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To cite this article: P Pierzyna 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **545** 012004

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The influence of the type of fly ash on selected physical properties of their water mixtures (multiphase mixtures)

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Abstract. Waste from energy or mining has been widely used in civil engineering for many years, ie in road engineering, construction, land reclamation as well as in mining. The most frequently performed technologies in underground mining with fine-fraction waste are the sealing of infarcted grouting of cavings and liquidation. In these technologies, transport and migration properties play a primary role. They depend on the type of fly ash. At present, in Polish hard coal mines located in Upper Silesia, most commonly used technologies are ashes with code 10 01 02 from conventional boilers, and as second ashes from code 10 02 82 from fluidized bed boilers. The article presents the results of research on selected physical properties of ash-water mixtures such as: water-ash index (W/FA), leveling, density and volume of excess water. Furthermore, for the tested ashes, the volume of water was determined, which can be utilized in the case of the technologies described above, and it will constitute an added value.

1. Introduction

Waste from energy or mining has been widely used in civil engineering for many years, i.e. in road engineering, construction, land reclamation as well as in mining. In mining, waste from energy is of particular technological importance. In Poland, they are often referred to as UPS (Coal Combustion Products) - the equivalent of the global CCP. UPS includes fly ash, ashes with flue gas desulphurization products, flue gas desulphurization products themselves, e.g. reagips, ash-slugs, slags and bottom ashes. UPS (if it is a waste and not a product) in accordance with the Regulation of the Minister of Environment of 9 December 2014 on the waste catalog UPS are included in group 10 as waste from thermal processes. Paper [1] describes legal aspects regarding the recovery of energy waste in mining plants. The number of used UPSs in the Polish mining system is systematically decreasing every year [2]. UPS are used in the following underground mining technologies [3]:

- grouting of cavings as fire prevention,
- elimination of unnecessary dog headings,
- filling shallow voids in the rock mass,
- making insulation plugs,
- liquidation of shafts,
- extinguishing fires.

The most frequently performed technology in underground mining with fine-fraction waste is the sealing of infarcted goafs [1]. The technology uses various types of fine-grained waste, in particular fly ash. Fly ash has a diverse chemical, phase and morphological composition, which affects their



physico-chemical properties [4]. Fly ash can be divided into two main groups: low-calcium ash (LCFA) and high-calcium ash (HCFA) [5]. Another criterion for the division may be the type of furnace in which they arise. Two main types of furnaces in which hard coal is burnt are: conventional boilers and fluidized bed boilers. Such a division is often used by practitioners from mines. At present, in classic boilers in which hard coal is burnt, ash with the code 10 01 02 arises. They are generally low-calcium ash (LCFA). On the other hand, fluidized bed boilers primarily produce ashes with code 10 01 82, which contain flue gas desulfurization products and are usually highly calcium-refractory (HCFA). These ashes differ mainly in the content of silicates, aluminum, calcium, and in particular its free form and sulfur compounds. Currently, in Polish hard coal mines located in Upper Silesia, the most commonly used technologies are ashes with the code 10 01 02 from conventional boilers, and as second ashes with code 10 02 82 from fluidized bed boilers. As previously mentioned, fly ash was most often used in the technology of sealing the infarcted grouting of cavings and in the elimination of unnecessary dog headings. Transport and migration properties play the first role in these technologies. They depend, inter alia, on the type of fly ash. The article presents the results of research on selected physical properties of ash-water mixtures such as: water-ash index (W/FA), leveling, density and volume of excess water. Furthermore for the tested ashes, the volume of water is determined, which can be utilized in the case of the technologies described above.

2. Material and methods

The tests were carried out for the following wastes:

- fly ash (LCFA) coming from conventional "A" power plant boilers with code 10 01 02,
- fly ash (HCFA) coming from the fluidized bed boiler of the "B" power plant code 10 01 82.

The tested ashes come from selected power plants located in the south of Poland, in which coal is burning.

The research results of physical properties presented in the article were carried out in accordance with the PN-G 11011: 1998 standard. Tests of chemical composition in the oxide form were made using the X-ray fluorescence method (XRF) using the Epsilon 1 spectrophotometer by PANalytical. In contrast, the chemical composition of the water extract was tested in accordance with PN-EN 12457-4: 2006 standard.

