THE INFLUENCE OF COMPACTION AND SATURATION ON THE COMPRESSIBILITY OF COLLIERY WASTE

by

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Using colliery waste to produce building materials, especially in earthworks to build different types of road and railway embankments, or to fill cavities and open-pit mines, requires us to determine the value of the settlement and the ability of fly ash to reduce its volume about its usability for mentioned purposes. Economic benefits and the need to protect the environment are the main reasons for using fly ash as secondary raw material. The purpose of this paper is to determine the effect of initial compaction and water conditions on the process and values of settlement as well as oedometric modulus of primary compression, decompression and secondary compression of fly ash. The tests were carried out in oedometers. The subject of the research was fly ash from Skawina Power Plant. Literature analysis covers the processes of waste production and management, types of waste depending on the grain size and composition, as well as the methods and ways of testing the compressibility of mineral and anthropogenic soils.

The results of the tests allowed formulating conclusions on the influence of compaction and water conditions on the possibility of settling, consolidation and the values of compressibility moduli of the tested material. They also allowed determining the usability of the material for earth constructions and other purposes.

Keywords: *coal power plant waste, fly ash, geotechnical parameters*

Introduction

Colliery waste is material created as a result of burning black or brown coal. In terms of grain size, it is divided into coarser (slag) and finer fractions (ash) [1-3]. Slag is a residue after coal combustion in power boilers, that falls to the bottom or remains on the grate and afterwards it is taken out of the boilers. Fly ash, also known as cyclone dust or electrostatic precipitator dust, is one of the most important colliery wastes. It is created as a result of coal combustion in furnaces and captured from a dynamic exhaust stream by electrostatic or mechanical dedusting devices [4-7]. In coal-fired power plants, the deposition of slug and fly ashes on heating surfaces such as combustion chamber walls and plate superheaters is a very serious problem [8-10]. This problem has become even more serious in recent years due to the necessity of co-combustion of biomass [11].

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Polish industry produces 128.3 million tonnes of waste a year (2016) (130.9 million tonnes in 2015, and 131.1 million tonnes in 1998 not including municipal waste). In 1998, 4.1 million tonnes of fly ash from coal was produced in Poland, 91.6% of which was used, while 5.1% was disposed of and stored on the premises of the power plants or in other areas [12]. In 2015, 3.2818 million tonnes of fly ash from coal was produced in Poland, 93.3% of which was used, while 6.6% was disposed and 0.1% of which landfilled [13]. In 2016, 3.258 million tonnes of fly ash from coal was produced, 86.7% of which was used, while 11.3% was disposed and 0.0% of which landfilled [14]. For decades these wastes were a serious environmental problem because the degree of their economic use was unsatisfactory and a significant part was stored on landfills [15]. These landfills require large areas, and at the same time, they degrade the natural environment [16, 17]. In 1997 the area of landfills where waste from energy industry was stored was 2370 hectares, 119 of which were reclaimed, in 2015 – 8341.7 hectares, 59 of which were reclaimed, and in 2016 – 8374.3 hectares, 27.4 of which were reclaimed [12-14]. The production of electricity in Poland is mainly based on coal (90%), and a great amount of furnace waste is a by-product of that [18]. It causes negative effects in the natural environment, so waste management, especially industrial waste, is a priority in the environmental policy of the country. There are different kinds of coal and different types of furnaces, so properties of fly ashes are diversified, which is important in relation to their utilization [19, 20]. Ashes from brown coal combustion are used entirely to reclaim mine pits; the problem is the utilization of furnace waste from hard coal combustion. Considering fly ashes as a harmful waste is quite common, but wrong. This alumina silicate material has numerous uses. It can even be a raw material for more advanced technologies [21, 22]. Compared to previous decades, the amount of industrial waste produced in Poland has been systematically decreasing, over the past few years it was about 124 million Mg, and there are more than 1.8 million Mg of waste on landfills. In 2016 the total quantity of waste produced by industry was 36.5 million Mg. The tests that were carried out proved that these wastes, at different time and place, can be very useful material. For years attempts have been made to use them in different ways. There has been a significant increase in their usage in Poland over the last 10-15 years. Because in Poland the pure ash has a relatively low share in energy waste, the rate of their utilization is extremely high and equals about 96%, whereby they are mainly used in the building materials industry, currently, it uses over 55% of these wastes. The countries of the EU addressed the problem of energy waste in the 60's and this problem, though not without difficulties, was solved. The EU countries have also shown that ashes and slags are or can be a significant base of materials. Ashes are used to produce concrete, including cellular concrete, lightweight aggregates, construction ceramics, asphalt concrete, cement, and pozzolanic binders. Ashes can also be used in earthworks to fill the post-mining voids, perform ground injections and road foundations, improve soil workability, stabilize roads or build road and railway embankments [23-27].

