

Article

Tests of Strength Parameters of Hydro-Mixtures Based on Ashes from a Fluidized Bed Boiler in the In-Situ Approach

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Abstract: The paper presents the practical use of a solidifying hydro-mixture based on ashes from fluidized bed boilers under hard coal mine conditions for filling an incline connecting the headgate and tailgate of a longwall running along the strike with roof caving. The reason for filling the incline with a material of preset strength parameters was to minimize the methane hazard in the extracted coal seam. Due to a great demand for fill material, which translates into economic considerations, the option of applying fine-fraction waste material was selected. Preliminary laboratory tests of the physical and mechanical properties of hydro-mixtures based on ash obtained from a fluidized bed boiler of a power plant, allowed us to select a specific hydro-mixture meeting the requirements. After 95 days, the incline filled with the proposed hydro-mixture was subjected to exploitation along with the advance of longwall working. This enabled the in-situ collection of a number of fill material samples from various places along the entire length of the incline. Then their strength was tested and the results compared with the obtained test results of identical material seasoned under laboratory conditions. The obtained results constitute a unique research material since it is practically impossible to verify the laboratory-determined strength parameters of the solidifying fine-fraction hydro-mixtures under in-situ conditions. This results mainly from the lack of technical capabilities and poor access to the places where fine-fraction hydro-mixtures are applied, mostly abandoned cavings or parts of workings separated by dams.



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1. Introduction

For many years, Polish hard coal mines have been using large amounts of waste materials, including fine-fraction energy-generation wastes, in the form of hydro-mixtures in various underground mining techniques, such as sealing of caving goaves, construction of dams and filling plugs, or the filling of underground voids [1–3]. The use of ash-water hydro-mixtures in underground mining is legally defined by the Regulation of the Ministry of Environment [4] issued with the Waste Management Act [5] and has the legal form of waste recovery. Additionally, hydro-mixtures' required physical and mechanical properties are defined in the Standard PN-G/11011: 1998 [6], which is not binding, but due to the lack of other standard regulations, it is commonly recommended and used for ore and hard coal mining. Currently, the energy waste market is dominated by fly ash in various forms, captured in electrostatic precipitators with codes 10 01 02 and 10 01 82 [7]. The ashes with the code 10 01 02 are fly ashes from coal, produced in conventional boilers without desulphurization processes. Due to the lack of binding properties, their application in the underground mines is possible only in fire prevention for sealing goaves or filling sublevel workings and post-mining voids. Yet, such wastes are widely used in the construction industry to produce building elements or the production of cement and concrete. One example where dog headings effected by the completion of hard coal mining were filled with ash-water mixtures is the extraction of the seam with a thickness of approx. 4.0 m at Mining Plant Ekoplus [8]. The filled workings are mined using AM-50 roadheaders,

used to fill workings and underground voids. In such cases, the ash-water hydro-mixture should be characterized by the following [2,6,10]:

- A significant range of penetration;
- The smallest possible amount of seepage (excess) water;
- Binding properties and strength properties in the low range;
- Resistance to water (impact of groundwater).

From the viewpoint of the binding process and final strength parameters, the proportion of water in the mixture should be optimized in terms of the effectiveness of the hydration process. However, since the mixtures are delivered hydraulically to the places of their application using gravity pipeline transport installations, the amount of water in the mixture is higher than required based on the criteria mentioned above, and the possibilities of such transport must be accounted for [11]. Thus, the optimization of the mixture composition must consider both the mentioned requirements for the binding process and strength after solidification, as well as the requirements for flow conditions in the transport system and subsequent penetration properties in the working area.

Taking the above into account, we can formulate a research thesis that states that it is possible to use hydro-mixtures based on fine-fraction energy waste, in particular fluidized ashes, in mining technologies that require preset strength parameters. It should be emphasized that the preset strength parameters are to be understood as parameters obtained immediately after the accepted standard-specific seasoning time and additional water soaking time.

To prove the formulated research thesis, the paper presents the results of comparative studies of laboratory tests and in-situ tests involving strength properties of hydro-mixture samples made based on ash from a fluidized bed boiler in a selected power plant in the province of Silesia used to fill a dog heading in a chosen hard coal mine.

