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Possible use of selected types of fly ash in the technology of caving goaf sealing

Piotr Pierzyna

https://orcid.org/0000-0003-4684-210X

Silesian University of Technology in Gliwice
Faculty of Mining, Safety Engineering and Industrial Automation
e-mail: piotr.pierzyna@polsl.pl

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Abstract

This article presents selected properties of mixtures produced from two types of fly ashes from one coal-fired power plant. Mixtures made of fly ashes from a conventional boiler without flue gas desulfurization products (10 01 02) and from a fluidized bed boiler with flue gas desulfurization products (10 01 82) are subjected to testing. The mixtures are prepared using mine water. The tested mixtures are characterized by a liquid consistency in terms of flowability in a range from 160 mm to 280 mm. The mixtures made of 10 01 82 ashes show twice as much water demand, shorter setting time, and higher strength than those made of 10 01 02 ashes, but, unfortunately, they have a much higher volume of excess water. Moreover, the mixtures of 10 01 82 ash do not undergo full slaking, in contrast to the mixtures of 10 01 02 ash (conventional boiler). The requirements of the PN-G 11011:1998 standard, relative to the discussed parameters, are met by the mixtures made on the basis of ash 10 01 82 originating from a fluidized bed boiler in terms of flowability of up to 240 mm. This is the ash type useable in sealing technology.

Introduction

Wastes from the power industry or mining sector have been commonly used for many years in civil engineering, i.e., in road construction, building industry, geoengineering, as well as in mining (Cała et al., 2016; Jarema-Suchorowska & Kuczak, 2011). In mining, waste from the power industry is of particular technological importance. In Poland, about 130 million Mg of mineral waste is produced annually, where about 77 % is waste from the power industry and mining (Drobek, Kanafek & Pierzyna, 2016). Energy waste is generated in the amount of about 20 million Mg per year, where about 12 million Mg is used for economic purposes (Stępień & Białecka, 2017). The most frequently used energy wastes are various types of fly ashes, including those from biomass co-combustion (Kotowicz & Bartela, 2007; Uliasz-Bocheńczyk, Pawluk & Pyzalski, 2016). Currently, in Polish hard coal mines located in Upper Silesia, ashes with the code 10 01 02 from conventional boilers are most often used in technology, and ashes with the code 10 01 82 from fluidized bed boilers come second (Drobek, Borecki & Pierzyna, 2015a; Galos & Uliasz-Bocheńczyk, 2005).

Fly ashes are most frequently used in the technology of caving goaf sealing and in the liquidation of redundant dog headings. Transport and migration properties play a key role in these technologies. They are dependent, among others, on the type of fly ash. In addition, fly ashes are used in other technologies, such as those previously detailed (Plewa, Mysłek & Strozik, 2008; Pierzyna, 2019b; Badura et al., 2022): filling shallow voids in the rock mass, making insulation plugs, liquidation of shafts and fore-shafts, extinguishing fires, or reconsolidation of caving rubble. They are often a component of shotcrete used in underground mine workings (Drobek, Borecki & Pierzyna, 2015b). The technology of sealing the goafs allows us to improve the ventilation conditions in the longwall, eliminate the flow of air through the goafs and thus reduce the risk of fire, especially in seams prone to spontaneous combustion. It is a typical fire-fighting technology (Zając & Madaj, 2010) that consists of injecting ash-water mixtures into the goafs of an active or closed excavation.

In the case of an active longwall excavation, the injection can be carried out from the face of the longwall with a system of trailing pipes or from longwall galleries. Moreover, the sealing of old goafs (liquidated workings), depending on their accessibility, can be performed from adjacent workings or by means of holes drilled from the surface, or from the existing or specially made workings above the goafs (Jendruś et al., 2008a).

