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The influence of increased proportion of mixing water in a hydromixture made on the basis of selected energy waste on the gravity performance of a transport installation

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Abstract: Polish hard coal mining has been successfully used for many years for the fire prevention of hydromixtures produced on the basis of fine-grained energy waste. These hydromixtures are transported and introduced by the pipeline system into the infarct space behind the progress of the mechanized complex, where leftover coal residues pose a threat of spontaneous ignition. The basic task of this technology is the possible maximum filling of free rock rubble spaces with fine-grained hydromixtures which results in minimizing the presence of oxygen, necessary for initiating a fire phenomenon. The effectiveness of this technology depends mainly on the efficiency of the installation that transports the hydromixtures and this is closely related to the amount of goafs water. The article presents laboratory tests of selected ash and goafs water from the point of view of its capability and transport efficiency in an example of a gravity pipeline installation in relation to the amount of hydromixture necessary for its preparation.

1. Introduction

One of the most serious threats occurring during hard coal exploitation in Polish coal mines is the threat of endogenic fires that arise in the goafs, the reason for which is the remnant of coal residues. This coal, when contacts with the mine's oxygen in the air, warms up and can go into the burning process. In order to avoid this unfavorable phenomenon, many preventive methods are used, the most common of which is the use of fine-grained mixture in the infarct space using pipelines fed by gravity method [1, 2]. The flow of hydromixtures in such installations is a self-steering process. This means that flow parameters such as performance or hydrotransport velocity result mainly from the spatial layout of the installation route, in particular from the ratio of its length to the difference in the height of the inlet and outlet from the installation [3]. The fine-grained mixture is carried out in surface mixers, in which depending on the installation, the automation of this process is at various levels of advancement. The simplest type of operation of these installations is based on flow mixers (counter-current) without the need for advanced dosing systems. These mixers are used in the case when it is not required to obtain a highly-concentrated hydromixture with constant over time density parameters and the ratio of solids to water concentrations. In the case of the necessity of obtaining a mixture with constant density parameters, mixing systems with an automatic dosing system of components and an internal mixing system are used to ensure failure-free operation and correctness of the process [4]. The regulation of the concentration factor affecting the consistency of the hydromixture, defined by the leveling parameter (according to PN-G / 11011: 1), mainly depends on the amount of water introduced into the mixing system. The result of the increase in

the water content in the mixture is a reduction in the concentration of solids and the density of the mixture as well as a decrease in viscosity. From the point of view of hydrotransport, the mixture with lower concentration of solids ensures lower resistance of flow in the installation, and thus provides higher flow velocity and a greater range of transport - which is important especially in the case of a significant horizontal distance of works from the stowing shaft or a small level difference between the surface and the place of carrying out the filling works. In the case of hydromixtures with greater leveling, we obtain a greater penetration range of the debris and a better filling of the debris, but on the other hand, the mixture contains a much larger amount of excess water that flows off to underground workings [1, 2, 5].

The paper presents the results of measurements of hydromixtures with a different proportion of mixing water and the impact of this contribution on the efficiency of the example gravity pipeline hydrotransport installation, which, in this case, allows the optimization of the hydrotransport process.

2. Methodology for determining the flow parameters of fine-grained mixtures in gravity installations

The basis for determining the efficiency of a mixture of water flowing through the gravity hydrotransport installation is to determine the flow velocity, the permissible speed of which in any cross section will be [5, 6, 7]:

$$v_{mK_{\max}} = \sqrt{2g\left(\frac{p_B}{\rho_m g} - \frac{p_v}{\rho_m g} + H - h_K - \frac{1}{\rho_m g}\sum_A^K l_{A-K}\Delta p_{A-K}\right)} \tag{1}$$

In the expression under the element the height of energy losses is also a function of velocity. Therefore, when determining the maximum flow rate, it is needed to know the equation for energy losses. In practice, the average speed of the hydromixture flow should be in the range of:

$$v_{kr} \leq v_m \leq v_{gr} \tag{2}$$

where:

v_{kr} - critical speed below which solid particles are deposited at the bottom of the pipeline,

v_{gr} - limiting speed causing excessive consumption of pipelines. In practice, it is assumed <12 m/s

