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The impact of changes in the rheological parameters of fine-grained hydromixtures on the efficiency of a selected industrial gravitational hydraulic transport system

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Abstract: Polish hard coal mines commonly use hydromixtures in their fire prevention practices. The mixtures are usually prepared based on mass-produced power production wastes, namely the ashes resulting from power production [1]. Such hydromixtures are introduced to the caving area which is formed due to the advancement of a longwall. The first part of the article presents theoretical fundamentals of determining the parameters of gravitational hydraulic transport of water and ash hydromixtures used in the mining pipeline systems. Each hydromixture produced based on fine-grained wastes is characterized by specified rheological parameters that have a direct impact on the future flow parameters of a given pipeline system. Additionally, the gravitational character of the hydraulic transport generates certain limitations concerning the so-called correct hydraulic profile of the system in relation to the applied hydromixture characterized by required rheological parameters that should ensure safe flow at a correct efficiency [2]. The paper includes an example of a gravitational hydraulic transport system and an assessment of the correctness of its hydraulic profile as well as the assessment of the impact of rheological parameters of fine-grained hydromixtures (water and ash) produced based on laboratory tests, depending on the specified flow parameters (efficiency) of the hydromixture in the analyzed system.

1. Introduction
Hydraulic transport of fine-grained mixtures in pipeline systems that is in use in Polish hard coal mines is most often of a gravitational type. In systems of that kind, the flow of the hydromixture is a self-controlled process, which means that the parameters of flow result from the spatial configuration of the system, especially the ratio of its length to the difference between the inlet and outlet altitudes, the diameter of the pipeline and the thickness of the mixture. Along with the increase of the length to altitude difference ratio, the flow efficiency parameters of the backfill mixture decrease, which results from the decreased flow rate [3]. To ensure stable flow parameters of the mixture, the system should be characterized by a correct hydraulic profile, that is, a profile in which the pressure curve does not cross the hydraulic profile of the system. In cases where the system is characterized by a disadvantageous hydraulic profile, the flow of the mixture in the system is disrupted and the achievement of the assumed flow parameters becomes impossible. In such a case the system contains negative pressure areas, which may lead to cavitation resulting in the decreased life of the pipeline. In case of using water and ash mixtures, the rheological properties such as viscosity and flow limit of
the mixture have a significant impact on the parameters of hydraulic transport and should be considered in the calculations. Currently in the Polish mining industry the hydraulic gravitational transport of fine-grain mixtures is commonly used for fire prevention in the technology of additional gob grouting.

The paper presents an analysis of the geometric parameters of the system for the transport of fine-grain hydromixtures to a gob grouting location in an underground coal mine. Subsequently, an analysis of the impact of the rheological parameters of the hydromixtures on the efficiency parameters of the process was conducted.

2. Method for determination of flow parameters of fine-grain mixtures in gravitational systems

The flow of the fine-grain hydromixture in gravitational systems proceeds due to the force of gravity. It is assumed that the movement of the hydromixture is described by a modified D. Bernoulli equation, while the unitary energy losses are determined empirically. The notion of the modified Bernoulli equation should be understood as a generalized Bernoulli equation used for the description of the actual movement of liquid in pipeline, containing additional corrective factors, in which the density of the liquid has been replaced with the kinetic density of the hydromixture. At a specified flow rate of the hydromixture in gravitational system, the pressure at the end of the vertical string, figure 1 is approximately [4, 5]:

\[ p_B = h_1 \rho_m \delta \eta - \Delta p_{A-B} h_1 \]  

(1)

In the formula, the symbol \( \rho_m \) denotes the so-called kinetic density of the hydromixture, that is, the mass of solid particles and water in 1 m\(^3\) of the hydromixture in movement. The \( \eta \) coefficient is a corrective factor, which was named – quite incorrectly – the hydrodynamic efficiency factor of the system.