Material and methods

Mixtures made of fly ashes from a conventional boiler without flue gas desulfurization products (10 01 02) and from a fluidized bed boiler with flue gas desulfurization products (10 01 82) were subjected to testing. The mixtures were prepared using mine water with a density of 1023 g/dm^3. The fly ashes in question originate from one of the power plants located in the south of Poland, where hard coal is burnt. The prepared mixtures had a liquid consistency, which is measured by flowability. In the conditions of the Polish mining industry, the transport of mixtures from the surface to underground excavations is carried out by gravity (Plewa, Strozik & Jendruś, 2006). In the Polish mining industry, it is permissible to use mixtures with a minimum flowability of about 140 mm (Jendruś et al., 2008b). As demonstrated in earlier work (Piotrowski & Mazurkiewicz, 2006), the optimal flowability of ash-water mixtures is at the level of 170–180 mm, and it is connected with the minimum volume of excess water. Four levels of flowability were used in the tests: 160, 200, 240, and 280 mm. It should be noted that a change in the flowability level results in a change in the density or viscosity of the mixtures (Strozik, 2010). This again affects the transport and penetration properties (Palarski, Plewa & Strozik, 2014; Strozik, 2018). The tests of the mixtures were carried out in accordance with the applicable PN-G-11011:1998 standard "Materials for solidified backfill and goaf sealing. Requirements and tests" (Standard PN-G-11011:1998, 1998). To imitate typical climatic conditions prevailing in underground mine workings, samples of the mixtures were seasoned in a climatic chamber LTB 650 RV by Elbanton, the Netherlands, with a temperature of 25 ± 1 °C and humidity of 90 ± 2 %.

Results and discussion

Flowability of mixtures

Flowability is a measure of mixture consistency and is obtained by determining a specific ratio of water to solid material; in this case, the latter is ash. It is defined as a water-ash ratio (W/FA). Ratios for the tested ash-water mixtures, corresponding to their respective flowabilities of 160, 200, 240, and 280 mm, are shown in Figure 1.

The mixtures made of ash 10 01 02 (conventional boiler) are characterized by the W/FA ratio in the range of 0.40 to 0.67 for flowability of 160–280 mm. Moreover, the mixtures of ash 10 01 82 (fluidized bed boiler) are characterized by more than two times higher W/FA ratio than the mixtures made of ash 10 01 02; they ranged from 1.04 to 1.54.

The conducted research clearly demonstrates a strong difference between the tested ashes in terms of the demand for water for a given flowability. Fly ash from a fluidized bed boiler is much more water-demanding than fly ash from a conventional boiler. This is due to the fact that the grains of fluidized bed ash have an irregular shape and are highly porous (Iwanek, Jelonek & Mirkowski, 2008). In addition, they contain flue gas desulfurization products originating from the dry method. The increased water demand of ash 10 01 82 allows for the use of twice as much saline and, therefore, undesirable mine water, when unused for economic purposes, is a waste that is usually discharged into surface watercourses (Rado & Lubaś, 2005).

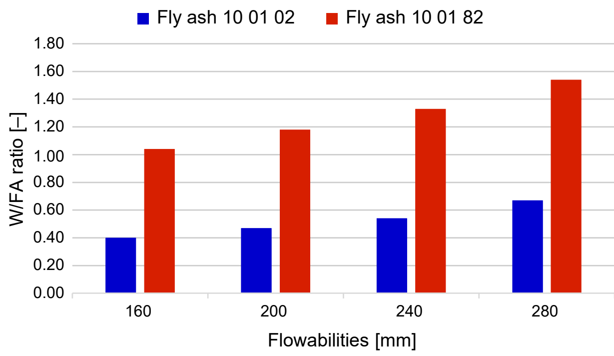

Figure 1. W/FA ratio (water to ash ratio) for the tested ash-water mixtures corresponding to their flowabilities of 160, 200, 240, and 280 mm

This generates costs, and worse, causes pollution of the natural environment. In extreme cases, under conducive conditions, it can even cause an ecological disaster, for example, in the case of the ecological disaster on the Odra River in 2022, when a low level of the river combined with its high salinity caused the development of undesirable bacterial organisms – i.e., golden algae (PAN, 2022).

Density of mixtures

The density of the tested ash-water mixtures, depending on their flowability, is shown in Figure 2.