2. Characteristics of the Filled Dog Heading: Materials and Methods

In Polish underground mining of hard coal, ash-water mixtures are more and more frequently used to eliminate redundant underground workings. Such solutions are primarily used when it is necessary for the filling material to achieve some assumed strength parameters. The most important of such parameters include uniaxial compressive strength R_c and water resistance, understood as the loss of R_c strength under the impact of water. The subject matter presented in the paper concerns comparative strength tests of hydro-mixture samples made based on selected fluidized ash, prepared in laboratory conditions and collected in situ from an abandoned working. The working in question was a transport incline, which was filled with a binding hydro-mixture based on fluidized ash from a selected power plant, and the basic criterion for selecting this fluidized ash were the expected strength parameters such as strength R_c after 7 days, min 0.1 MPa and strength R_c after 28 days, min 0.5 MPa. The filled incline was located on the course of the longwall being mined and posed a fire hazard. In effect, a decision was made to temporarily fill it with a binding hydro-mixture, and then after about 55 days, the incline was liquidated during further exploitation of the longwall. A fragment of the mining map with the marked incline is presented in Figure 2. The liquidation of the incline provided access to the filling material and the in-situ sampling of the bound hydro-mixture for strength tests. In the liquidation process of underground workings by filling them with a binding hydro-mixture, it is practically impossible to collect samples of the solidified hydro-mixture for laboratory tests due to the lack of access to such workings. In the presented case, the safety considerations which enforced the decision to have the incline filled with the binding hydro-mixture allowed access to this place and enabled collection of samples during the advance of the longwall and mining out the filled incline.



Figure 2. View of the incline filled with binding material made on the basis of fluidized ash.

2.1. Filling Process of the Incline

Filling the incline with the solidifying hydro-mixture made based on fluidized ash was carried out using a mixing installation located on the ground surface, equipped with a system that dosed the amounts of fly ash and water used. The installation was connected with a pipeline system, in which the supply and hydrotransport is carried out by gravity. The said method is based on the attainment of supply pressure equal to the hydrostatic pressure obtained in the vertical part of the pipeline located in the shaft. This pressure makes it possible to overcome the unit energy losses of the flow through the horizontal sections of the pipeline leading to the deposition place of hydro-mixture. In the discussed case, the length of the vertical section was approx. 460 m, and that of the horizontal sections was approx. 600 m. The mixing installation on the surface can monitor the mixing process of fluidized ash with water to ensure that the hydro-mixture introduced into the pipeline complied with the consistency defined by the table spread parameter and measured in line with the Standard [Standard PN]. The spread of the hydro-mixture significantly determines its physical properties, including also strength parameters. Mixtures with table spread values above 200 mm show good pipeline transportability and good penetration properties in the working zone. Mixtures with table spread values below 200 mm are characterized by a more compact consistency, increased hydrotransport resistance, higher strength values after solidification, and a smaller amount of excess water [12]. Due to large volume of the filled incline, the works were carried out for several days, and the hydro-mixture was introduced cyclically in the amount of approx. 150–200 m³ in one cycle. When the hydrotransport process is carried out cyclically, it is necessary to flush the transport pipeline before and after each cycle. The process water used to rinse the pipeline system was redirected to the goaf of the adjacent longwall, which allowed to avoid the rise of excess water level in the filled incline, which would have had an adverse effect on the time and processes of hydro-mixture binding and its target strength parameters.

2.2. Sampling Points of the Bound Hydro-Mixture

After 57 to 59 days from filling, the incline was liquidated, which made it possible to collect spot samples from the solidified hydro-mixture. Figure 3 shows schematically the places where 10 samples were collected for strength tests, while Figures 4 and 5 show the exemplary exposed places of the incline before sampling.

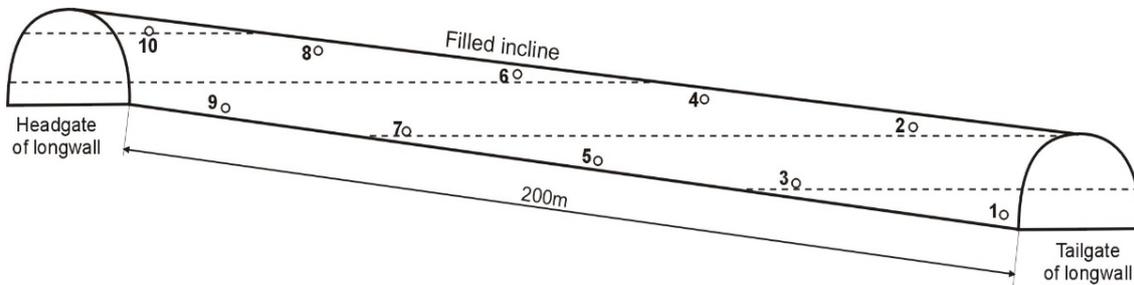


Figure 3. Diagram of collection points of 10 samples for strength tests on the longitudinal section of the incline filled with binding hydro-mixture.