![Figure 1. Scheme of gravitational backfill installation.](image)

Unitary energy losses in the vertical pipeline A-B were assumed to be similar to the unitary energy losses of hydromixture flow in a horizontal pipeline with a similar diameter. The generalized Bernoulli equation for the A-A and B-B sections of the gravitational system have been presented in figure 1 after assuming that the hydromixture was replaced with an adopted homogenous fluid with a density corresponding to the mean actual density of the hydromixture that is fixed at all sections and all points of the stream, is as follows:
\[ h_l \rho_m g + p_A = \frac{v_m^2}{2} \rho_m + p_B + \Delta p_{A-B} h_l \]  

(2)

where:

\[ p_A = p_B - \text{atmospheric pressure (barometric)}, \]

After a transformation, the following form is obtained:

\[ p_B = h_l \rho_m g + p_A - \frac{v_m^2}{2} \rho_m - \Delta p_{A-B} h_l \]  

(3)

In practice, in gravitational systems with depth higher than 100 m, the value of the expression \( p_A - \frac{v_m^2}{2} \rho_m \) is small in comparison to the \( h_l \rho_m g \) value and may be neglected.

The unitary energy losses assume smaller values in a vertical pipeline than in a horizontal pipeline, subject to the assumption that the pipeline is accurately vertical. It may be thus noted that the factor may be assumed to be equal to 1. In a gravitational system, steady flow proceeds due to the fixed difference in the hydromixture levels. If the distance between the level of the outlet cross-section of the hydromixture and the level of the hydromixture in the hopper is denoted by \( H \), figure 1, then, by applying the D. Bernoulli rule to the top surface and any K-K section, the following formula is obtained:

\[ H + \frac{p_B}{\rho_m g} = h_k + \frac{p_k}{\rho_m g} + \frac{v_m^2}{2g} + \frac{1}{\rho_m g} \sum_{A}^{K} l_{A-K} \Delta p_{A-K} \]  

(4)

After a transformation of the formula (4), the following form is obtained:

\[ \frac{p_k}{\rho_m g} = \frac{p_B}{\rho_m g} + H - h_k - \frac{v_m^2}{2g} - \frac{1}{\rho_m g} \sum_{A}^{K} l_{A-K} \Delta p_{A-K} \]  

(5)

The equation indicates that the pressure at any section of the gravitational system decreases along with the increase of the speed of the hydromixture and along with the increase in the energy losses of the flow, which assume higher values at a higher mean flow rate.

The continuous flow of the hydromixture in the pipeline is possible when the absolute pressure at each point of the pipeline does not drop below the pressure of vapour of saturated fluid in which the solid particles are transported in a given temperature

\[ \left( \frac{p_v}{\rho_v g} = 0.238 \text{ m H}_2\text{O in the temperature of } 20^\circ\text{C} \right) \]

If the vaporization pressure is denoted by \( p_v \), the condition of the flow continuity may be presented as:

\[ \frac{p_{min}}{\rho_m g} = \frac{p_B}{\rho_m g} + H - h_k - \frac{v_m^2}{2g} - \frac{1}{\rho_m g} \sum_{A}^{K} l_{A-K} \Delta p_{A-K} \geq \frac{p_v}{\rho_v g} \]  

(6)

Thus, the maximal allowable flow speed of the hydromixture at any K-K section:

\[ v_{max} = \sqrt{2g \left( \frac{p_B}{\rho_m g} + \frac{1}{\rho_m g} \sum_{A}^{K} l_{A-K} \Delta p_{A-K} \right) + \left( H - h_k - \frac{v_m^2}{2g} \right)} \]  

(7)

In the expression under the square root sign, the volume of the energy losses is also a function of speed. That is why while determining the maximal flow rate one needs to know the energy losses equation. In practice, the mean flow speed of the hydromixture should be within the range of:

\[ v_s \leq v_m \leq v_{gr} \]

The sedimentation speed (critical) is a speed below which particles are deposited at the bottom of the pipeline. To ensure the safe flow and to prevent the deposition at the bottom of the pipeline, it is assumed that the minimal value of the movement safety factor \( M \), which is the ratio of the flow speed
of the mixture in the pipeline and the critical speed, should be at least 1.3. The threshold speed is a conventional speed of hydromixture flow, above which the abrasibility of the pipeline increases significantly. The tests of pipe abrasibility in gravitational systems have indicated that the speed above which the abrasibility increases significantly is 10 to 12 m/s.