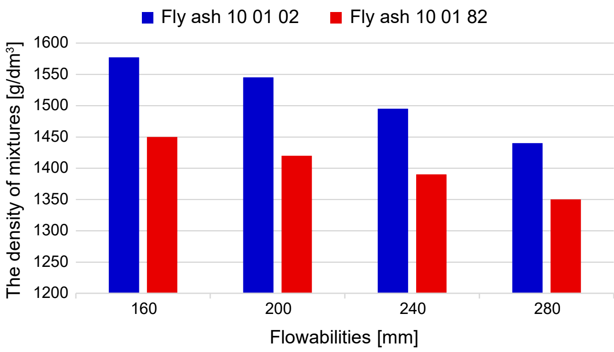

Figure 2. Dependence of the density of the tested ash-water mixtures on their flowability in the range of 160–280 mm

The mixtures made with the use of ash 10 01 02 (conventional boiler) are characterized by density in the range from 1577 g/dm^3 down to 1440 g/dm^3 for flowability in the range of 160–280 mm. Furthermore, the mixtures made of ash 10 01 82 (fluidized bed boiler) are characterized by lower density, ranging from 1450 g/dm^3 down to 1350 g/dm^3. The tested mixtures differ in density depending on the type of ash they are made of. Yet, the difference in the values of the discussed parameter is not as significant as in the case of the previously examined water demand. In addition, it is evident that the density of the tested mixtures, regardless of the type of ash from which they are made, systematically decreases with the rise of their flowability (i.e., the rise of the W/FA ratio). Bearing in mind the recommendations of the standard PN-G 11011:1998 involving the minimum density of the backfill mixture of 1200 g/dm^3, we can state that all the tested mixtures indisputably meet the above standard.

Volume of excess water

The volume of excess water of the tested ash-water mixtures, depending on their flowability, is shown in Figure 3.

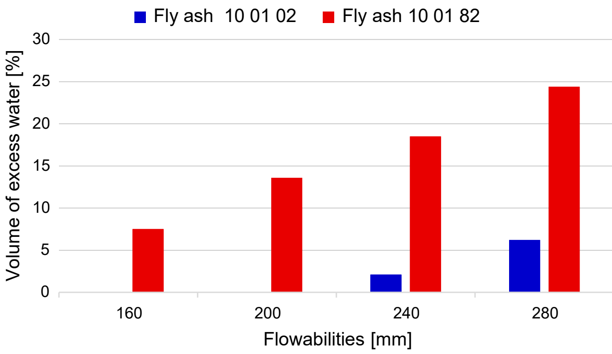

Figure 3. Dependence of excess water volume of the tested ash-water mixtures on flowability in the range of 160–280 mm

The tests carried out on the volume of excess water clearly demonstrate the differences resulting from the types of ashes from which the mixtures are made. The mixtures composed of ash 10 01 82 (fluidized bed) have a volume of excess water from about 7.5 % to about 24.5 %. Whereas the mixtures made of ash 10 01 02 (conventional boiler) are characterized by a much lower volume of excess water compared to the previously discussed mixtures. In the flowability range of up to 200 mm, the said mixtures are characterized by the lack of excess water, which then increases to about 7 % at the flowability level of 280 mm. Such behavior from the mixtures composed of this type of ash has been confirmed in previous work (Pierzyna, 2019a). In general, excess water is undesirable for many reasons and should be minimized since it is an additional source of environmental pollution, apart from the economic aspects related to the additional cost of drainage. Unfortunately, mines use mixtures with high flowability, often exceeding 300 mm, in order to obtain adequate transportability. The reduction of mixture flowability while maintaining appropriate transportability can be achieved by using various chemical additives, e.g., plasticizers (Gołaszewski, Ponikiewski & Kostrzanowska, 2010). Relative to the discussed parameter, the PN-G 11011:1998 standard defines a maximum value of 15 % for materials used as sealing mixtures. This condition is met by the tested mixtures, except for mixtures made of ash 10 01 82 with flowabilities of 240 and 280 mm.

Setting time

The setting time in terms of values is not specified in the standard PN-G 11011:1998, according to which it is the time needed to obtain the load capacity of 0.5 MPa. Practically, it can be interpreted as the time after which it is possible to penetrate the backfilled area by the employees of the mining plant (Pierzyna, 2022). The setting time of the tested ash-water mixtures, depending on their flowability, is shown in Figure 4.