Figure 4. Exposed upper part of the incline filled with hydro-mixture based on fluidized ash; (1) upper elements of the powered roof support of the longwall complex.

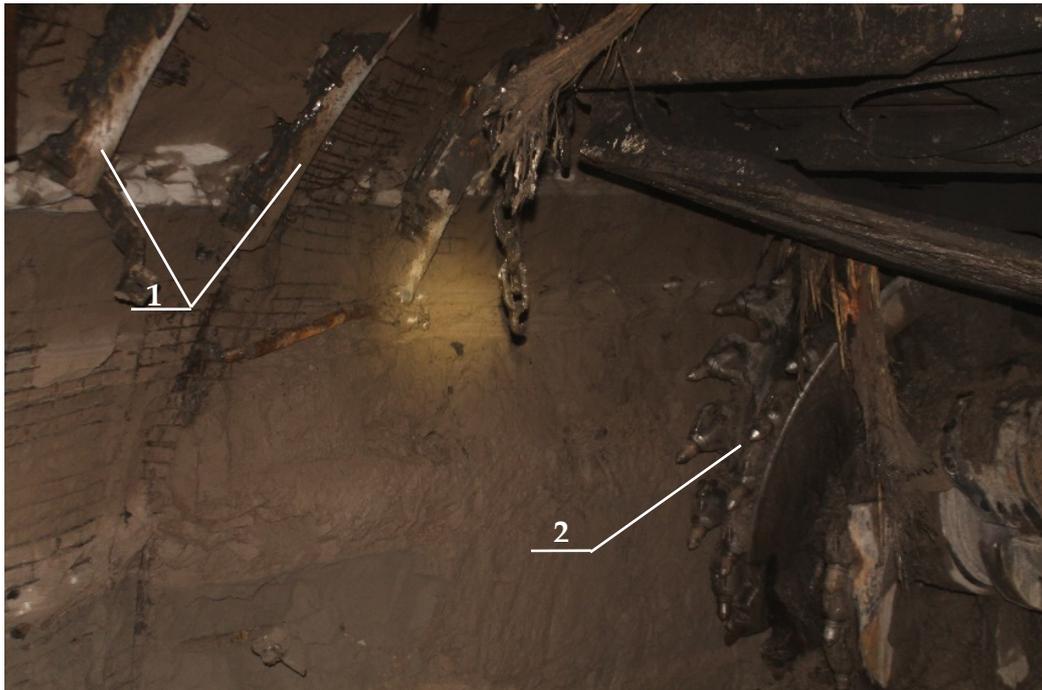


Figure 5. Exposed lower part of the incline filled with solidified hydro-mixture made on the basis of fluidized ash: (1) part of the old steel support of the incline; (2) mining head of the longwall shearer.

3. Methodology and Research Results

For comparative tests of strength parameters of fine-fraction hydro-mixtures made on the basis of fluidized ash, the following methodology was adopted, divided into two tasks:

- Methodology of making fine-fraction hydro-mixtures in laboratory conditions and their testing;
- Methodology of in situ sampling and strength tests carried out in the laboratory.

3.1. Methodology of Making and Testing Hydro-Mixtures in Laboratory Conditions

Laboratory tests of hydro-mixtures prepared on the basis of fluidized ashes were carried out in the laboratory of the Department of Deposits Exploitation (Institute of Mining, Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, Gliwice, Poland) in compliance with PN-G-11011. The research comprised the determination of the following selected parameters:

- The mass ratio of S/W (dry ash/water) and density;
- Amount of excess water;
- Compressive strength;
- Water resistance.

Laboratory tests of hydro-mixtures prepared for different S/W ratios were carried out to show the difference in physical and mechanical properties resulting from a different proportion of batch water in the hydro-mixture with fluidized ash.

