Influence of pipe roughness and coating built-up on pipe walls on the flow of solidifying Non-newtonian fly ash-water mixtures in hydraulic transport systems in coal mines

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Abstract. Due to favourable physical properties, the most frequently used fill materials in underground technologies are mixtures of fly ash from hard coal combustion and water. The mixtures are delivered by pipelines from the ground surface to the places of application gravitationally, so the reliable assessment of flow parameters is crucial for the successful fill operations. In first place rheological properties of mixtures must be known for further flow parameters prediction. These parameters may be obtained from measurements in laboratory pipeline loop, which reflect the operation conditions of industrial pipelines in terms of flow rate range and variability of rheological properties of mixtures. Further considerations focused on the problems of range of flow and influence of pipe roughness on reduction of mixture delivery distance. Among other, the conclusion is that the transport distance occurring with technologically acceptable flow rate decreases rapidly with increasing pipe roughness and may finally lead to pipeline failure. As it has been shown on an example to any point of mining operations may be delivered fill mixtures with a certain maximal value. This maximal density is varying widely in relation to actual length and height of gravitational pipeline. Flow parameters of fill mixtures in gravitational pipelines may be affected heavily by increasing of pipe roughness. Variability of absolute pipe roughness have been discussed in relation to typical abrasion and corrosion processes of pipe walls and also considering potential coating built-up created by solidified mixture layers. Operation of gravitational pipeline in systems of underground voids filing should be considered as a dynamic process, where the geometrical parameters and roughness of the pipeline may undergo continuous and rapid changes.

1. Introduction
Underground hard coal mines in Poland are practicing widely a lot of quasi-backfill operations with use of fly ash from hard coal combustion. Filling voids accompanying longwall system with caving is the most frequently adopted technology aimed on spontaneous coal combustion mitigation and improvement of ventilation conditions in longwalls. Approximately in 30 from about 80 currently running longwalls this technology is adopted and allows to safe and efficient coal production. Coal mines also use fly ash – water mixtures for other purposes, as for example liquidation of abandoned workings or construction of backfill plugs. The wide range of applications means that fly ash – water mixtures with different characteristics must be produced on the surface and delivered underground.

Growing distances between shafts (mine centers) and mining operations areas create increasingly challenging conditions for hydraulic transportation of fill mixtures. A research program has undertaken to analyze the influence of concentration of a fly ash in mixture with water on its
rheological properties, which were measured in laboratory pipeline loop. Fly ash from a power plant combustion vessel with semi-dry desulphurization method was selected as an adequately representative example from the range of coal combustion solid waste and by-products available on local market, however it should be kept in mind that each of such substances may exhibit different rheological and solidifying characteristics in mixture with water [1].

2. Measurement of fly ash – water mixture rheological properties in laboratory pipe loop

Head loss/flow velocity relations have been measured for fly ash – water mixtures in the range of density from 1105 to 1605 kg/m$^3$ circulating in a pipe loop of diameter 80 mm, which was able to keep a flow velocity from around 1.0 m/s up to 4.5 m/s. Analysis of measurement results have been conducted assuming homogeneity of fly ash water mixtures and constant value of rheological properties during the time of flow in the pipeline. First assumption was discussed on the basis of the classification of mixtures concerning existence of pseudo homogenous, quasi-homogenous and heterogenous mixtures [2] with respect to their dispersity [3].

The second assumption is justified by the time differences between flow time in mine pipelines systems (maximally up to about half an hour in the state of continuous movement counteracting binding) and initiation of binding (more than 2 hours in an immobilized state).