The fact that the fly ash is used is beneficial: production material costs are reduced, a lot of technical features of the produced materials are improved, and additionally, the amount of waste stored in landfills is reduced [28]. In this context, the fly ash from coal combustion seems like a valuable mineral resource for industry, although ashes from different suppliers have to meet certain requirements. In order to define possibilities of further usage of ashes in the industry, it is necessary to determine their geotechnical parameters. The subject of this work is the study of the course and values of settlement and compressibility modulus of fly ash from Skawina Power Plant. This research allows reducing the cost of production of materials and improving many technical properties of manufactured materials. The tests were carried out in standard oedometers, in a geotechnical laboratory of the Department of Hydraulic Engineering and Geotechnics of the University of Agriculture in Cracow, Poland.

Characteristics of the ash from Skawina Power Plant

Chemical composition

The chemical composition of the ash is based on tests ordered by Skawina Power Plant and carried out by *Energopomiar* Research and Testing Centre for Power Plants. The basic component of the ash is silicate SiO_2, which was about 55% of dry matter, whereas alumina, Al_2O_3, was about 24.4%. The content of other components (iron, magnesium, potassium and phosphorus oxides) did not exceed 20%. Detailed chemical composition of the ash is shown in tab. 1.

Table 1. Chemical composition of the ash slag from Skawina Power Plant

Component	Symbol	Content [%]		Mean
		Sample 1	Sample 2	
Ignition loss	–	0.92	2.0	1.46
Silica	SiO_2	56.3	53.0	54.65
Iron	Fe_2O_3	7.10	8.07	7.59
Alumina	Al_2O_3	24.1	24.6	24.35
Manganese	Mn_3O_4	0.13	0.15	0.14
Titanium	TiO_2	1.02	1.07	1.05
Calcium	CaO	3.17	2.85	3.01
Magnesium	MgO	2.31	2.36	2.34
Sulphur	SO_3	0.61	1.04	0.83
Phosphorus	P_2O_5	0.34	0.24	0.29
Sodium	Na_2O	0.88	1.66	1.27
Potassium	K_2O	2.52	2.41	2.47
Barium	BaO	0.13	0.08	0.11
Strontium	SrO	0.03	0.03	0.03
Total		99.56	99.56	99.56
Flammable parts (in a dry state)		1.00	1.64	1.32

Physical properties

The grain size distribution of the ash was determined using a wet sieve and hydrometer. According to the geotechnical nomenclature it corresponds with silt, tab. 2. The basic fraction in the grain size distribution of the fly ash is silt (0.002 to 0.063 mm), which is about 89%.

Table 2. Basic physical parameters of the ash from Skawina Power Plant

Parameter	Symbol	Unit	Value
Fraction content:			
gravel 63 – 2,0 mm	Gr	%	0
sand 2,0 - 0,063 mm	Sa	%	6
silt 0,063 - 0,002 mm	Si	%	89
clay <0,002 mm	Cl	%	5
Nam acc. to PN-EN ISO 14688-2:2004	–	–	Si
Specific density	ρ_s	g/cm^3	2.24
Optimum water content	w_{opt}	%	28.35
Maximum dry density	ρ_{ds}	g/cm^3	1.22

The remaining 17% of the sample weight is sand and clay fractions, of which grains with a diameter not exceeding 0.0063 mm (about 89.5% of the sample weight) have the largest share. Grains above 0.5 mm are only 0.3%. The optimum water content and the maximum dry density of the soil were tested in a Standard Proctor apparatus in two rounds. The optimum water content of the ash was on average 28.35% at the dry density of 1.22 g/cm^3, fig. 1. The specific density was 2.24 g/cm^3, and it was determined using a pycnometer.