Selected fly ash A and B were mixed with water to form ash-water mixtures. The proportions of fly ash and water (W/FA ratio) were determined in such a way that the resulting mixtures had a liquid consistency, the measure of which is pourability. The liquid consistency results from the fact that the transport of ash-water mixtures from the surface to the underground excavation is carried out by means of pipelines in a gravitational manner. The fluidity of the mixture determines by about their transport and penetration capabilities.

3. Results and discussion

3.1. Chemical properties

The chemical composition in the oxide form of the tested ashes is shown in table 1.

Table 1. Chemical composition in the oxide form of the tested ashes.

Chemical ingredient	Fly ash "A" (from a conventional boiler)	Fly ash "B" (from a fluidized boiler)
	% by mass	% by mass
SiO ₂	50.08	37.82
Al ₂ O ₃	25.80	19.63
Fe ₂ O ₃	6.10	5.74
CaO	3.80	18.52
MgO	2.23	1.76

Na ₂ O	0.97	1.09
K ₂ O	3.02	2.01
SO ₃	0.67	7.91
TiO ₂	1.08	0.72
P ₂ O ₅	0.50	0.29
CaO free	0.17	3.88
LOI	4.79	3.84

The tested ash are mainly different in content of SiO₂ and CaO and to a lesser extent Al₂O₃. Ash "A" (conventional fired) contains more silicon and aluminum than ash "B" (fluidized bed boiler). In contrast, ash "B" contains much more calcium, in particular its free form, than ash "A". This is due to the fact that ash "B" comes from a fluidized bed boiler, where dry flue gas desulfurization is used. The content of free lime, sulfur or unburned coal in the ashes increases their demand for water, so their water demand increases [6]. Bearing in mind the guidelines of the American ASTM standard in terms of silicon, aluminum and iron content, fly ash "A" could be classified as class F (LCFA) and fly ash "B" to grade C (HCFA). The tested ashes, however, do not fully meet ASTM requirements in terms of alkali, and in the case of ash B also in terms of sulfur. Such acceptance of classification is quite frequent, as the authors of the paper write about [6].

The results of the leaching tests (1:10) from the tested fly ashes are presented in table 2.

Table 2. The results of the leaching tests (1:10) from the tested fly ashes.

Substance	Fly ash "A" (from a conventional boiler)	Fly ash "B" (from a fluidized boiler)
	mg/l	mg/l
chloride	32	191
sulphate	389	1102
Cr	0.14	0.054
Zn	<0.05	0.050
Cd	<0.001	<0.05
Mg	<0.5	<0.5
Mn	<0.005	<0.005
Cu	<0.005	<0.005
Ni	<0.005	<0.005
Pb	<0.005	<0.005
K	16.85	13.10
Na	29.40	16.85
Fe	<0.005	<0.005

The ash investigated in terms of the chemical composition of water extracts differs mainly in the content of sulphates and chlorides. Fly ash "A" (from a conventional boiler) is characterized by several times lower content of chlorides and sulphates than ash "B" (from a fluidized bed boiler).

3.2. Grain size composition

The grain size composition of the examined ashes was determined by the traditional sieve method. The curves of the grain composition of ash "A" and ash "B" are shown in figure 1.