For the purposes of further considerations basic parameters of fly ash – water mixtures together with their rheological properties accordingly to Bingham plastic model have been listed in table 1. Mixture of densities smaller than about 1400 kg/m$^3$ are Newtonian fluids ($\tau_0 = 0$ Pa)

Remarkable is strong increase of yield point and Bingham viscosity coefficient, which are in exponential relation with density and concentration of a mixture. From the point of the view of production of fly ash-water mixtures in mine fill preparation plants, an important conclusion from the analyse of the data in table 1 is that even small relative fluctuations in water to solid material ratio (W/S) result in high variability of rheological parameters. For example a 10% decrease of W/S ratio from 0.526 to 0.472 increases the yield point of the mixture by 110%, from 3.644 to 7.644 Pa.

**Table 1.** Parameters of fine-grained mixtures used in laboratory measurements [4].

| Number of sample | Density $\rho$ (kg/m$^3$) | Yield point $\tau_0$ (Pa) | Bingham Viscosity $\mu_0$ (Pa.s) | Volume Concentration $C_v$ (-) | W/S ratio (-) |
|------------------|---------------------------|---------------------------|-------------------------------|-------------------------------|---------------|
| 1                | 1382                      | 0.000                     | 0.0173                        | 0.342                         | 0.910         |
| 2                | 1447                      | 0.589                     | 0.0313                        | 0.400                         | 0.709         |
| 3                | 1486                      | 1.994                     | 0.0469                        | 0.435                         | 0.614         |
| 4                | 1529                      | 3.634                     | 0.0606                        | 0.473                         | 0.526         |
| 5                | 1559                      | 7.644                     | 0.0807                        | 0.500                         | 0.472         |
| 6                | 1605                      | 24.542                    | 0.1256                        | 0.541                         | 0.400         |

*) mass of fly ash per 1 m$^3$ of mixture

3. Gravitational flow of mixtures in pipes

To ensure successful operation of a longwall it is necessary to be able to deliver the fill mixture at the full length of longwall panels and to each point of an accessed part of a coal seam. This requirement, however, could be difficult to meet due to considerable dimensions of longwall panels and large distance between the mine shafts and areas of mining operations.

Flow of a liquid (either homogenous mixture) in a pipeline is governed by Darcy-Weisbach equation [5, 6]:

$$\Delta p = \lambda \frac{L}{D} \frac{\rho_av^2}{2} \quad (Pa)$$

where: $L$ – length of pipeline, m, $D$ – pipe diameter, m,
\( v_m \) – velocity of flow, m/s
\( \lambda \) – Darcy friction factor, -.
\( \Delta p \) – total head loss, Pa.

Darcy friction factor \( \lambda \) depends on Reynolds number of the flow, which in turn is related to flow velocity, density of the liquid (homogenous mixture) and its rheological properties. The main area of interest of the above mentioned research work was the assessment of Darcy friction factor for flows of fly ash – water mixtures under different flow conditions (laminar, turbulent and transient zone) in a wide range of fly ash concentration in mixtures.

In gravitational pipeline transport systems the only source of energy is potential energy of a mixture represented by its hydrostatic pressure resulted from level difference between inlet and outlet of the pipeline. This pressure is also formulated as disposable pressure and must be balanced by the head loss:

\[
\Delta p = \rho_m g \Delta H \quad \text{(Pa)}
\]

For the analyses of flow in rough pipes in turbulent zone the commonly used equation of Colebrook-White has been adopted [7, 8]:

\[
\frac{1}{\sqrt{\lambda}} = -2 \log \left[ \frac{2.51}{\sqrt{\lambda} Re} + \frac{\varepsilon}{3.71D} \right] \quad \text{(Pa)}
\]

where: \( \varepsilon \) – absolute pipe roughness, m.

Equation (3) is valid in the area of turbulent flow with laminar sublayer of the thickness smaller than the roughness of the pipe wall, so the friction factor \( \lambda \) depends both on Reynolds number and pipe roughness. This formulation is valid for relatively low range of \( Re \), from round \( 4 \times 10^3 \) up to about \( 10^5 \) [9]. By increasing value of \( Re \) the fraction containing it may be neglected and the Darcy friction factor depends only on pipe roughness in highly turbulent flows [7].