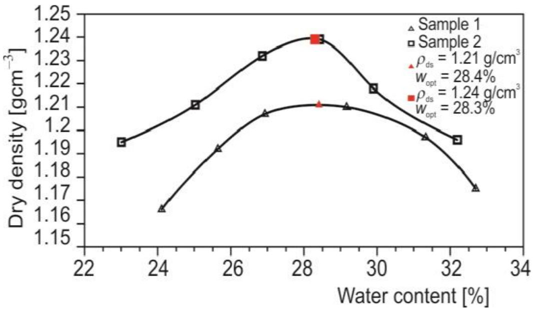

Figure 1. Dry density vs water content (Sample 1 and Sample 2)

Test method

The tests were carried out in standard oedometers, the samples were about 60 mm in diameter and about 20 mm high. Two series of tests were carried out which were aimed at determining the influence of the initial compaction, water content and saturation of the ashes on the course and extent of the settlements as well as compressibility modulus of the ashes. The first series was carried out without saturation of the samples, whereas during the second series the samples were saturated. All tests were carried out at three compaction indexes: 0.90, 0.95, and 1.0. The samples were formed at the water content close to optimum, which was about 28%. In each series, the testes were carried out in two rounds for two samples with identical initial parameters and then the results were averaged. The samples were subjected to a vertical consolidation load of 12.5, 25, 50, 100, 200, and 400 kPa. Each loading step, during both primary and secondary load, was kept for one day, whereas the last loading step of 400 kPa was kept until the sample was fully consolidated. Then the samples were unloaded gradually to 12.5 kPa, each step was unloaded every hour after that secondary load was applied up to 400 kPa. Changes in the thickness of the samples were recorded using dial gauges in set

Table 3. Initial parameters of the fly ash in the compressibility tests

<table>
<tr><th>Number of the sample</th><th>Compaction index</th><th>Water content</th><th>Bulk density</th><th>Dry density</th></tr>
<tr><td></td><td>[–]</td><td>[%]</td><td>[gcm^{-3}]</td><td>[gcm^{-3}]</td></tr>
<tr><td colspan="5">Ist series – no saturation</td></tr>
<tr><td>1</td><td rowspan="2">0.90</td><td rowspan="6">27.9</td><td>1.484</td><td>1.160</td></tr>
<tr><td>2</td><td>1.484</td><td>1.160</td></tr>
<tr><td>3</td><td rowspan="2">0.95</td><td>1.567</td><td>1.225</td></tr>
<tr><td>4</td><td>1.568</td><td>1.226</td></tr>
<tr><td>5</td><td rowspan="2">1.0</td><td>1.405</td><td>1.099</td></tr>
<tr><td>6</td><td>1.406</td><td>1.099</td></tr>
<tr><td colspan="5">IInd series – with saturation</td></tr>
<tr><td>7</td><td rowspan="2">0.90</td><td rowspan="6">28.5</td><td>1.491</td><td>1.160</td></tr>
<tr><td>8</td><td>1.491</td><td>1.160</td></tr>
<tr><td>9</td><td rowspan="2">0.95</td><td>1.569</td><td>1.221</td></tr>
<tr><td>10</td><td>1.569</td><td>1.221</td></tr>
<tr><td>11</td><td rowspan="2">1.0</td><td>1.412</td><td>1.099</td></tr>
<tr><td>12</td><td>1.412</td><td>1.099</td></tr>
</table>

time intervals, *i. e*. after 1', 2', 5', 15', 30', 1 h, 2 h, 4 h, 6 h, 1-4 days. After the tests, the final water content and bulk density of each sample were determined in order to define changes caused by consolidation. Initial parameters of the samples are in tab. 3.

The results of the tests

The effect of compaction on the compressibility of the fly ash

Based on the carried out tests it can be stated that the consolidation of the ash is a long-term process. The main settlements usually occurred directly after the load was applied. The influence of compaction on the course and extent of the settlements is presented in fig. 2. Ash at the lowest compaction index I_s = 0.90 showed the biggest settlements in the whole range of load and the final settlement equaled 0.548 mm, whereas the settlements of compacted (I_s = 0,95) and highly compacted ashes (I_s = 1.0) were much smaller and equaled adequately 0.345 and 0.337 mm.