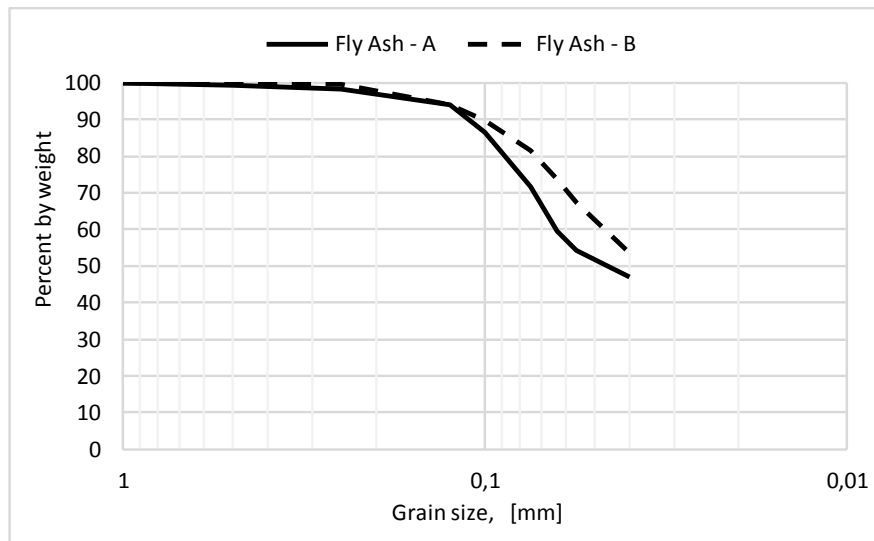


Figure1. Grain composition curves for the examined ashes.

The ash "A" coming from a conventional boiler is characterized by a slightly coarser grain size than the ash "B" coming from a fluidized bed boiler in the tested range up to 0.063 mm, which was also demonstrated, for example, in [7]. However, these ashes significantly differ in the structure of the grain. Ashes from conventional boilers, such as ash "A", are made of spherical grains, which reduces the need for water [8]. In contrast, ashes from fluidized bed boilers ("B" ash) are characterized by fine grains of very irregular shape, which are often compacted together to form agglomerates [9]. This state is reflected in the examined ashes. An exemplary image of grains of fly ash formed from the combustion of hard coal in conventional and fluidal boilers is shown in figure 2 [9].

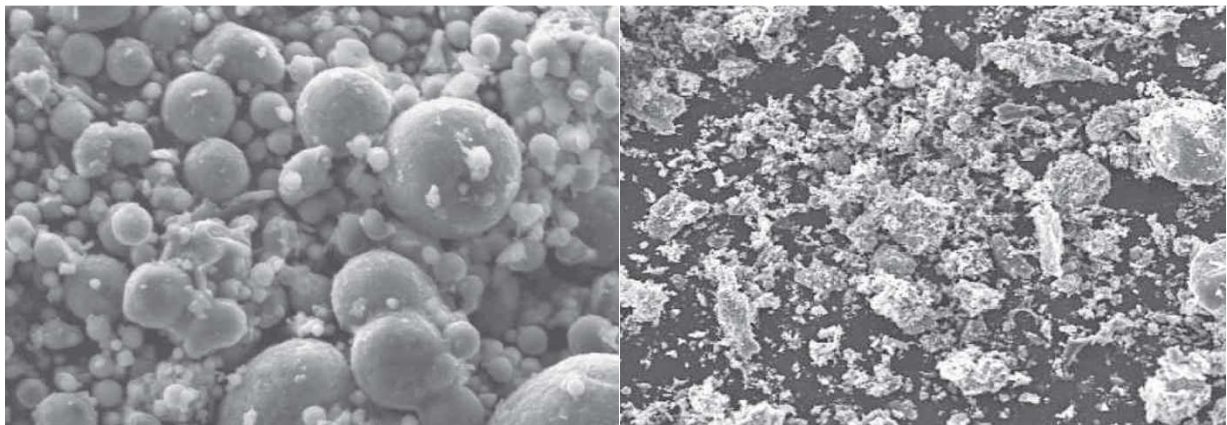


Figure 2. An exemplary image of grains of fly ash resulting from hard coal combustion in conventional and fluidized boilers [9].

The grain size composition of fly ash influences, among others on their water demand [10]. The specific surface of the grain also affects the water demand [11]. The specific surface of fly ash from conventional Polish power plants, i.e. ash "A", according to research carried out by the author of the work [12] is in the range from about 2500 cm³/g to about 4000 cm³/g, on average 3083 cm³/g. However, the specific surface of fly ash from fluidized bed boilers, i.e. ash "B", according to work [12], is very diverse in the range from approximately 4500 cm³/g to 7000 cm³/g, on average 5797 cm³/g. The quoted surface test results indicate that fly ash from fluidized bed boilers is characterized by almost twice as large surface area as ash from conventional boilers. The specific

surface also affects the pozzolanic reactivity of fly ash with concrete and cement produced with their participation [13].

3.3. The leveling

The dependence of leveling, which is a measure of the fluidity of mixtures, from the water-and-ash indicator (W/FA) is shown in figure 3.