To obtain an appropriate fluidity of the mixture, which determines its physical properties, water was added into dry ash in the amount necessary to get a specific table spread of the mixture. To better illustrate differences in the tested parameters, depending on the proportion of water in the hydro-mixture, six different hydro-mixture consistencies were adopted (160, 180, 200, 220, 240, and 260 mm), defined by the table spread parameter in compliance with PN-G-11011.

The mixture table spread is increased by increasing the proportion of water in the mixture. The increase of water share results in a reduction of the solids concentration,

reduction in mixture density, a decrease of viscosity, longer binding time, deterioration of strength properties of the solidified mixture, and even loss of its solidification capacity.

Mixtures with table spread values below 200 mm are characterized by a more compact consistency, increased hydrotransport resistance, higher strength values after solidification, and a smaller amount of excess water. From the viewpoint of hydrotransport, the mixture with a lower concentration of solids (table spread above 200 mm) ensures lower flow resistance in the installation. It thus provides higher flow velocity and a larger range of hydrotransport options, which is essential, especially in the case of significant horizontal distance between the working sites and the backfill shaft or a slight difference in the levels between the ground surface and the filling works place. On the other hand, a mixture of high table spread contains much more water than that which can be bound by the fly ash contained therein. The excess water flowing out of the place where the hydro-mixture is collected with mine water and may contribute to a possible increase in the water hazard. Considering the above, we should always try to optimize the composition of hydro-mixture in terms of the proportion of excess water [13–15]. The currently used mixing installations, equipped with modern dosing and monitoring systems, are able to successfully meet the requirements mentioned above [16].

As mentioned above, hydro-mixtures made in laboratory conditions based on fluidized ash were prepared for six different proportions of ash to water mass, whereby hydro-mixtures with six table spread levels from 16 to 260 mm were obtained. After the hydro-mixtures were prepared, the density and amount of excess water were determined, and the results are summarized in Table 1. At the same time, samples were prepared from these hydro-mixtures for future strength tests.

Table 1. Results of determinations of selected physical properties of the hydro-mixtures based on ash from a fluidized bed boiler.

S/W Ratio	Density [kg/m ³]	Table Spread [mm]	Amount of Excess Water [%]
1:0.75	1450	160	2.5
1:0.85	1430	180	4.5
1:1.00	1420	200	7.9
1:1.05	1410	220	10.2
1:1.12	1400	240	14.3
1:1.20	1380	260	17.6

As can be seen from the conducted research, as the proportion of water in the mixture composition is increased, its table spread increases and its density decreases. With the rise of the table spread in the range from 160 to 260 mm, the density of the mixtures decreased from 1480 to 1350 kg/m³, while the S/W mass ratio increased from 0.75 to 1.20.

The amount of excess water that flows out of the hydro-mixture at the place where it is located ranges from 2.5% to 17.6%. The highest amount of excess water, 17.6%, was found in the hydro-mixture with the highest proportion of water and the highest table spread of 260 mm. The smallest amount of excess water, 2.5%, was contained in the hydro-mixture with the lowest water content and the lowest table spread of 160 mm.

The tests of uniaxial compressive strength R_c of the hydro-mixtures made on the basis of fluidized ash were carried out after 7, 14, 28 and 60 days. In order to map the typical climatic conditions in the underground workings of mines, the samples of the mixtures were seasoned in the LTB 650 RV climatic chamber manufactured by Elbanton (Geldermalsen, The Netherlands) in the following storage conditions: temperature 25 °C, humidity 95%. Additionally, after 60 days, the samples were soaked with water for 24 h in order to determine their water resistance, i.e., the loss ratio of strength R_c . The results of these tests are summarized in Table 2 and in the diagram shown in Figure 6.

Table 2. Uniaxial compression strength and water resistance of hydro-mixtures prepared on the basis of selected fluidized ashes depending on table spread.