Practice shows that mine gravitational pipelines do not operate at Reynolds number high enough to reach the fully developed turbulent flow, where the friction factor depends only on pipe wall roughness. Also laminar flow is not a typical operational mode in gravitational pipelines. Observations of mine gravitational pipelines operation have shown that in most cases the flow of mixtures occurs at Reynolds number values in a range from about 3000 up to 12000 and therefore in transient zone and not fully-developed turbulent flow regime, where the influence of pipe roughness on the Darcy friction factor is substantial. Similar is the range of the Reynolds number in laboratory tests of fly ash – mixture flow, varied from about 1000 do 30000. Comparability od Reynolds number is one of the similarity criteria for flows.

4. Analysis of transport range in mine gravitational pipelines

Each particular system of gravitational hydraulic transport can be described by its length, diameter, and height (elevation difference between inlet and outlet of a pipeline) [10]. In case of hydraulic systems for filling underground voids in longwall cavings the situation is much more complex, while both the length and height of a pipeline are variable. Considering simplified example of a longwall mining layout shown in figure 1 the main route of pipeline from point P0 (mixture preparation plant) on the surface to the point P1 is 2880 m long and the elevation difference is 750 m. During operation of each longwall from L1 to L4, fly ash – water mixture must be delivered to each point of current position of a front of a longwall. So the pipelines must reach points from EP1 to EP 4 in longwalls L1 to L4 respectively. In such a case variability of length and height of pipeline can be described for each longwall as follows:

- Longwall 1: length \( L_{L1} \) from 3380 to 4580 m, \( \Delta H_{L1} = 690 \) m,
- Longwall 2: length \( L_{L2} \) from 3200 to 4350 m, \( \Delta H_{L2} = 710 \) m,
- Longwall 3: length \( L_{L3} \) from 3040 to 4040 m, \( \Delta H_{L3} = 730 \) m,
- Longwall 4: length \( L_{L4} \) from 2880 to 3660 m, \( \Delta H_{L4} = 750 \) m.
Transport range in the context of delivery of fly ash – water mixtures to longwalls for the purposes of filling of voids in underground mines is such a maximal length of a gravitational pipeline, which in given conditions of pipeline height and mixture density ensures at least such a minimal flow rate, which is acceptable from any adopted technological requirements. In this case a flow rate of \( Q_m = 100 \text{ m}^3/\text{h} \) has been chosen, because most of existing mixture preparation plants are equipped with mixers of such a capacity. In a pipeline of a constant diameter \( D = 100 \text{ mm} \) it results in flow velocity \( v_m = 3.538 \text{ m/s} \). Relevant Reynolds number values accompanying the flow are varying from 2427 for the mixture of density 1605 kg/m\(^3\) up to 28327 for the mixture of density 1382 kg/m\(^3\). Lengths of pipelines (transport ranges) at which the flow occurs with the velocity \( v_m = 3.538 \text{ m/s} \) have been listed in Table 2.

As it can be seen, possibility for the use of the mixture of the highest density is very limited, and is possible only in parts of longwalls L1 and L2 where the pipelines in horizontal gates are short. Remarkable observation is that the use of mixture of density 1605 kg/m\(^3\) is not possible when the roughness of the pipeline have been taken under consideration.

Permissible maximal density of fill mixture is subsequently decreasing in more distant parts of the longwall panels L1 ÷ L4. During mining of these longwalls, the current mixture properties should be constantly adjusted in aim to achieve best possible effects of filling.