The oedometric moduli of primary compression are diverse depending on the load and the compaction index. However their increase at each loading step can be noticed, fig. 3. For average compacted ash (I_s = 0.90) they are from 3 to 28 MPa, for compacted ashes (I_s = 0.95) from about 5 to 38 MPa, whereas for highly compacted ashes they are usually the biggest and equal from about 5 to 41 MPa. The effect of compaction on compressibility was the most noticeable at the higher loading steps whereas the relation between moduli and compaction was mostly the same.

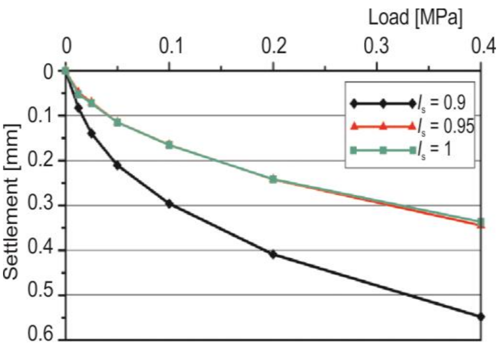

Figure 2. Settlements of the ash during primary load; I[st] series – not saturated samples

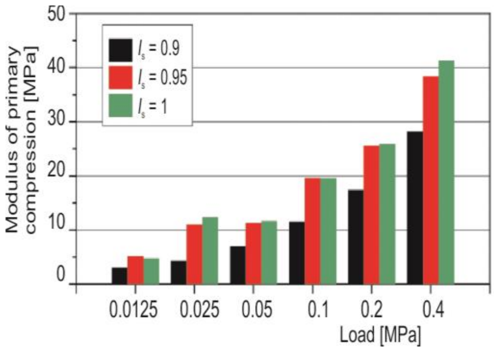

Figure 3. Oedometric modulus of primary compression of the ash at different compaction during each loading step; I[st] series – not saturated samples

The values of settlement under secondary load, fig. 4, were a few times lower than under the primary load and equaled adequately from 0.099 to 0.123 mm. Under the secondary load, the biggest settlements were for compacted ash (I_s = 0.95), whereas the smallest for the highly compacted ash (I_s = 1.0). This shows that consolidation of the ash under the primary load has a significant impact on the further settlements under the secondary load, whereas the influence of the compaction is not that noticeable. The moduli of secondary compression, fig. 5, are much higher than the moduli of primary compression (see fig. 3) which is the result of reduced settlements. The decrease in the value of the module along with the increase in the applied load from 0.025 to 0.05 MPa is typical. In case of further loading steps, the values of the module slightly increase.

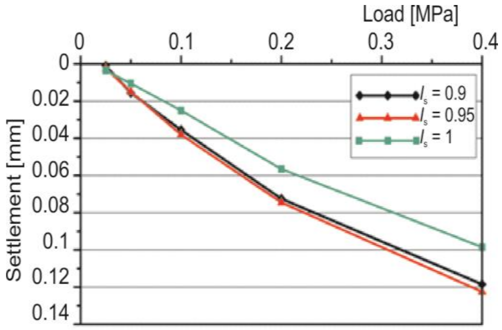

Figure 4. Settlements of the ash during secondary load; Ist series – not saturated samples

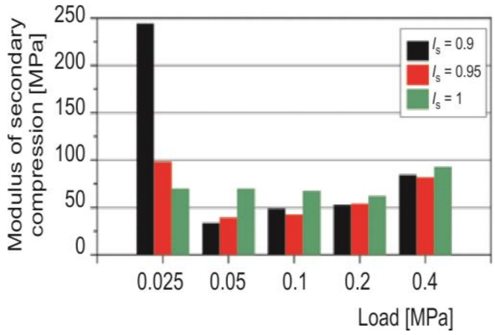

Figure 5. Oedometric modulus of secondary compression of the ash at different compaction during each loading step; Ist series – not saturated samples

The effect of saturation on the compressibility of the ash

Settlement of the saturated ash under the primary load, fig. 6, was much bigger than in case of not saturated ash. The ash at the lowest compaction index showed the biggest settlements - the final value was 1.14 mm.

The values of modulus of primary compression of the saturated samples were lower than the ones for not saturated ash. These values were comparable in the initial loading steps (0.0125 – 0.05 MPa) for all compaction indexes, but as load increased, the values of the moduli increased, and a clear effect of compaction was noticed, fig. 7.