The basic problem while determining the parameters of the hydraulic transport of fine-grained mixtures is constituted by the necessity of a correct determination of unitary flow drag. The knowledge of the rheological parameters is the condition of a correct determination of unitary energy losses of non-Newtonian fluids flow, which include the high-density ash and water mixtures.

The rheological parameters may be specified by determining the flow curve in the laminar flow zone and by selecting a corresponding rheological model.

The following rheological models are usually applied to describe the flow of fine-grain mixtures:

- **Newtonian model**
  \[ \tau = \tau_0 + \eta \frac{\Delta v}{\Delta y} \]  
  (8)

- **Ostwald de Waele's model**
  \[ \tau = k \left( \frac{dv}{dy} \right)^n \]  
  (9)

- **Bingham’s model**
  \[ \tau = \tau_0 + \eta_p \frac{dv}{dy} \]  
  (10)

- **Casson’s model**
  \[ \sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta \frac{dv}{dy}} \]  
  (11)

where:
- \( \tau \) – steady stress, Pa,
- \( \tau_0 \) – flow threshold, Pa,
- \( \eta \) - viscosity, Pa*s,
- \( \frac{dv}{dy} \) – shearing speed, s\(^{-1}\),
- \( k, n \) – model’s parameters.

Flow curves of fine-grained mixtures may be determined using the measurements of steady stresses in the function of shearing speed using rotational viscometers with coaxial measurement cylinders. Knowing the flow curve and selecting an optimal rheological model, rheological parameters and unitary drags of flow of the mixture in the laminar flow zone may be determined.

In the turbulent flow zone, where a part of the mixture is dispersed into chaotic movement of solid particles and water, it is most convenient to determine the flow parameters including the unitary drags of flow, based on the measurements of flow of mixture in laboratory systems. The measurements allow for the determination of the \( \lambda \) linear drags coefficient which is used in the basic dependency allowing for the determination of the flow speed in turbulent flow at a known volume of unitary flow energy losses:

\[ \Delta p = \lambda \rho_m g \frac{v_m^2}{2D} \]  
[Pa/m]  
(12)

The knowledge of the flow speed allows for the determination of the efficiency parameters for the flow of a fine-grain mixture:

- **Volumetric flow rate of the mixture** \( Q_m \):
  \[ Q_m = v_m \frac{\pi D^2}{4} \]  
  [m\(^3\)/s]  
(13)
Volumetric flow rate of solid particles $Q_s$:

$$Q_s = C_v Q_m$$  \[m^3/s\]  \(14\)

Volumetric flow rate of water $Q_w$:

$$Q_w = (1 - C_v)Q_m$$  \[m^3/s\]  \(15\)

After giving consideration to the density of the transported material $\rho_s$ [kg/m$^3$], the volumetric flow rate of solid particles $Q_{sm}$ [Mg/h] may be determined, which provides information on the hourly use of the backfill materials, and thus the necessary efficiency of the dosing equipment [7].

In case of fine-grain mixtures, which permanently bond a certain amount of water both physically and chemically, the efficiency of filling the voids is difficult to determine. It may be generally assumed that the efficiency of filling the voids corresponds to the volumetric flow rate of the mixture, decreased by the amount of water which – in given conditions – is neither bonded during the solidification process nor absorbed by the surrounding gobs.

3. The characteristics and assessment of geometric parameters of a gravitational pipeline system

A diagram of an example of a pipeline route serving the hydraulic transport of mixtures has been presented in figure 2, while the basic geometrical parameters of the pipeline course in concern have been presented in table 1. Based on the above, a hydraulic profile of the pipeline course has been developed and presented in figure 3.