Knowing the flow velocity allows you to determine the performance parameters for the flow of a small-fraction mixture:

- volumetric flow rate of mixture Q_m:

$$Q_m = v_m \frac{\pi D^2}{4} \ \ (\text{m}^3/\text{s}) \tag{3}$$

- volumetric flow rate of Q_s solids:

$$Q_s = C_V Q_m \ \ (\text{m}^3/\text{s}) \tag{4}$$

- volumetric flow rate Q_w:

$$Q_w = (1 - C_V)Q_m \ \ (\text{m}^3/\text{s}) \tag{5}$$

Generally, it can be assumed that the voids filling capacity (Q_p) corresponds to the volume flow of the mixture reduced by the amount of water, which under the given conditions will not be bound in the solidification process or absorbed by the surrounding goaf.

The condition of correct determination of unitary energy losses of non-Newtonian liquid flows, which include high-density ash-water mixtures, is the knowledge of rheological parameters [9, 10]. The rheological parameters can be determined by designating the flow curve in the laminar flow zone and

choosing the appropriate rheological model. The practical and most frequently used rheological model describing the flow of fine-grained mixture is the Bingham's Model [5, 8]:

$$\tau = \tau_0 + \eta_p \frac{dv}{dy} \tag{6}$$

where: τ - tangential stress, Pa,
τ_0 - flow limit, Pa,
η - viscosity, Pa * s,
dv/dy - shear rate, s^{-1},
k, n - model parameters.

The flow curves of fine-grained mixtures can be determined using tangential stress measurements as a function of shear rate in a viscometer or rotary rheometer with coaxial measurement cylinders. Knowing the course of the flow curve and choosing the optimal rheological model, it is possible to determine the rheological parameters and the unit resistance of the mixture flow in the laminar flow zone.

3. Characteristics of an example installation for gravity hydrotransport

For calculations and analysis, there was adopted an exemplary pipeline hydrotransport installation fed with gravitational pressure running through the shaft to mine workings. The installation is used for transporting ash and hydromixtures based on fine-grained energy waste. The adopted route consists of nine mining excavations and can be classified as moderately complicated from the point of view of the spatial layout. The installation is supplied from a modern mixing and feeding junction equipped with full monitoring and control of the production process of the water mixtures. The diagram of the adopted route and its geometrical parameters are shown in table 1 and its hydraulic profile is shown in figure 2.

Table 1. General geometric parameters of transportation pipeline.

Pipeline route (name of working)	Length of pipeline segment (m)	Height of begin/end of pipeline segment		Height of begin/end of pipeline segment
		H_p (m)	H_p (m)	
Shaft	150	291.5	-199.8	491.3
Shaft I tour	70	-199.8	-199.8	0.0
Horizontal excavation No 1	90	-199.8	-200.5	0.7
Shaft II tour	130	-200.5	-200.4	-0.1
Horizontal excavation No 2	100	-200.4	-196.3	-4.1
Incline I	635	-196.3	-315.1	118.8
Cross-cut	100	-315.1	-324.5	9.4
Incline II	690	-324.5	-402.0	77.5
Incline III	840	-402.0	-459.2	57.0
SUM	**2805**	**-**		**750.5**