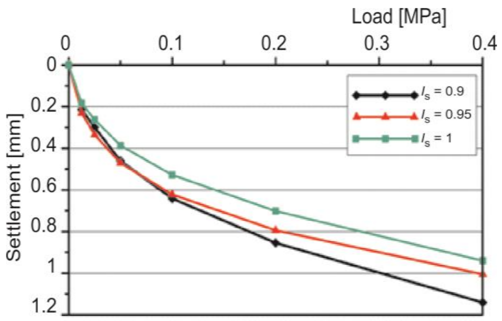

Figure 6. Settlements of the ash during primary load; IInd series – saturated samples

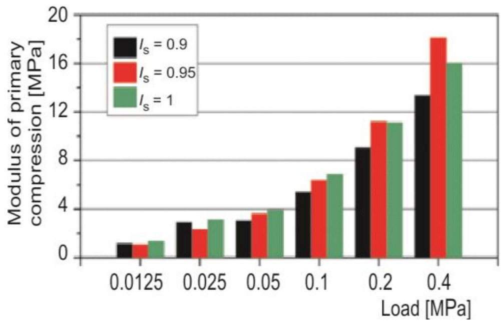

Figure 7. Oedometric modulus of primary compression of the ash at different compaction during each loading step; IInd series – saturated samples

Settlement of the saturated ash under the secondary load is much smaller than in the case of the primary load, and there is no effect of the initial compaction, fig. 8. The values of the modulus of the secondary compression of the saturated ash, fig. 9, are higher than the values of the modulus of the primary compression, and they are related to the load – the modulus increases as the load increases. Under the first loading step, the effect of the compaction on the moduli of secondary compression is clearer, whereas under further steps the compaction does not influence the values of the moduli. The moduli of secondary compression are comparable for saturated and not saturated samples (see fig. 5).

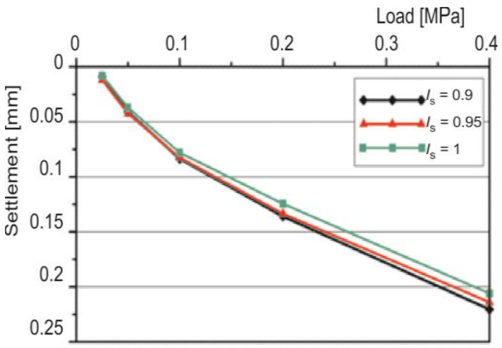

Figure 8. Settlements of the ash during secondary load; II^nd series – saturated samples

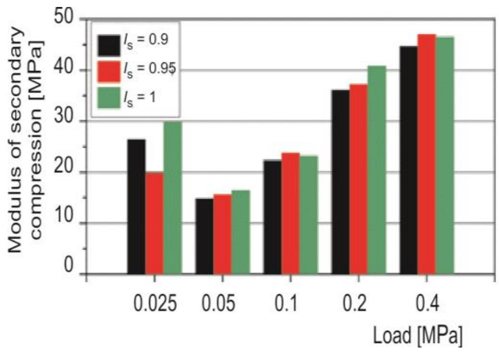

Figure 9. Oedometric modulus of secondary compression of the ash at different compaction during each loading step; II^nd series – saturated samples

Analysis of test results

In geotechnical terms, the fly ash from Skawina Power Plant can be classified as sandy silt. The optimum moisture content of the ash is on average 28.35%, and the maximum dry density is 1.22 g/cm^3. The specific density is 2.24 g/cm^3. This research showed that the ash is characterized by high compressibility and its saturation additionally increases the value of settlements. While comparing ashes at different compaction indexes and the same water content under the primary load, it can be noticed that ashes at the lowest compaction (I_s = 0.90 in tab. 4) showed the biggest settlements, which reached the value of 2.74% in relation to the initial height. Ashes at higher compaction indexes (I_s = 0.95 and 1.0) showed much smaller settlements – adequately 1.73 and 1.68%. The values of modulus of primary compression increased proportionally to the compaction index, reaching values form 28 MPa – for the average compacted sample – to 41 MPa - for the highly compacted sample, tab. 5. The values of the settlements under the secondary load were smaller for the highly compacted ash (I_s = 1.0) and equaled 0.50%, whereas for the other samples, at lower compaction indexes these values were higher and close to each other, tab. 4. The effect of the compaction was not as clear as in the case of the primary load. The values of modulus of secondary compression, tab. 5, were 2-3 times higher than the values of modulus of primary compression and reached values from 82 to 93 MPa, not showing a significant relation to compaction. It demonstrates that the ash has high compressibility under the primary load, especially when it is not well compacted at the beginning. During secondary load, the ash shows much smaller settlements, which is caused by significant consolidation under the primary load.