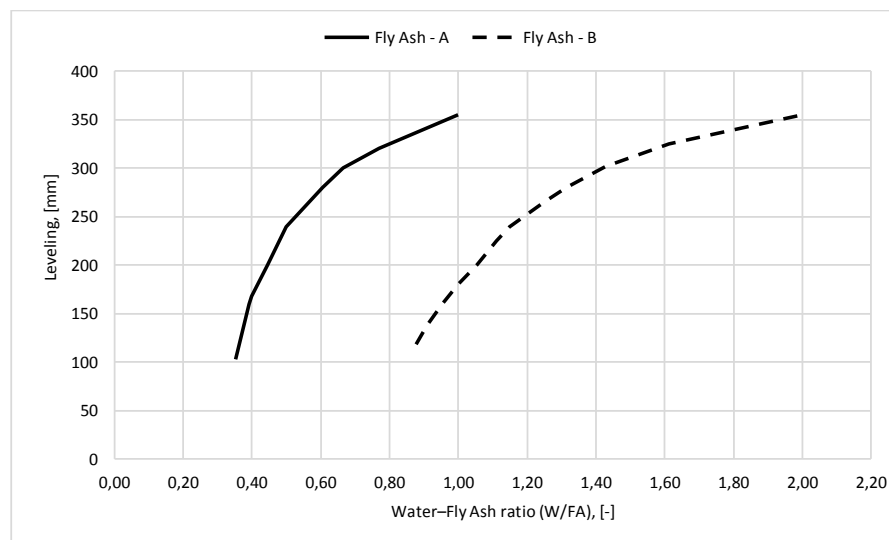


Figure 3. The dependence of the leveling from the water-and-ash indicator (W/FA).

The testing of leveling was carried out in the range of water-ash indicator (W/FA) from 0.35 to 1.00 for ash "A" and in the range from 0.88 to 2.00 for ash "B" (FCB). This range of water and ash indicators made it possible to reach leveling in a very wide range from 100 mm to 355 mm. The conducted research clearly shows the strong dissimilarity of the examined ashes in terms of water demand for a given level of leveling. Fly ash "B" coming from a fluidized bed boiler is much more water than the fly ash "A" coming from a conventional boiler. The reason for this is primarily the different grain shape of the fly tested ash, as well as the differences in the chemical composition, in particular in the content of SiO₂ and CaO, which has been described above. For example, for 160 mm water level, the water-ash indicator for ash "B" is 2.4 times higher than for ash "A". However, for the 355 mm leveling, the quotient decreases to 2.00. In the range of 160 mm to 355 mm leveling, the average value of the ratios "B" to ash "A" is 2.25. This is reflected in the specific surface, which for ash from fluidized bed boilers (ash "B") is about twice as large as ash from conventional boilers (ash "A"). A further reason for the difference in the water demand of the tested ashes is related to their chemical composition, which has been described above. The water-ash indicator ratio (from a fluidized bed boiler) to ash "A" (from a conventional boiler) for selected fillings are presented in figure 4.

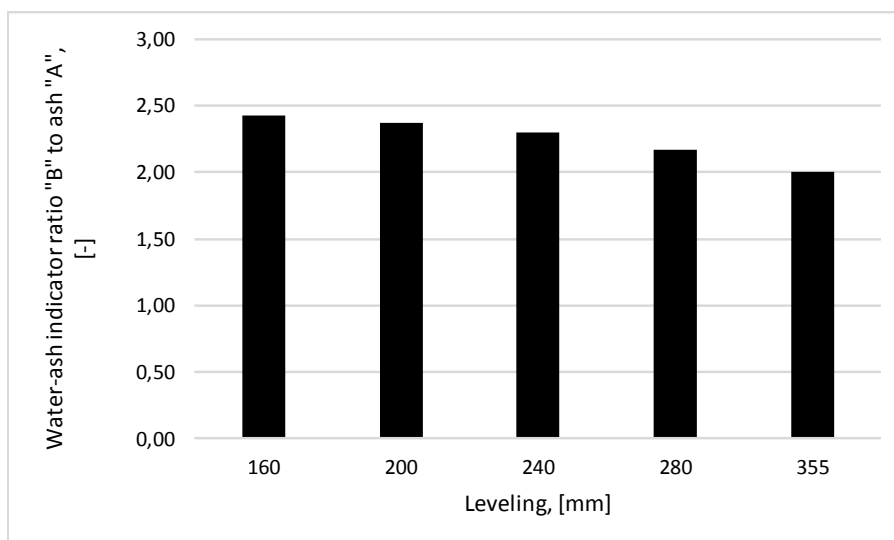


Figure 4. Water-ash indicator ratio ash "B" to ash "A" for selected leveling.