As shown in table 1, the basic geometric parameters of the pipeline installation are:
- pipeline total length $L_c = 2805.0$ m,
- pipeline diameter $D = 0.150$ m,
- height difference between the inlet and the outlet of the installation $\Delta H = 750.5$ m,
- the ratio of length to height difference $L_c/\Delta H = 3.738$.
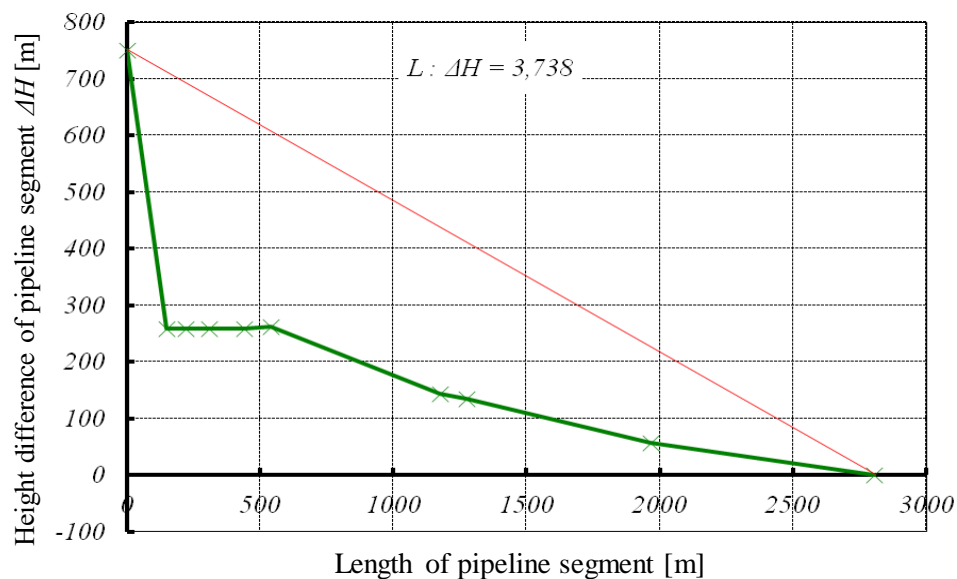
Figure 1. Hydraulic profile of pipeline installation for transport of fine-grained mixtures.

The considered installation leading through the shaft to underground workings is characterized by a correct hydraulic profile and favorable values of geometrical parameters (table 1 and figure 2). The ratio of length to height difference is 3.738 in its case, which will ensure a much higher transport efficiency of mixtures, as well as the possibility of transporting mixtures with larger unit flow resistance (higher density). In the analyzed pipelines' route there is a no-outflow zone beginning on the shaft bottom and runs to the end of the horizontal excavation No. 2. The length of the pipeline section in this zone is 540 m and its maximum depth in relation to the above-mentioned height. The hydrostatic pressure of the liquid stagnating in the non-outflow part of the pipeline will amount to a maximum of 0.35 MPa for water up to approximately 0.6 MPa for the ash-water mixture with a density of 1600 kg/m^3. Within these excavations, the location of the valve in the pipeline and the receipt of a liquid stagnating in the pipeline, the volume of which will be about 14 m^3 can be considered.

4. Determination of hydrotransport parameters based on rheological measurements and the amount of excess water

For making hydromixtures, fine-grained materials in the form of energy ash from waste group 10 01 02 with different proportions of water to solids were used. Measurements of rheological parameters of hydraulic mixtures were made on the Brookfield RS rheometer and measurements of the amount of excess water in accordance with PN-G / 11011: 1998. In the tests based on the author's experience, the range of consistency of a mixture of 130 – 250 mm measured with a Ford cup [1] was adopted. To describe the rheological properties of fine-grained mixtures, Bingham's rheological model defined by two values: flow limit and dynamic viscosity [5, 7] was used. The determined values of rheological parameters and the amount of excess water are summarized in table 2.

As can be seen in table 2 in the range of flowability of the tested mixtures from 130 to 250 mm, their density varies from 1430 to 1495 kg/m^3. Along with the increase in pourability, the dynamic viscosity of the hydromixture drops in the range from 0.039 to 0.216 Pa·s. A similar relationship occurs in the case of the flow limit, where along with the increase in flow it falls in the range from 60.52 to 7.74 Pa. It can be assumed that with the flow rate from 130 to 250 mm, the dynamic viscosity decreases by one order of magnitude and the flow limit by about two orders of magnitude.

Table 2. General rheological properties of fly ash – water mixture.

Table spread R (mm)	Density of a mixture ρ_m (kg/m^3)	Dynamic viscosity η_B (Pa·s)	Yield point τ_0 (Pa)	Amount of excess water (%)
130	1495	0.216	60.52	0.5
150	1480	0.159	40.25	5.6
170	1470	0.114	28.32	9.1
180	1465	0.097	22.30	10.6
200	1455	0.071	16.24	13.1
220	1445	0.057	11.83	15.4
230	1440	0.051	10.05	16.4
250	1430	0.039	7.74	17.9

As can be seen in table 2, the amount of excess water is directly proportional to the leveling of the hydromixtures. With increasing flow from 130 to 250 mm, the amount of excess water increases from 0.5% to 18.7%.