Table 4. Values of the settlements of the ash as a percentage of the initial height of the sample

Water content [%]	Settlements as a percentage of the height of the sample under load					
	Primary			Secondary		
	I_s = 0.90	I_s = 0.95	I_s = 1.0	I_s = 0.90	I_s = 0.95	I_s = 1.0
I^st series – not saturated w_p = 27.9%	2.74	1.73	1.68	0.61	0.62	0.50
II^nd series – saturated w_p = 28.5%	5.70	5.03	4.70	1.16	1.12	1.07

Table 5. Generalized values of the compression moduli of the ash

Water content [%]	Compression moduli [MPa]					
	Primary			Secondary		
	I_s = 0.90	I_s = 0.95	I_s = 1.0	I_s = 0.90	I_s = 0.95	I_s = 1.0
I[st] series – not saturated w_p = 27.9%	28.19	38.36	41.28	84.71	81.63	93.04
II[nd] series – saturated w_p = 28.5%	13.39	18.11	16.06	44.77	47.06	46.53

Under the primary load and at the same compaction index and initial water content (about 28%) the values of settlements, tab. 4, of saturated samples were almost 2 times higher and the modulus of primary compression, tab. 5, was lower than in case of not saturated samples. Saturated samples at the lowest compaction index (I_s = 0.90) showed the biggest settlements, reaching 5.7%, whereas the most compacted ash (I_s = 1.0) showed the smallest settlements (4.7%). In the case of saturated samples, there is also a clear effect of compaction on the value of settlements under the primary load. Under the secondary load, the values of settlements of the saturated ash, tab. 4, were also 2 times higher than for not saturated ash, although 4 times lower than in case of the primary load. The influence of the compaction is clear, the highest values of settlements were reached by average compacted ash (I_s = 0.90) and the lowest by highly compacted ash (I_s = 1.0). The values of modulus of primary compression of saturated ash, tab. 5, are about 2.5-3 times lower than the values of modulus of secondary compression. They do not show any relation to the initial compaction.

At the end of the research, another wet sieve and hydrometer tests were carried out to verify changes in the grain size distribution. Specific density was also tested again using a pycnometer. The results of tests and their analysis were compiled and presented in tables and figures. The grain size distribution of the ash before and after the compressibility test in oedometers, as well as bulk density, is presented in tables. The graphs show the grain size curves of the ash. The basic fraction in the grain size distribution of the fly ash before the oedometric test was silt (0.002 to 0.05 mm), which was about 83%. The remaining 17% was sand and clay, although grains with a diameter not exceeding 0.0063 mm had the largest share (about 89.5% of the sample weight). Grains with a diameter above 0.5 mm were only 0.3%.

After the oedometric test, tab. 6, silt fraction content decreased and was 79%, whereas sand and clay content increased and reached adequately about 10 and 11%, not saturated sample, the lowest compaction index (I_s = 0.90). At the compaction index of I_s = 0.95, the silt content also decreased to 79% and the content of sand fraction (about 11%) and clay fraction (about 10%) increased. The grain size distribution of highly compacted ash (I_s = 1.0) also changed, but only to a minor extent. Silt fraction content was 81%, sand about 9% and the rest of the sample was clay (about 10%). The specific density of not saturated ash slightly decreased after the oedometric test, although this decrease was small and equalled only 0.01 g/cm^3. The results of tests on saturated ash are presented in tab. 7.

In the case of the lowest compaction index (I_s = 0.90), the silt fraction content decreased to 80%, whereas the content of sand and clay fractions increased to 10%. At the compaction index of 0.95, the silt content was 77.5%, whereas sand and clay content increased to adequately 10.5 and 12%. The following changes occurred in case of highly compacted ash (I_s = 1.0): the content of silt and sand fraction slightly decreased, only by 1 and 1.5%, whereas clay fraction content increased up to 9%. The specific density of saturated ash did not change after the test. Only in case of highly compacted ash (I_s = 1.0), the specific density decreased, although this decrease was negligible and equalled only 0.01 g/cm^3.