3.4. Density of mixtures

The dependence of the density of the water mixtures of the ashes from the leveling is presented in figure 5.

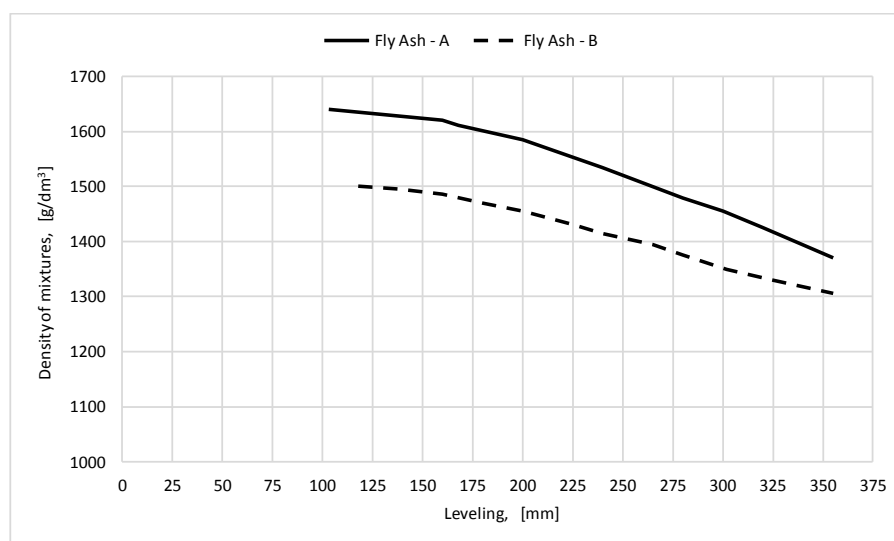


Figure 5. Dependence of the density of water mixtures of the ashes from the leveling.

The fixed proportions of water to ash (W/FA index) and the resulting leveling rate determine the density of the obtained mixtures. The density of mixtures produced with the ash "A" in the range from 103 mm to 355 mm is from 1370 g/dm³ to 1640 g/dm³, respectively. However, the density of mixtures with the share of ash "B" is from 1295 g/dm³ to 1500 g/dm³ corresponding to the leveling range from 118 mm to 355 mm. The conducted studies show the diversity of the density of water mixtures of the tested ashes. This is mainly due to the fact that the ashes tested largely differ in the water demand, which is expressed by the W/FA index, as previously described, and the reason for which is the diversified grain shape and chemical composition, as previously discussed. The density of mixtures made of ash "A" is higher than for mixtures with ash "B". Depending on the leveling, this is from

about 9% for leveling in the limit of 110 mm, up to around 5%, for leveling of about 350 mm. The quotient of water mixtures density ash "A" (from a conventional boiler) to the ash "B" (from a fluidized bed boiler) for selected levels is shown in figure 6. In the range of 160 mm to 355 mm leveling, the average value of the ash density quotients "B" up to ash „A" is 1.078, or about 8%.