Table Spread Value of Hydro-Mixture	Strength Rc [MPa]					Rc60 + 24 h Soaking with Water	Water Resistance k [%]
	7 days	14 days	28 days	60 days			
160	0.48	0.85	1.08	1.35	1.28	5.2	
180	0.42	0.75	0.95	1.25	1.17	6.4	
200	0.32	0.62	0.88	1.18	1.09	7.6	
220	0.26	0.52	0.82	1.06	0.95	10.4	
240	0.19	0.42	0.76	0.97	0.84	13.4	
260	0.15	0.36	0.68	0.84	0.71	15.5	

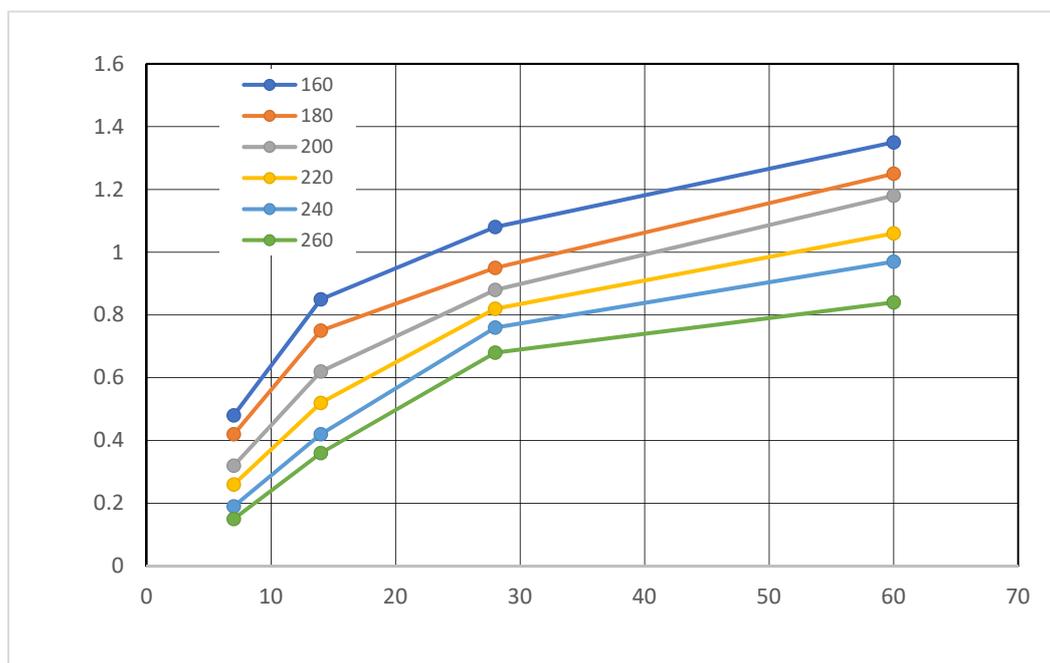


Figure 6. Uniaxial compression strength in time of hydro-mixtures based on fluidized bed boiler ash for various table spread levels.

The tests of uniaxial compression strength of the samples performed under laboratory conditions showed that the Rc strength increases with the increase of seasoning time in the climatic chamber. Additionally, the strength Rc decreases with increasing table spread. After 7 days of seasoning in the climatic chamber, the strength of the hydro-mixtures in terms of the table spread range from 160 to 260 mm was 0.48 to 0.15 MPa, respectively. After 14 days, within the same range of table spread, the strength Rc was from 0.85 to 0.36 MPa, after 28 days from 1.08 to 0.68 MPa, and after 60 days from 1.35 to 0.84 MPa.

After 60 days of seasoning in the climatic chamber and after 24-h soaking in water, all tested samples showed the loss of strength Rc. It was also observed that with the increasing table spread, the loss of strength was higher. The lowest water resistance of 5.2% was recorded for the hydro-mixture with the table spread of 160 mm, while the highest water resistance of 15.5% was reported for the hydro-mixture with the table spread of 260 mm.

3.2. Methodology of Sampling and In-Situ Testing

For the liquidation of the incline described in Section 2 of the paper, ash-water hydro-mixtures made of fluidized ash were used, their strength parameters were tested in laboratory conditions, and the results are shown in Section 3.1. Due to the applied liquidation method of the incline consisting in pouring the hydro-mixture into the working by gravity

and its free flow down to the bottom of the working, it was assumed that the hydro-mixture should have a table spread of at least 200 m. This table spread is sufficient to ensure complete filling of the volume of the incline. Approximately 55 days after filling the incline, the mining works carried out during the coal seam extraction necessitated that the incline filled with hydro-mixture also had to be mined out. As rightly assumed on the basis of the laboratory tests performed earlier, the hydro-mixture based on fluidized ash had solidified, which allowed for its safe exploitation. Additionally, when the incline was opened, it became possible to safely collect samples of the solidified hydro-mixture for strength laboratory tests. Examples of 10 sampling points of the solidified hydro-mixture are shown in Figure 3. From each point, 6 samples were cut out in the form of cubes measuring about 10 cm × 10 cm × 10 cm and then subjected to strength tests in laboratory conditions. Three cubes were used for direct strength tests and the remaining three for water resistance tests. Table 3 shows the results averaged from three measurements for each sampling point. The test of water resistance was performed similarly to the tests of hydro-mixtures described in Section 3.1.