Table 6. Physical properties of the ash from Skawina Power Plant after the oedometer test; Ist series – not saturated

Parameter	Value before the oedometer test	Results after the test without saturation (Ist series)		
		I_s = 0.90	I_s = 0.95	I_s = 1.0
Fraction content[%]:				
sand 2.0 - 0.05 mm f_p	10.5	10	11	9
silt 0.05 - 0.002 mm f_π	83.0	79	79	81
clay < 0.002 mm f_i	6.5	11	10	10
Specific density ρ_s [g/cm^3]	2.24	2.23	2.23	2.23

Table 7. Physical properties of the ash from Skawina Power Plant after the oedometer test; IInd series – saturated

Parameter	Values before the test in oedometer	Values after the test with saturation (IInd series)		
		I_s = 0.90	I_s = 0.95	I_s = 1.0
Fraction content[%]:				
sand 2.0 - 0.05 mm f_p	10.5	10	10.5	9
silt 0.05 - 0.002 mm f_π	83.0	80	77.5	82
clay < 0.002 mm f_i	6.5	0	12	9
Specific density ρ_s [g/cm^3]	2.24	2.24	2.24	2.23

Conclusions

Based on the carried out tests and analysis it was stated that the fly ash form Skawina Power Plant is characterized by high compressibility, and the values of settlements and compression moduli depend on their initial compaction and water conditions:

- Under higher loads, the influence of compaction on the compressibility parameters is very clear. Under the primary load, it is significant, whereas under the secondary load it is practically unnoticeable.
- Saturation and initial compaction of the ash also have a great effect on its compressibility parameters. The settlements of the saturated ash were much bigger than in case of ash that was not saturated.
- The values of settlements under the secondary load are much lower than under the primary load and similar at three compaction indexes (I_s = 0.90, 0.95, and 1.0). It shows that the consolidation under the primary load has a great effect on the further process and ash behavior under the secondary load.
- Heavily compacted ash is characterized by much smaller settlements, and the influence of saturation on the consolidation process as well as the values of compressibility moduli is limited. It is crucial in case of using ashes in earthworks for example building causeways, road or railway embankments or filling land dips, especially if they were to be used as a construction ground.
- Using fly ash as secondary raw material is beneficial from both economical and environmental point of view. It lowers the cost of material production and improves a lot of technical properties of the produced materials. It also allows to significantly reducing the amount of waste transported to landfills.

Nomenclature

f_i – clay fraction content, [%]
f_p – sand fraction content, [%]
f_π – silt fraction content, [%]
I_s – ash compaction index, [–]
w_{opt} – optimum water content, [%]
w_p – water content, [%]

Greek symbols

ρ_{ds} – maximum dry density, [gcm^{-3}]
ρ_s – specific density, [gcm^{-3}]