**Figure 2.** Exemplary route of pipeline for gravitational hydraulic transport of fine-grained mixture.
Table 1. General geometric parameters of transportation pipeline.

| No. | Pipeline route (name of working) | Length of pipeline segment (m) | Height of begin/end of pipeline segment | Height difference of pipeline segment ΔH (m) | Diameter of pipeline segment D_(i) (m) | Equivalent length of pipeline segment L_{ekw} (m) |
|-----|---------------------------------|-------------------------------|----------------------------------------|---------------------------------------------|-----------------------------------------|----------------------------------------|
| 1   | Szyb Jas II                      | 660.0                         | 258.1                                  | 660.0                                       | 0.150                                    | 51.3                                    |
| 2   | Podszybie poz. 400               | 56.0                          | -401.9                                 | -401.9                                      | 0.0                                      | 56.0                                    |
| 3   | Przekop Wschodni I               | 1718.0                        | -401.9                                 | -395.8                                      | -6.1                                     | 1718.0                                  |
| 4   | Skrzyżowanie                     | 30.0                          | -395.8                                 | -395.7                                      | -0.1                                     | 30.0                                    |
| 5   | Przekop oddziałowy południowy    | 388.0                         | -395.7                                 | -393.9                                      | -1.8                                     | 388.0                                   |
| 6   | Pochylnia wentylacyjna W2        | 366.2                         | -393.9                                 | -449.3                                      | 55.4                                     | 366.2                                   |
| 7   | Chodnik wentylacyjny W2 w pokł. 510/1-2 | 465.4      | -449.3                                 | -484.9                                      | 35.6                                     | 465.4                                   |
| 8   | Pochylnia transportowa W2        | 154.8                         | -484.9                                 | -523.3                                      | 38.4                                     | 154.8                                   |
| 9   | Chodnik nadścianowy 23-W2        | 744.2                         | -523.3                                 | -619.5                                      | 96.2                                     | 744.2                                   |
| 10  | Ściana 23-W2                     | 112.0                         | -619.5                                 | -640.7                                      | 21.2                                     | 112.0                                   |
| 11  | Sum                              | 4694.7                        | 898.8                                  | 4086.0                                      |                                         |                                         |

Figure 3. Hydraulic profile of pipeline installation for transport of fine-grained mixtures.

It follows from the table 1 that values of general geometric parameters of pipeline installation amount:
- Total length of pipeline.
- Total length of segments of 0,150 m diameter.
- Total length of segments of 0,09 m diameter.
- Equivalent diameter of the pipeline.
The considered course of the pipeline serving the transport of fine-grain mixtures is characterized by a correct hydraulic profile that ensures favourable flow conditions. Considering the ratio of the transport length and the difference between the altitudes of the inlet and the outlet, one may initially conclude that it should ensure safe and effective flow in the gravitational hydraulic transport system.

4. Methods and results of tests of rheological parameters of fine-grain hydromixtures

Depending on the requirements of technology and the transportation possibilities, mixtures with different concentration of solid parts are applied in mining. As a result, there is a high variability of the rheological parameters of water and ash mixtures. A change in these parameters has a direct impact on the future rates of the gravitational hydraulic transport. The paper exhibits the changes of flow parameters in a pipeline system depending on the changes of the rheological parameters of the hydromixture. Fine-grain materials in the form of power-production ash from a fluidized bed boiler and varying proportions of water and solid particles were used to produce the hydromixtures. In the mining industry it is assumed that table spread is the measure of consistency, which, in line with PN-G/11011:1993, is the diameter of the circle formed upon spilling the hydromixture from a Ford cup onto a horizontal glass surface.[2]

The rheological properties of the mixtures used in gob grouting were determined by means of rotational viscometry using the Bingham’s rheological model to describe the rheological properties of fine-grain mixtures. The determined values have been presented in table 2.

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

| No. | Table spread R (mm) | Density of a mixture $\rho_m$ (kg/m$^3$) | Volume concentration of a mixture $C_V$ (-) | Dynamic viscosity $\eta_B$ (Pa·s) | Yield point $\tau_0$ (Pa) |
|-----|---------------------|--------------------------------|----------------------|------------------|-------------------|
| 1   | 155                 | 1481                          | 0.3195               | 0.223            | 17.79             |
| 2   | 160                 | 1484                          | 0.3183               | 0.201            | 14.90             |
| 3   | 170                 | 1486                          | 0.3171               | 0.173            | 10.65             |
| 4   | 180                 | 1489                          | 0.3160               | 0.146            | 7.55              |
| 5   | 200                 | 1445                          | 0.2958               | 0.111            | 4.06              |
| 6   | 205                 | 1448                          | 0.2947               | 0.103            | 3.48              |
| 7   | 210                 | 1450                          | 0.2936               | 0.096            | 2.97              |
| 8   | 215                 | 1452                          | 0.2924               | 0.09             | 2.45              |
| 9   | 235                 | 1415                          | 0.2754               | 0.071            | 1.2               |
| 10  | 245                 | 1417                          | 0.2743               | 0.065            | 0.84              |
| 11  | 250                 | 1419                          | 0.2732               | 0.061            | 0.7               |
| 12  | 255                 | 1421                          | 0.2722               | 0.058            | 0.55              |