Table 3. Uniaxial compression strength and water resistance of hydro-mixture samples made on the basis of fluidized ash collected in situ after solidification.

Marked Sampling Points	Time of Sample Collection since the Placement of the Mixture [days]	Strength Rc on Average after 60 days [MPa]	Rc60 + 24 h Water Soaking [MPa]	Water Resistance k [%]
1	57	1.04	0.95	8.7
2	57	0.98	0.92	6.1
3	57	1.06	0.94	11.3
4	58	0.95	0.84	11.6
5	58	1.04	0.93	10.6
6	58	1.05	0.97	7.6
7	59	0.85	0.78	8.2
8	59	0.98	0.92	6.1
9	59	0.91	0.84	7.7
10	59	0.94	0.87	7.4
Average	-	0.98	-	8.53

As it can be seen in the Table 3, the uniaxial compressive strength of samples collected in situ 60 days after their placement in the incline ranged from 0.91 to 1.06 MPa. It is difficult to observe any tendency that would make the value of the achieved strength dependent on the place of sampling. The average value of the strength was 0.98MPa. The study of water resistance showed that all the tested samples showed a loss of some strength Rc after 24 h of soaking in water. This loss ranged from 6.1% to 11.6% as compared to the strength Rc before soaking in water. The mean loss of strength was 8.53%. Figure 7 presents the results of strength tests of the samples collected in situ after 60 days, compared to samples additionally soaked with water for 24 h.

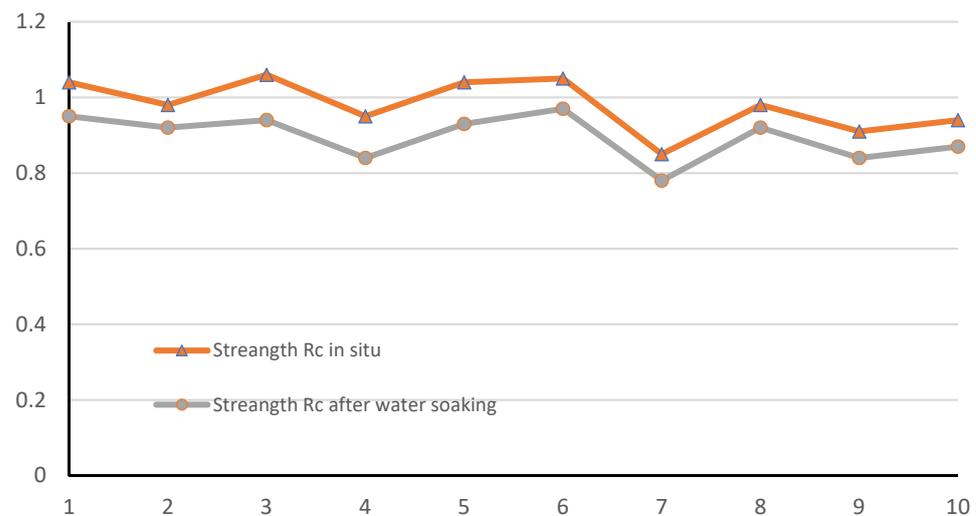


Figure 7. Strength Rc of hydro-mixture samples made on the basis of fluidized ash collected in situ from the incline before and after soaking in water.

4. Discussion

The paper presents comparative results of strength tests of a solidifying hydro-mixture based on ashes from a fluidized bed boiler. The comparative tests consisted in carrying out strength tests of hydro-mixtures of laboratory conditions and strength tests of solidified samples of hydro-mixtures of the same composition, taken in situ from the underground working area. This research approach is unique because after placing the hydro-mixture in underground workings, it is practically impossible to collect samples due to safety measures and the lack of access to the location.