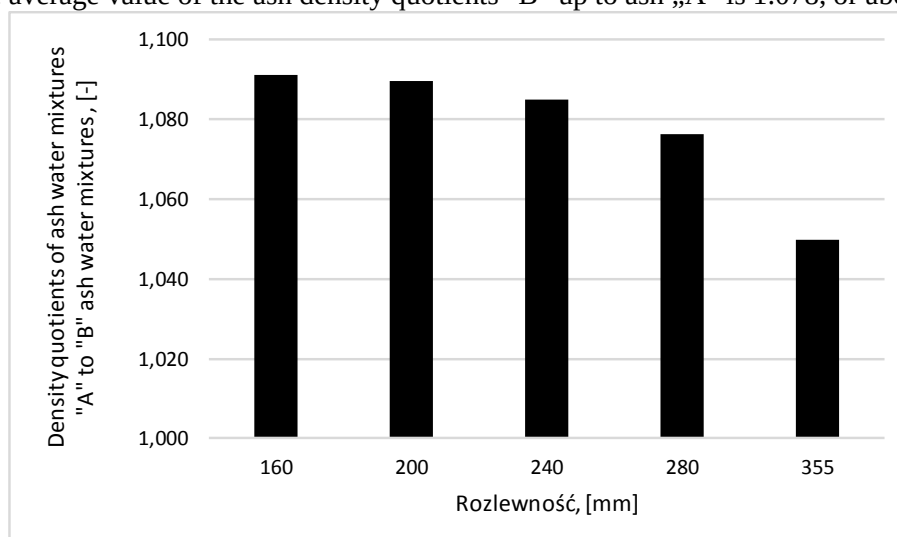


Figure 6. Density quotients of ash water mixtures "A" to "B" ash water mixtures for selected leveling.

3.5. The volume of excess water

Excess water is the water that accumulates over the sediment. It is undesirable because it has to be discharged. Usually it goes to the mine drainage system, generating unnecessary costs associated with its pumping to the surface. However, mines very often use mixtures with significant leveling at 300-350 mm. This is dictated by significant transport distances and the lack of possibility to obtain a full power supply, i.e. with a hydraulic height equal to the distance from the surface to the place of application. The basic factor of the inability to get a full power supply is the diameter of the used pipelines. In some cases, it may also be related to the inability to produce a mixture with a low water and ashes index (W/FA) or to obtain adequate capacity in the generating installation. The dependence of the volume of excess water from the tested ashes on the leveling is presented in figure 7.

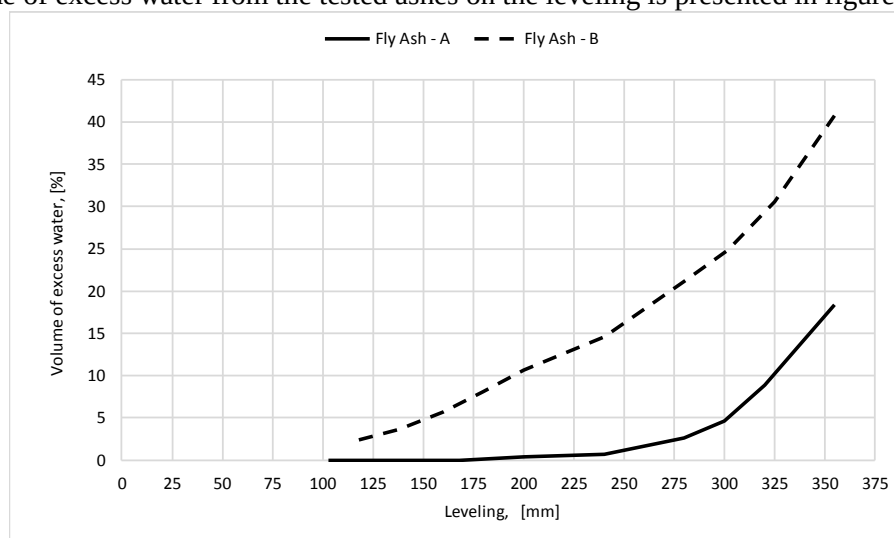


Figure 7. Dependence of the volume of excess water from the tested ashes.

The water volume of excess mixtures produced with ash "A" in the leveling range from 103 mm to 355 mm is from 0% to about 18%, respectively. It should be noted that ash water mixtures "A" practically do not exceed about 170 mm, they do not give off excess water. It is reflected in the work [14]. However, this can not be said for mixtures made of ash "B" (from a fluidized bed boiler). Analyzing further the course of the variability of excess water exudation from the "A" ash mixtures, it should be noted that for the leveling of about 250 mm its volume is negligible (less than 1%). A significant increase in excess water release can only be observed from the 300 mm level, at which the mixture gives off about 5%. The increase in leveling from 300 mm to 355 mm, i.e. by 50 mm, causes an increase in the volume of excess water to about 18% - a fourfold increase.