On the basis of the determined rheological parameters of ash and water mixtures listed in table 2, the basic parameters of gravitational hydrotransport were determined for the pipeline route accepted in the reference paper. The sizes obtained for each of the liquid mixtures are summarized in table 3.

Table 3. Parameters of hydraulic transport of mixtures in an exemplary transport pipeline.

Table spread R (mm)	Flow velocity v_m (m/s)	Volumetric flow rate (m^3/h) Mixture Q_m	Solid parts Q_s	Water Q_w	Fell efficiency Q_p (m^3/h)
130	3.240	206.12	76.14	129.98	98.98
150	3.786	240.85	86.28	154.58	112.16
170	4.108	261.34	91.66	169.68	119.16
180	4.292	273.05	94.75	178.29	123.18
200	4.565	290.41	98.61	191.80	128.19
220	4.787	304.54	101.13	203.40	131.47
230	4.908	312.23	102.52	209.71	133.28
250	5.130	326.36	104.73	221.63	136.14

The analyzed hydrotransport route of ash-water mixtures has a favorable length / height ratio of the pipeline, amounting to 3.738. Therefore, it is possible to flow ash-water mixtures in the entire flow range from 130 to 250 mm. The volume flow of the mixture in the pipeline leading along the whole route will be from about 206 m^3/h. for a 130 mm leveling mixture up to approx. 326 m^3/h. Considering the range of flow velocities from about 3.2 to 5.1 m/s, it can be concluded that the mixture flow along the route will be much more resistant to possible fluctuations in the concentration of solids to water.

As can be seen from the course of the variability of the composition of ash-water mixtures in the considered extent of the flowability of fine-grained mixtures, changes in the flow rate of solids are relatively small compared to changes in the amount of water necessary to produce a mixture of a given level. Also from the point of view of caulking sealing, it is not advantageous to use mixtures with a low concentration of solids, i.e. with a flow rate of 200 m and more. From the point of view of water balance and sealing technology for caulked goafs, one should therefore aim to reduce the amount of water, thereby increasing the concentration of the mixture. As it can be seen, the choice of the level of fine-grained mixture (concentration of the mixture) has a small influence on the achieved capacity of filling voids and the consumption of industrial waste for the production of the mixture. As the level of the

mixture increases, the amount of water necessary for its production increases and the migration properties of the mixture change as well.

As can be seen in figure 2, the filling capacity of voids with granular material is approx. 99 m³/h. (table 3), the pipeline route under analysis reaches a level of approx. 130 mm at bottling water level reaching at the same time an amount of excess water of about 0.5% which is a very low value and fully acceptable from the point of view of the excavation dewatering system. Increasing the leveling by adding more water for production increases the filling capacity up to 136.14 m³/h. however, there is a significant increase in the amount of excess water leachate to underground workings, amounting to 17.9% for this capacity (table 2). In summary, we can see that with an increase in flow from 130 to 250mm, we can achieve an increase in plant performance by about 37%, while at the same time we get a very unfavorable high increase in excess water about 35 times. In practice, it is assumed that an acceptable amount of excess water, such as a depot to underground workings, additionally feeding the mine drainage system, should not be greater than 5% [8]. Therefore, it is necessary to control the dosing and feeding system of the pipeline system in such a way that it does not exceed this size. Mention should also be made of the unfavorable phenomenon of abrasion (abrasiveness) of the internal walls of transport pipelines, which intensifies as the flow rate of granular materials increases.
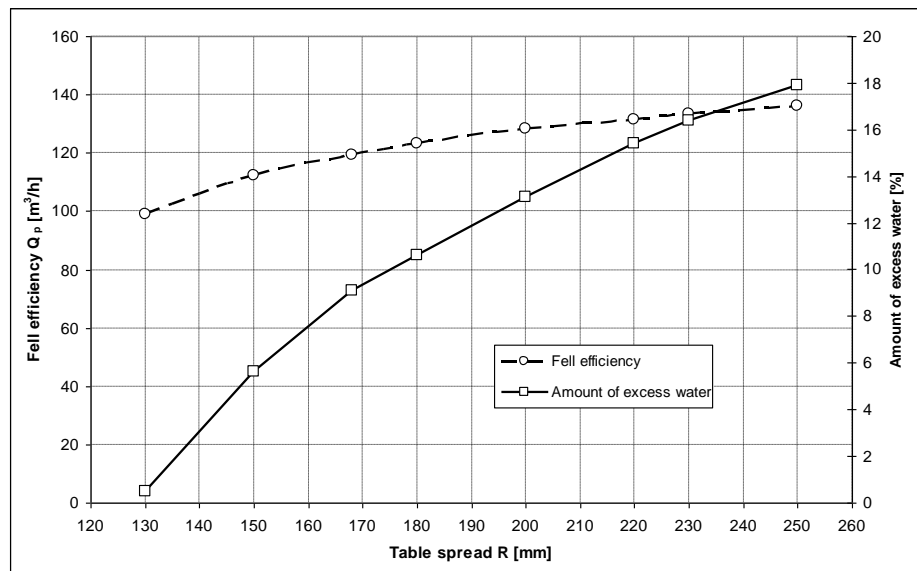
Figure 2. The characteristics of the backfilling efficiency and the amount of excess water depending on the table spread of the ash-water hydromixture.