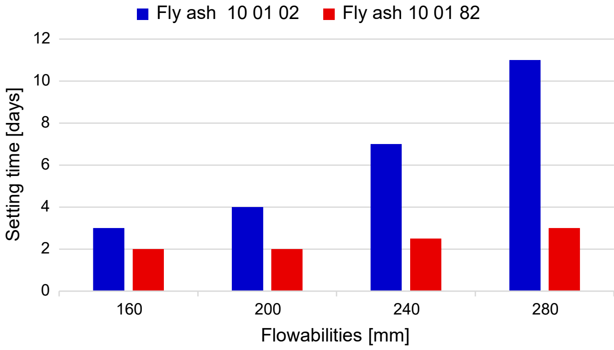

Figure 4. Dependence of the setting time of the tested ash-water mixtures on flowability in the range of 160–280 mm

Moreover, in the case of this parameter, the conducted research shows a significant difference resulting from the type of ash used. The setting time of the tested mixtures increases with the rise of flowability, and it occurs more intensively in the case of ash 10 01 02 (conventional boiler) than for ash 10 01 82 (fluidized bed boiler). The setting time of the mixtures made of ash 10 01 82 is in the range of 2 to 3 days, and for the mixtures with ash 10 01 02, in the range of 3 to 11 days, both for flowability of 160–280 mm. Referring the obtained results to the standard PN-G 11011:1998, it should be noted that the standard does not precisely define the value of the discussed parameter; it is left to be determined individually for a given application.

Compressive strength

The results of compressive strength tests after 7, 14, and 28 days of seasoning in an air-conditioned environment of the tested mixtures in the flowability range of 160–280 mm are presented in Table 1.

Figure 5 shows the dependence of the compressive strength on the flowability of the tested mixtures after 28 days of seasoning, as required by the standard PN-G 11011:1998.

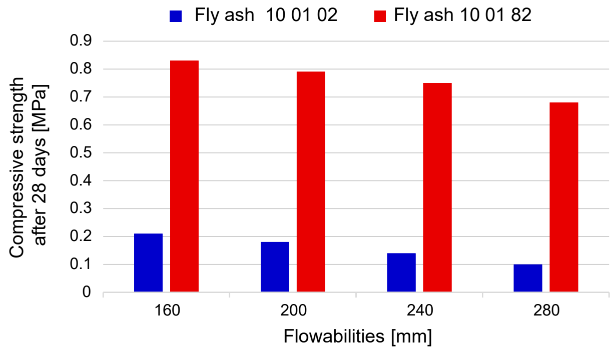

Figure 5. Compressive strength after 28 days of the tested mixtures made of ashes 10 01 02 and 10 01 82 depending on flowability

The conducted research clearly demonstrates the differences between the types of ash. The mixtures with fly ash 10 01 82 (fluidized bed boiler) reached almost 4 times higher strength than the mixtures with fly ash 10 01 02 (conventional boiler). The mixtures made of ash 10 01 02 were not bound; they remained plastic after 7 and 14 days of seasoning. For this reason, it was not possible to carry out strength tests. After 28 days, they reached a strength in the range of 0.10–0.21 MPa for flowability of 280–160 mm. The mixtures made of ash 10 01 82, depending on the flowability, have a compressive strength after 7 days in the range of 0.25–0.32 MPa, and after 14 days from 0.55 MPa to 0.83 MPa. This accounts for about 80 % of their strength obtained after 28 days, which does not exceed 1 MPa. It can be concluded, based on the obtained compressive strength results and referring to the PN-G 11011:1998 standard, that all the tested mixtures can be used in sealing technology.