The mixture made from ash "B" (from a fluidized bed boiler) gives off much more excess water than the above-described mixtures made of ash "A" (from a conventional boiler). The water volume of the excess mixtures produced with ash "B" in the flow range from 118 mm to 355 mm is suitably from about 2.5% to about 41%. Ash water mixtures "B" are characterized by lack of leveling for which they would not give off excess water. Excess water for ash mixtures "B" increases with the increase in the W/FA ratio. The quantities of the excess water volume of the ash "B" mixtures (from the fluidized bed boiler) to the ash mixtures "A" (from the conventional boiler) for the selected leveling are shown in figure 8.

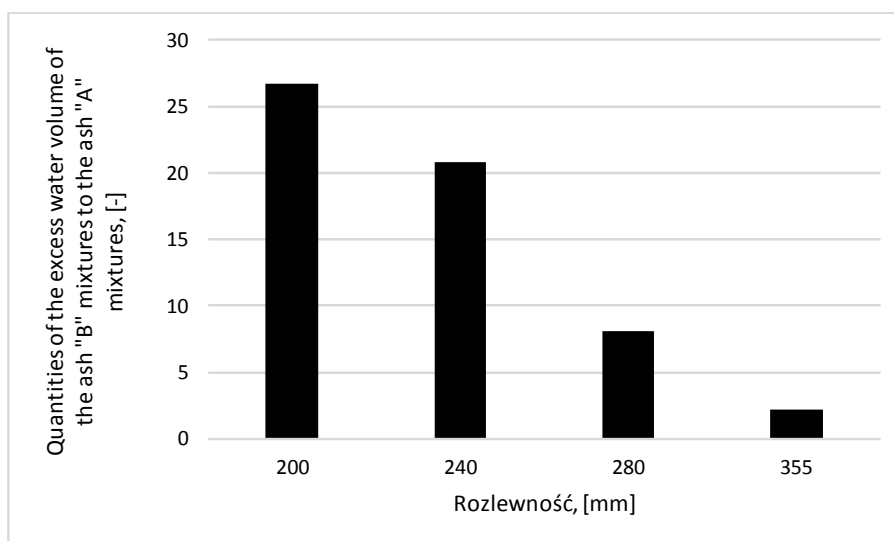


Figure 8. Quantities of the excess water volume of the ash "B" mixtures to the ash "A" mixtures for selected leveling.

The quotient presented in figure 8 illustrates the very strong differentiation of the volume of excess water volume for the tested ashes depending on the level of flow. The greater the flow rate, the smaller the quotient. For example, for 200 mm pourability, the volume of excess water released by the mixture of ash "B" (from the fluidized bed boiler) is about 27 times higher than for the ash mixture "A" (from a conventional boiler). However, for the 355 mm leveling, the quotient decreases to about 2. In the flow range from 160 mm to 355 mm, the average value of the quotients of the amount of excess ash "B" to ash "A" is about 14.

3.6. The volume of water that can be absorbed

Taking into account the water and ash indicator (W/FA) and the results of the density and volume tests of excess water, you can calculate the volume of water that can be absorbed by ash. The volume of water that can be bound by the mass of 1 Mg of the tested ashes depending on the leveling is shown in figure 9.