Table 2. Transport range of fly ash water – mixtures in relation to density of mixture, pipe wall roughness and elevation difference. Flow rate \( Q_m = 100 \text{ m}^3/\text{h} \), pipe diameter \( D = 100 \text{ mm} \) [4]

| Roughness \( \varepsilon \) [mm] | Density \( \rho_m \) [kg/m\(^3\)] | \( \Delta H = 690 \text{ m} \) | \( \Delta H = 710 \text{ m} \) | \( \Delta H = 730 \text{ m} \) | \( \Delta H = 750 \text{ m} \) |
|-------------------------------|-------------------------------|-----------------|-----------------|-----------------|-----------------|
|                               | 1382                          | 1447            | 1529            | 1559            | 1605            |
| 0                             | 6660                          | 4676            | 4374            | 3763            | 2936            |
| 1                             | 3973                          | 3392            | 3338            | 2976            | 2516            |
| 3                             | 2724                          | 2446            | 2463            | 2240            | 2010            |
|                               | \( \Delta H = 710 \text{ m} \) |                               |                               |                               |
| 0                             | 6853                          | 4812            | 4500            | 3872            | 3021            |
| 1                             | 4088                          | 3490            | 3434            | 3063            | 2589            |
| 3                             | 2804                          | 2517            | 2533            | 2306            | 2069            |
|                               | \( \Delta H = 730 \text{ m} \) |                               |                               |                               |
| 0                             | 6730                          | 4948            | 4627            | 3982            | 3107            |
| 1                             | 4015                          | 3590            | 3531            | 3150            | 2661            |
| 3                             | 2754                          | 2587            | 2605            | 2370            | 2127            |
|                               | \( \Delta H = 750 \text{ m} \) |                               |                               |                               |
| 0                             | 7238                          | 5083            | 4754            | 4091            | 3191            |
| 1                             | 4319                          | 3688            | 3627            | 3235            | 2734            |
| 3                             | 2962                          | 2659            | 2677            | 2436            | 2184            |

For the conditions of discussed example, considering the pipeline as hydraulically smooth, the range of transport is changing from 2936 m to 6660 in dependence to density of mixture. Distribution of maximal mixture’s density over the area of exemplary mining operations are shown in figure 1. As it can be seen from the figures, shortening of the pipeline allows to use thicker (with higher water to solids ratio) fly ash – water mixtures, which is beneficial for the results of the filling of underground voids. Alternatively, the picture shows maximal densities of mixture, which exceeding may lead to a failure of the transport system. To avoid such a risk, reliable control of mixture parameters in mixture preparation plant, precise analysis and determination of gravitational pipelines work parameters, and regular measurements of rheological parameters of fly ash – water mixture must be ensured. The last one is often an underestimated risk factor for the operation of mine systems of voids filling. Rheological measurements conducted on regular basis show that the physical properties of fly
ash may undergo substantial variability from one delivery to another, even if they come from the same source.

**Figure 1.** Filling of cavings in a panel of longwalls – distribution of maximal density of fill mixture calculated for hydraulically smooth pipeline (see text for details).

5. **Roughness of pipelines for hydraulic transport of mine fill mixtures**

Roughness of pipes in mine gravitational transport systems can be significantly differentiated depending on the type of pipes used for the pipeline assembly, their technical condition, and degree of wear. Moreover, pipe roughness can increase along with the time of pipeline’s lifetime due to corrosion, wear, and – in case of mixtures which exhibit binding properties – build-up of a coating formed from solidified layers of fly ash–waters mixture. Although roughness of new steel pipes is less than 0.1 mm, used and slightly corroded pipes may exhibit absolute roughness of about 0.4 to 1.0 mm. In case of cast iron pipes, even relatively insignificantly eroded pipe surfaces have roughness of more than 1.5 mm [10].

During a flow of fly ash–water mixture in laminar mode or in turbulent mode with laminar sub-layer, what is a case by low values of Reynolds number as observed in mine pipelines, a thin stationary film of a mixture covers pipe walls and may be able to solidify if there is no or incorrect rinsing of the pipeline after cycle of transport. As the fill materials after solidification often do not undergo deterioration in the presence of water, subsequent mixture flow cycles may lead to the build-up of rough and durable coating of the pipe walls (mostly at the bottom).