Table 1. Test results of the compressive strength of mixtures made of the tested ashes 10 01 02 and 10 01 82 in the flowability range of 160–280 mm

Type of fly ash	Flowability [mm]	Compressive strength after time [MPa]		
		7 days	14 days	28 days
Fly ash 10 01 02 (conventional boiler)	160	malleable	0.18	0.21
	200	malleable	0.14	0.18
	240	malleable	malleable	0.14
	280	malleable	malleable	0.10
Fly ash 10 01 82 (fluidized bed boiler)	160	0.32	0.71	0.83
	200	0.30	0.68	0.79
	240	0.28	0.62	0.75
	280	0.25	0.55	0.68

Slaking

Slaking is defined as a percentage loss of compressive strength as an effect of the impact of the water environment in which the material is being seasoned, i.e., after 28-day seasoning in an air-conditioned environment in this case. As presented in another paper (Pierzyna, 2022), this parameter is very important for safety reasons. The material that undergoes a 100 % slaking is re-liquefied, creating a mixture capable of migration at an indefinite time and manner. This creates a direct threat to the safety of people working underground (Bensted & Munn, 2012; Łagosz et al., 2008). The slaking of the tested ash-water mixtures, depending on their flowability, is shown in Figure 6.

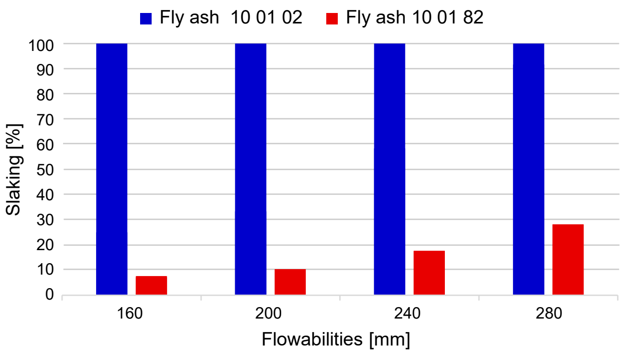

Figure 6. Slaking of the tested ash-water mixtures depending on flowability

The carried out flowability tests demonstrate significant differences in the properties of the used ashes. The mixtures made of ash 10 01 82 (conventional boiler) reached a slaking ratio in the range of 7–28 % for flowability in the range of 160–280 mm. Such ashes contain flue gas desulphurization products generated with the use of the dry method. Moreover, the mixtures with ash 10 01 02 (conventional boiler), which do not contain flue gas desulphurization products, have a 100 % slaking ratio. Thus, these mixtures are not resistant to the water environment. Such a behavior of the mixtures clearly indicates the lack of binding properties of this type of ash. The compressive strength reached by the mixtures in question (ash 10 01 02) relates only to their draining and drying. To prevent the mixtures from totally slaking, a 2 % addition of cement should be used (Pierzyna, 2021).

Addressing the obtained results of slaking to the requirements of the standard PN-G 11011:1998, we can conclude that it is possible to apply the mixtures made of ash 10 01 82 in underground mining applications.

Conclusions

The tests involved the mixtures made of fly ashes from a conventional boiler without flue gas desulphurization products (10 01 02) and from a fluidized bed boiler with flue gas desulphurization products (10 01 82), in which hard coal from Power Plant "S" is used as fuel. The mixtures were prepared using mine water with a density of 1023 g/dm^3. The tested mixtures were characterized by flowability in the range from 160 mm to 280 mm. This corresponds to the water-ash index (W/FA) for mixtures containing ash 10 01 02 in the range of 0.40–0.67, and for the mixtures containing ash 10 01 82 in the range of 1.04–1.54. The ash 10 01 82 allows for the management of more than twice as much undesirable mine water than the ash 10 01 02. Considering the volume of excess water, mixtures made with ash 10 01 82 enable additional removal of mineralized water (net) of approximately 1.25 times that of mixtures with conventional ash 10 01 02 on average. Yet, it should also be noted that the mixtures with the ash 10 01 82 are characterized by a much higher amount of excess water than the mixtures made with the ash 10 01 02. Examining the mechanical properties, the mixtures made of ash 10 01 82 reach the load capacity of 0.5 MPa much faster and, thus, have a shorter setting time and higher compressive strength than the mixtures made of ash 10 01 02. Moreover, the mixtures of ash 10 01 82 (fluidized bed boiler) do not undergo total slaking, in contrast to ash mixtures 10 01 02 (conventional boiler).

The requirements of the standard PN-G 11011:1998 in terms of the discussed parameters are met by mixtures made on the basis of ash 10 01 82 originating from a fluidized bed boiler in the flowability range of up to 240 mm. This is the ash type useable in sealing technology.

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