5. Summary and final conclusions

One of the most serious threats occurring in hard coal mining in Polish mines is the threat of endogenous fires arising in goafs. One of the methods of prophylaxis helping to overcome this threat is the technology of caulking infills with fine-grained liquids. For the preparation of these mixtures, fine-grained energy waste is commonly used in the form of volatile fly ash mixed with water in surface mixers and the resulting mixture is introduced into the pipeline network [9]. The supply of the pipeline network is carried out in a gravitational manner, that is, the created column of the mixture in the vertical section of the installation (shaft) provides pressure, which allows to overcome the resistance of the pipeline built in underground workings. The flow of hydromixtures in such installations is a self-steering process. This means that flow parameters such as performance or hydrotransport velocity result mainly from the spatial layout of the installation route, in particular from the ratio of its length to the difference in the height of the inlet and outlet from the installation. The obtained performance parameters of such an installation depend mainly on the consistency (pourability) of the transported hydromixture, which

in turn depends on the amount of mixing water used to make the hydromixtures. An increased share of the quantity of mixing water results in increased efficiency but also an increased amount of excess water as it flows off to underground workings. The paper presents the rheological parameters of hydromixtures measured on the basis of the selected fly ash, and based on them, the hydraulic transport parameters in the chosen pipeline network were determined based on calculation algorithms. For the same mixtures, tests were also carried out on the amount of surplus water that can be at most fired into underground workings. The results of the obtained tests and calculations were compiled and analyzed. Based on them, the following conclusions can be formulated:

- The pipeline route considered for the transport of ash-water mixtures ensures correct geometrical parameters allowing effective gravitational transport of fine-grained mixtures and the value of the ratio of the equivalent length to the height difference is 3.738.
- In the considered pipeline, there is a section of the route forming a septic zone after the end of the installation's operation cycle. Its presence requires careful rinsing of the pipeline with water after the mixture has been transported. In this case, the possibility of installing a drain valve to drain water from this part of the pipeline it should be considered.
- Calculations and analyzes carried out in the work showed the possibility of conducting effective hydrotransport of fine-grained mixtures in the range of their flow from 130 to 250 mm. Under full power conditions, the potential flow rate of the hydromixture will range from about 206 to 326 m^3/h. and filling capacity from approx. 100 to approx. 136 m^3/h. depending on the leveling.
- As shown in figure 2, with increasing leveling of the hydromixtures, the efficiency of the installation slightly increases, while the amount of excess water which will be drained from the location to the underground workings increases significantly. At the same time, it may cause some fly ash from the sealed goafs to be carried along with the water, loading the mine drainage systems and clearing the underground water.

6. References

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