Absolute roughness of such a surface is similar as in case of concrete and its average roughness is about 3 mm. Old, highly eroded, and pipes with severe wall coating built-up may exhibit roughness even of 10 mm [11].

Figure 2 shows how increased pipeline roughness reduces transport capability of a gravitational pipeline. In the same conditions as in the case presented in figure 1, where the flow parameters have been calculated assuming that the pipeline is hydraulically smooth, absolute roughness of 1.0 mm
reduces densities of mixture, which may be delivered to any points of considered longwalls. As it can be seen in this example, when the pipeline is hydraulically smooth in the most part of the mining area mixture of density 1559 kg/m³ may be used (figure 1), although considering rough pipe, the actual density of mixture, which may be used for filling of cavings is only 1447 – 1529 kg/m³. Also significantly decreased must be density of the fill mixture for filling of voids in the most distant part of longwalls L1 and L2. Larger difference between actual and assumed (or neglected) pipeline roughness results in much more rapid decrease of maximal mixture density values and in practice may lead to immobilization of mixture in pipeline.

Average pipeline roughness may undergo continuous and rapid changes in time. Corrosion and abrasion are processes that take place slowly over time. A rough wall coating may be built up after only a view pipeline operation cycles. Also connecting or disconnecting of a pipeline section may result in rapid change of average roughness of the whole pipeline.

Figure 2. Filling of cavings in a panel of longwalls – distribution of maximal density of fill mixture calculated for rough pipeline (ε = 1.0 mm) (see text for details).

The often encountered situation in mine pipelines is that the output of the pipeline lies at higher altitude as the lowest part of the pipeline. In such a case a non-runoff trough is present in the geometric and also hydraulic profile of the pipeline (figure 3). Mostly there is no possibility to discharge water left after rinsing from the recessed parts of the pipeline and the pipe walls are exposed on increased corrosion effects. Also rinsing of such a pipelines is more difficult than in typical, uniformly inclined conduits, and the conditions for coating built-up process are favourable.

Due to rigorous mine safety regulations as well as difficult operational conditions, until recently plastic pipes had not been implemented in underground coal mines. However UHMWPE polyethylene pipes [12] started to be used, which are highly abrasion and wear resistant and may be used for transport of liquid media under pressure of up to 20 MPa. From the point of the view of hydraulic friction polyethylene pipes maybe considered as hydraulically smooth and offering better flow conditions especially at long distances.
6. Conclusion
Hydraulic transport of fly–ash water mixtures in gravitational pipeline systems requires very careful composition of the mixtures because of their highly variable rheological properties. In order to obtain the best results in the filling of voids, fly ash – water mixtures of density in range of about 1450 ÷ 1550 kg/m$^3$ should be used. Such a mixtures exhibit properties of Non-newtonian fluids and may be characterized by viscosity coefficient in the range of about $\mu_B = 0.03 \div 0.08$ Pa·s and yield point of about $\tau_0 = 0.6 \div 6.0$ Pa in terms of Bingham (plastic) rheological model parameters. Mixture of such rheological properties require reliable assessment of flow parameters in pipelines to avoid immobilization of the flow. Also mixture preparation plants must be able to eliminate fluctuations of components proportions. In case of highly viscous Non-newtonian mixtures implementation special attention should be given to the evaluation of pipeline roughness. Appropriate incorporation of the pipe walls roughness will allow precise and reliable determination of maximal thickness of fly ash – water mixture and reduce a risk of pipeline transport failure due to blockage of mixture flow in pipe. The optimization process of hydraulic fill technology in a coal mine is a permanent striving to a compromise between performance of a mixture as a fill material and safe operation of gravitational pipeline transport system. An additional difficulty is that in contrary to typical hydraulic transport pipelines, the system is not static and the length and elevation difference of a pipeline depends on its current position in longwall. Also average pipeline roughness maybe subject of continuous or step changes, thus requiring an appropriate design approach.

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