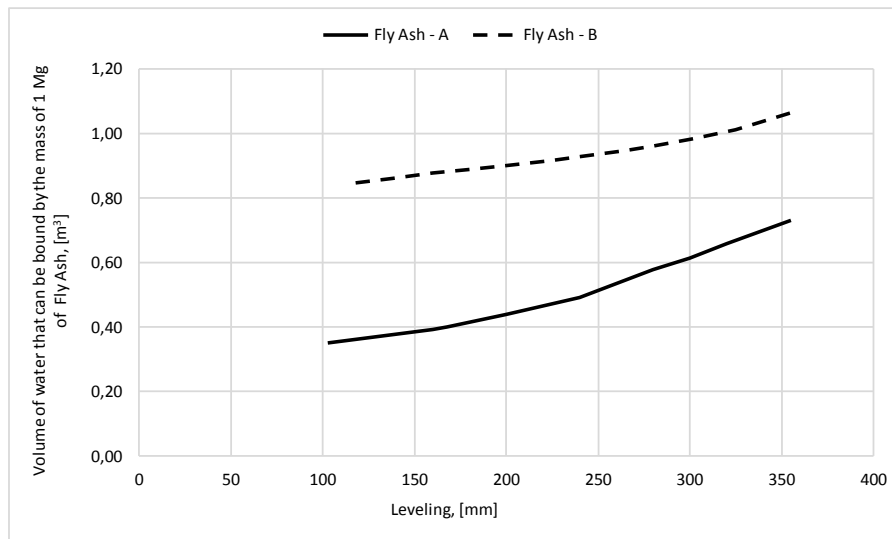


Figure 9. The volume of water that can be bound by the mass of 1 Mg of the tested ashes depending on the leveling.

The ash "A" (from a conventional boiler) allows, in the leveling range from about 100 mm to about 350 mm, the water absorption from about 0.35 m^3 to about 0.75 m^3 with respect to 1 Mg of dry matter. On the other hand, 1 Mg of ash "B" (from a fluidized bed boiler) allows absorption of about 0.8 m^3 to about 1.1 m^3 of water in the range of tested leveling. The quotient of the water volume that can be absorbed by the water mixtures of ash "B" into ash "A" is shown in figure 10.

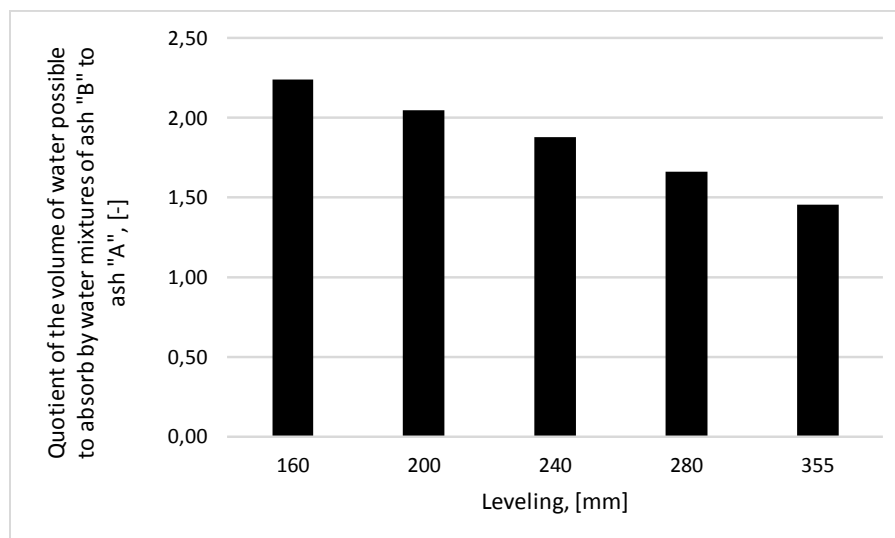


Figure 10. The quotient of the volume of water possible to absorb by water mixtures of ash "B" to ash "A".

At 160 mm, the ash "B" absorbs about 2.2 times more water than the ash "A", and at a flow rate of 355 mm about 1.5 times more. The average value of the quotient possible to absorb the volume of ash water "B" to ash "A" in the range of tested leveling is about 1.9. In general, ash "B" coming from a fluidized bed boiler allows the management of almost twice as much volume of mine water.

4. Conclusions

- Fly ash "B" (from a fluidized bed boiler) has a 2.4-2.0 times higher water-ash ratio (W/FA) compared to ash "A" (from a conventional boiler) with a leveling range of 160 mm, respectively up to 355 mm, average 2.25.
- Despite the significant differences in the W/FA ratio, the density of the water mixtures of the tested ashes is similar, and their difference varies from about 9% to about 5% for leveling rates from about 110 mm to 355 mm, respectively.
- Ash water mixtures "A" emit much less excess water than "B" ash. The volume of superfluous excess water is heavily dependent on the W/FA ratio, and hence on the level of leveling. With the leveling often used by mines of 280-350 mm, the volume of excess water released ranges from about 2.5% to about 18% for ash "A" and from about 20% to about 40% for as "B".
- Despite the large volume of excess water released by ash "B" in comparison to ash "A", it must be stated that ash from fluidized bed boilers allows the management of almost twice the volume of unnecessary mine water, compared to ash from conventional boilers.

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