References

[1] Gao, Q., *et al*., A General Mechanistic Model of Fly Ash Formation During Pulverized Coal Combustion, *Combustion and Flame, 200* (2019), Feb., pp. 374-386
[2] Chatterjee, A., *et al*., Modified Coal Fly Ash Waste as an Efficient Heterogeneous Catalyst for Dehydration of Xylose to Furfural in Biphasic Medium, *Fuel, 239* (2019), Mar., pp. 726-736
[3] Wang, G., *et al*., KOH Capture by Coal Fly Ash, *Fuel, 242* (2019), Apr., pp. 828-836
[4] Pallares, J., *et al*., Investigation on Co-Firing of Coal Mine Waste Residues in Pulverized Coal Combustion Systems, *Energy, 140* (2017), Dec., pp. 58-68
[5] Pena, B., *et al*., Experimental Study on the Effects of Co-Firing Coal Mine Waste Residues with Coal in PF Swirl Burners, *Energy, 157* (2018), Aug., pp. 45-53
[6] Milić, E. D., *et al*., Results of the Modernization of the Electrostatic Precipitator at Unit B1 of the Thermal Power Plant Kostolac B, *Thermal Science, 22* (2018), Suppl. 5, pp. S1623-S1634
[7] Stefanović, G. M., *et al*., CO_2 Reduction Options in Cement Industry: The Novi Popovac Case, *Thermal Science, 14* (2010), 3, pp. 671-679
[8] Taler, J., Taler, D., Tabular Type Heat Flux Meter for Monitoring Internal Scale Deposits in Large Steam Boilers, *Heat Transfer Engineering, 28* (2007), 3, pp. 230-239
[9] Taler, D., *et al*., Numerical Simulation of Convective Superheaters in Steam Boilers, *International Journal of Thermal Sciences, 129* (2018), July, pp. 320-333
[10] Trojan, M., Taler, D., Thermal Simulation of Superheaters Taking into Account the Processes Occurring on the Side of the Steam and Flue Gas, *Fuel, 150* (2015), C, pp. 75-87
[11] Taler, J., *et al*., Thermal Performance and Stress Monitoring of Power Boiler, *Proceedings*, ASME 2016 Power Conference, POWER2016, Charlotte, N. C., USA, 2016
[12] ***, Central Statistical Office, Environment 1999, Statistical Information and Elaborations, Warsaw, 1999
[13] ***, Central Statistical Office, Environment 2016, Statistical Information and Elaborations, Warsaw, 2016
[14] ***, Central Statistical Office, Environment 2017, Statistical Information and Elaborations, Warsaw, 2017
[15] Xu, J., *et al*., Coal Utilization Eco-Paradigm Towards an Integrated Energy System, *Energy Policy, 109* (2017), C, pp. 370-381
[16] Bhattacharya, S. S., Kim, K., Utilization of Coal Ash: Is Vermitechnology a Sustainable Avenue?, *Renewable and Sustainable Energy Reviews, 58* (2016), Maz, pp. 1376-1386
[17] Dindi, A., *et al*., Applications of Fly Ash for CO_2 Capture, Utilization, and Storage, *Journal of CO_2 Utilization, 29* (2019), Jan., pp. 82-102
[18] Taler, J., *et al*., An Assessment of Polish Power, *Modern Power Systems, 5* (2007), pp. 13-17
[19] Fu, Z., *et al*., Dry Coal Beneficiation by the Semi-Industrial Air Dense Medium Fluidized Bed with Binary Mixtures of Magnetite and Fine Coal Particles, *Fuel, 243* (2019), May, pp. 509-518
[20] Iqbal, A., *et al*., Synthesis and Characterization of Pure Phase Zeolite 4A from Coal Fly Ash, *Journal of Cleaner Production, 219* (2019), May, pp. 258-267
[21] Kovač, J., *et al*., Influence of Fly Ash Added to a Ceramic Bodyon its Thermophysical Properties, *Thermal Science, 20* (2016), 2, pp. 603-612
[22] Duan, S., *et al*., The Relevance of Ultrafine Fly Ash Properties and Mechanical Properties in its Fly Ash-Cement Gelation Blocks via Static Pressure Forming, *Con. and Bui. Ma., 186* (2018), Oct., pp. 1064-1071
[23] Bicer, A., Effect of Fly Ash Particle Size on Thermal and Mechanical Properties of Fly Ash-Cement Composites, *Thermal Science and Engineering Progress, 8* (2018), Dec., pp. 78-82
[24] Luo, Y., *et al*., An Eco-Friendly and Cleaner Process for Preparing Architectural Ceramics from Coal Fly Ash: Pre-Activation of Coal Fly Ash by a Mechanochemical Method, *Journal of Cleaner Production, 214* (2019), Mar., pp. 419-428

[25] Oclon, P., *et al*., Numerical Simulation of Heat Dissipation Processes in Underground Power Cable System Situated in Thermal Backfill and Buried in a Multilayered Soil, *Energy Conversion and Management, 95* (2015), May, pp. 352-370
[26] Oclon, P., *et al*., The Performance Analysis of a New Thermal Backfill Material for Underground Power Cable System, *Applied Thermal Engineering*, *108* (2016), Sept., pp. 233-250
[27] Oclon, P., *et al*., Thermal Performance Optimization of the Underground Power Cable System by Using a Modified Jaya Algorithm, *International Journal of Thermal Sciences, 123* (2018), Jan., pp. 162-180
[28] Ren, X., Sancaktar, E., Use of Fly Ash as Eco-Friendly Filler in Synthetic Rubber for Tire Applications, *Journal of Cleaner Production, 206* (2019), Jan., pp. 374-382

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