBR ratio of the embankment made of fuel ashes.

3. Analysing the usability of the wastes for road engineering purposes, it can concluded that:

- The ash–slag mixture proved to be most usable for road emgineering purposes because of its geotechnical properties such as: grain-size distribution, compactibility and bearing capacity. However, these materials have to be isolated from water.
- The geotechnical parameters of fly ash were not equally suitable. The fly–ash grain-size distribution and a significant deterioration in bearing capacity after saturation do not allow its use for road engineering purposes. Its usability may be improved by the addition of hydraulic binder.

REFERENCES

[1] GRUCHOT A., *Charakterystyka geotechniczna wybranych odpadów poenergetycznych w aspekcie wykorzystania ich do budownictwa drogowego*, Materiały XV Krajowej Konferencji Mechaniki Gruntów i Inżynierii Geotechnicznej, Wydawnictwa Uczelniane UTP, Bydgoszcz, 2009, 253–258.
[2] GRUCHOT A., *Wpływ dodatku popiołów lotnych na wskaźnik nośności odpadów powęglowych*, Przegląd Górniczy, 2010, 1–2, 53–56.
[3] HYCNAR J., *Eurocoalash weryfikacja popiołów ze spalania węgla*, Energetyka–Nauka–Przemysł, 2009, Vol. 1, 48–52.
[4] PISARCZYK S., *Grunty nasypowe. Właściwości geotechniczne i metody ich badania*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2004.
[5] ZABIELSKA-ADAMSKA K., *Popiół lotny jako materiał do budowy warstw uszczelniających*, Wydawnictwo Politechniki Białostockiej, Białystok, 2006.
[6] ZAWISZA E., GRUCHOT A., MICHALSKI P., *Wpływ stabilizacji cementem lub wapnem na wytrzymałość i mrozoodporność odpadów energetycznych ze składowiska Elektrociepłowni „Łęg" w Krakowie*, Inżynieria Morska i Geotechnika, 2006, Vol. 1–2, 22–30.
[7] ZAWISZA E., KŁĘK K., *Stabilizacja popiołów spoiwami „Silment" w drogownictwie*, Drogownictwo, 2006, Vol. 12, 396–401.
[8] ZAWISZA E., SOBULA K., *Wytrzymałość i mrozoodporność popiołów lotnych z Elektrociepłowni "Kraków" stabilizowanych cementem lub wapnem*, XXX ZSMGiG – Geotechnika w budownictwie i górnictwie, Szklarska Poręba, Prace Naukowe Instytutu Geotechniki i Hydrotechniki Politechniki Wrocławskiej, 76, 2007, Konferencje 42, 665–676.
[9] ZAWISZA E., ZYDROŃ T., *An analysis of the influence of compaction and moisture content on the shearing strength of coal ashes*, Proceedings of XIII Danube–European Conference on Geotechnical Engineering, Ljublana, 2006, 171–176.
[10] ZYDROŃ T., ZAWISZA E., *Badania wpływu metody zagęszczania na maksymalną gęstość objętościową szkieletu i wilgotność optymalną odpadów poenergetycznych*, Zeszyty Naukowe Akademii Rolniczej, Seria: Inżynieria Środowiska, 2005, Vol. 26, 425–433.
[11] PN-EN ISO 14688-1:2006. *Badania geotechniczne. Oznaczanie i klasyfikowanie gruntów*. Część 1: *Oznaczanie i opis*. Polski Komitet Normalizacji. Warszawa.
[12] PN-EN ISO 14688-2:2006. *Badania geotechniczne. Oznaczanie i klasyfikowanie gruntów*. Część 2: *Zasady klasyfikowania*. Polski Komitet Normalizacji. Warszawa.
[13] PN-B-02480:1986. *Grunty budowlane. Określenia, symbole, podział i opis gruntów*. Polski Komitet Normalizacji. Warszawa.
[14] PN-B-04493:1960. *Oznaczenie kapilarności biernej*. Polski Komitet Normalizacyjny. Warszawa.
[15] PN-S-02205:1998. *Drogi samochodowe. Roboty ziemne. Wymagania i badania*. Komitet Normalizacji Miar i Jakości. Warszawa.