As it can be concluded from rheological properties measurements, which results have been presented in table 2, that within the range of mixture table spread from 155 m to 255 m, their density varies from 1481 kg/m$^3$ to 1421 kg/m$^3$. Increasing table spread of mixtures is accompanying by decrease of dynamic viscosity in the range from 0.223 Pa·s to 0.058 Pa·s. Similar reaction occurs in case of yield point, which decreases from 17.29 Pa to 0.55 Pa by increasing table spread. It can be assumed that increase of table spread from 155 m up to 255 m results in reduction of dynamic viscosity by an order of magnitude and by two orders of magnitude for tables spread.

5. Determination and analysis of dependencies between the parameters of hydraulic transport of water and ash mixtures and their rheological parameters

The parameters of hydraulic transport parameters of water and ash mixtures defined in table 2 have been determined in line with the methods presented in section 2 of the paper and have been exhibited in table 3.
The choice of the fluidity of the fine-grain mixture (concentration of the mixture) has a low impact on the achieved efficiency of void filling and the use of the industrial wastes for the production of the mixture. The amount of water required for the production, however, increases along with the increase of the fluidity – and the migration properties of the mixture are changing as well. From the point of view of fire prevention using the above mixtures, it should be underlined that it is disadvantageous to use both mixtures characterized by excessive density (low fluidity range, quick loss of absorbability)
as well as ones that are too thin (flooding the gobs with water without proper filling which is supposed to provide a durable insulation).

6. Summary and conclusions
The paper presents tests of rheological properties of fine-grain hydromixtures produced based on power-production ashes and presents their impact on the flow parameters in a gravitational pipeline. The conducted tests and calculations allowed to formulate the following conclusions:

- The considered path of the pipeline for the transport of fine-grain mixtures ensures correct geometric parameters allowing for an effective gravitational transport of fine-grain mixtures.
- Based on the tests of rheological parameters of water and ash hydromixtures, it may be asserted that along with the increase of fluidity in the range from 155 mm to 255 mm, the value of the dynamic viscosity decreases in the range from 0.223 Pa·s to 0.058 Pa·s, the flow threshold decreases in the range from 17.79 Pa to 0.55 Pa, while the density decreases in the range from 1481 g/dm³ to 1421 g/dm³.
- The analysis of flow parameters of water and ash mixtures based on their rheological parameters, conducted in section 5, allows to conclude that the volumetric flow rate of the hydromixture changes along with the increase of the fluidity (from 155 to 255 mm) in the range from 55.65 m³/h to 72.69 m³/h, while the efficiency of backfilling increases in the range from 23.11 m³/h to 25.72 m³/h.
- Forecasts of the operating parameters of the system for the transport of ash and water mixtures based on laboratory tests of the rheological parameters of mixtures characterized by variable fluidity, have exhibited that the system provides the possibility of effective hydraulic transport of the backfilling mixtures within the entire range of the fluidity, that is from 155 mm to 255 mm.
- It should be noted that different types of fly ashes used for the production of water-ash mixtures may exhibit properties that are very different from those presented in the paper. In case of using other types of materials to produce the mixtures, the tests of their rheological properties must be conducted each time and recipes ensuring the effective hydraulic transport and the fulfillment of the technology requirements must be developed.
- In case of the determined hydraulic transport parameters, the volumetric flow rate of the mixture will be within the range from 55 m³/h to 72 m³/h. To produce such an amount of mixture, it is necessary for the plant producing the mixtures to mix fine-grain fly ashes in the maximal amount up to 50 Mg/h at a flow rate of water of up to approximately 53 m³/h.

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