In the laboratory tests, hydro-mixtures made on the basis of selected fluidized ash were used at a different mass ratios of ash to water S/W, whereby various consistencies of hydro-mixture were obtained and, consequently, a different table spread. It enabled the determination of the impact of water content in the hydro-mixture on strength parameters and later to estimate the consistency of the hydro-mixture introduced into the working, based on the results of in-situ strength tests of the samples. On the basis of the obtained results r laboratory tests, the table spread of hydro-mixtures was adopted in the range from 160 to 260 mm.

On the basis of the obtained results of laboratory tests of hydro-mixtures made with the ash from a fluidized bed boiler, as presented in Section 3.1 of the article, it should be stated that:

- With the rise of water share in the mixture, its density decreases. In the table spread range from 160 to 260 mm, the density was respectively from 1450 to 1380 kg/m³;
- With the increase of water share in the hydro-mixture, the amount of excess water grows. In the table spread range from 160 to 260 mm, the amount of excess water was 2.5% to 17.6%, respectively;
- With the increase of water content in the hydro-mixture, uniaxial compression strength Rc decreases. As shown in Table 2, after 28 days of seasoning in the table spread range from 160 to 260 mm, the strength drops from 1.08 to 0.68 MPa and after 60 days from 1.35 to 0.84 MPa;
- After 60 days of seasoning in a climatic chamber and after 24-h soaking in water, all tested samples showed a drop in strength. The lowest water-resistance of 5.2% was recorded for the hydro-mixture with the table spread of 160 mm, while the highest water resistance of 15.5% for the hydro-mixture with the table spread of 260 mm.

Based on the laboratory strength tests of solidified samples collected in situ from the decommissioned incline, as presented in Section 3.2, it should be stated that:

- The uniaxial compressive strength of samples collected in situ 60 days after their placement in the incline ranged from 0.91 to 1.06 MPa;
- The water resistance tests showed that all tested samples were characterized by some loss of strength R_c in the range from 6.1% to 11.6%.

To sum up, it should be stated that the results of strength tests of solidified samples of hydro-mixtures made on the basis of fluidized ash collected in situ confirm the ability of binding properties of the hydro-mixtures to solidify. It allows obtaining an average strength R_c of 0.98 MPa after 60 days, which decreases on average by approx. 8.53% when exposed to water impact. These results and the results of strength tests of hydro-mixtures performed in laboratory conditions are comparable. The obtained average strength of the samples in situ of 0.98 MPa corresponds to the hydro-mixture in laboratory tests with the table spread of about 240 mm (0.97 MPa). Considering the technology of incline filling, as a cyclical gravitational flow of the hydro-mixture down the working, the obtained test results confirm that to increase the range of migration and to ensure correct filling, the hydro-mixture must be characterized by a higher table spread properties. It should be remembered that with the table spread of 240 mm, the hydro-mixture contains about 14% of excess water (Table 1). Before introducing the hydro-mixture in the next cycle, this water should be pumped off or drained using the drainage pipes left behind. Otherwise, the water left in the working will combine with the new hydro-mixture and dilute it, which will result in its lower strength. In extreme cases, it is possible to feed fine-fraction hydro-mixtures into the water when liquidating waterlogged workings or shafts. In such cases, comparative laboratory tests should be performed, aiming to reproduce similar dosing and seasoning conditions of hydro-mixtures to confirm their suitability.

5. Conclusions

The research results presented in the paper allow concluding that the used hydro-mixtures based on selected fluidized ash can be successfully recommended for all liquidation and filling works in underground workings. An additional advantage of these hydro-mixtures is that the in situ strength R_c of about 1 MPa are obtainable, which will only slightly decrease (8.53%) in the case of future flooding of the filled excavation with groundwater.

As shown in the results of laboratory tests, the strength R_c is strongly influenced by the proportion of water in the hydro-mixture. Therefore, it is important in terms of desirable strength parameters under in-situ conditions to ensure that the mixing unit should prepare and feed a hydro-mixture having uniform consistency and possibly the highest compactness. It should be emphasized that currently, a significant amount of fine-fraction energy waste from the group of fluid ashes is available on the market, differing in physical and chemical properties involving the type of burned coal and the applied energy generation installation. For that reason, the use of such materials for the preparation of a solidifying hydro-mixture should always be preceded by laboratory tests that can verify their strength parameters. The same recommendation for periodic verification of strength parameters should be applied in the continuous operation of the installation for a more extended period of time, e.g., several months or several years.

Summing up, it should be stated that on the basis of the obtained results of laboratory and in-situ tests presented in the paper, the assumed research thesis has been proven.

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