Design of underground mine voids filling operations in difficult flow conditions of fly ash – water mixtures

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Abstract. Filling the underground voids created during mining extraction of minerals plays a crucial role in different phases of mining operations. A common practice in Polish coal mines is filling the cavings resulted from coal extraction in longwalls for various safety and technical purposes. Moreover, liquidation of redundant underground workings and decommissioning of mines also require filling of large volumes of voids. As the obsolete mining systems with hydraulic backfill have been entirely replaced by longwalls with caving, a need arose for flexible and easily available method for filing of voids. Nowadays, the most frequently applied are mixtures of fly ash and water, which are able to meet a wide range of requirements of specific applications. These objectives may be achieved by the selection of the type of fly ash and adjustment of concentration of solid in mixture in the respect to geometrical parameters of the transport pipeline. These correlations have been demonstrated on the example of measurements conducted on a laboratory pipeline loop for a wide range of fly ash – water mixtures and flow conditions. Measurement results revealed a complex relationship between rheological properties of mixtures and geometrical parameters of pipelines, which strongly influence the distance at which a mixture may be delivered.

1. Introduction
Handling of voids being left after extraction of minerals and surrounding waste rock belongs to the core of underground mining activities. With the exception for stable main access roads and mine workings in durable hard rocks, most of the mine voids undergo backfilling or are being intentionally left for spontaneously occurring process of rocks breaking and crushing accompanied by subsequent creation and compaction of voids. Such a voids, referred in underground mining of coal as cavings or gob, generate several safety and other adverse issues, which must be addressed by mining engineering [1, 2].

Numerous coal fired power plants distributed all over the area of Upper Silesia Coal basins produce valuable solid waste and by-products, which are easy accessible for coal mines in large quantities and at small distances, what makes them convenient for a bulk as raw material for preparation of different types of fill mixture. The most interesting among a range of coal combustion by-products and waste is fly ash, in particular the types, which due to containing desulphurization by-product, exhibit significant binding properties in mixture with water [3].

Fill mixtures prepared on the basis of fly with binding properties have found wide range of application in coal mines such as filling of cavings, solidifying backfill, filling of redundant mine
workings, underground fire control and extinguishing, reduction of methane emission, spontaneous coal combustion mitigation, ground waters flow control, and many other.

Variability of fly ash physical and chemical properties as well as requirements resulted from application conditions, create a necessity for preparation of mixtures, which exhibit widely differentiated flow properties [4]. In the face of the fact that the hydraulic transport systems in underground coal mines run only by means of gravity, correct assessment and anticipating of mixtures flow parameters is a key factor in successful fill operations.

2. Material and research method
A set of mixtures has been prepared using sample of an average, widely available, and commonly used by the mines type of fly ash. Its maximal grain size is 100 μm and 92% of grains pass through a sieve with 63 μm mesh. Hydraulic density of this fly ash is 2118 kg/m³. Selected parameters of mixtures used in measurements of flow conditions are listed in table 1.

Range of mixtures densities and concentration of solid particles reflects the full range of their application in underground mining technologies. In rough estimation samples No. 1 – 3 represent mixtures used for underground disposal of salt mine waters, No. 4 – 6 exemplify typical mixtures for filling of cavings, mixtures No. 7 - 8 might be used for filling of redundant mine workings, and No. 9 – 10 may be proposed as solidifying backfill mixtures. Both mass and volume concentrations have been shown while in hydraulic calculations volumetric concentration is in common use, however mixture preparation is triggered rather by mass concentration and water to solids ratio.

Table 1. Parameters of fine-grained mixtures used in laboratory measurements [5].

| Number of sample | Density ρ_m (kg/m³) | Volume Concentration C_v (-) | Mass Concentration C_m (-) | W/S ratio (-) | Unit mass of solids* u_{cs} (kg/m³) |
|------------------|---------------------|-----------------------------|--------------------------|--------------|----------------------------------|
| 1                | 1105                | 0.094                       | 0.180                    | 4.555        | 198.9                            |
| 2                | 1209                | 0.187                       | 0.327                    | 2.053        | 395.9                            |
| 3                | 1277                | 0.248                       | 0.411                    | 1.433        | 524.8                            |
| 4                | 1307                | 0.275                       | 0.445                    | 1.247        | 581.6                            |
| 5                | 1382                | 0.342                       | 0.524                    | 0.910        | 723.7                            |
| 6                | 1447                | 0.400                       | 0.585                    | 0.709        | 846.8                            |
| 7                | 1486                | 0.435                       | 0.620                    | 0.614        | 920.1                            |
| 8                | 1529                | 0.473                       | 0.655                    | 0.526        | 1002.2                           |
| 9                | 1559                | 0.500                       | 0.679                    | 0.472        | 1059.0                           |
| 10               | 1605                | 0.541                       | 0.714                    | 0.400        | 1146.1                           |

* mass of fly ash per 1 m³ of mixture

Flow parameters of the mixtures have been measured in a test loop, where specific head loss Δp in kPa/m against velocity of flow data sets have been collected for each mixture. Pipes of diameter 100 mm make a closed loop equipped with a pump, which allow to generate maximal flow velocity v_m of around 5 m/s. Differential measure gauge registers head loss of a flow in horizontal section of a pipe at a distance of two meters. Ultrasonic flowmeter and densimeter supply additional data. About 100 dm³ of mixture circulates continuously in the loop in aim to ensure good mixing of the mixtures compounds and stable flow conditions.

3. Results and analysis
For the reason of readability figure 1 presents results of measurements obtained only for mixtures of densities 1447 kg/m³ and higher, which are more interesting due to their complex rheological behaviour.
First of all the research have revealed that fly ash – water mixtures under tests behaved as quasi-homogenous ones, what was already predicted theoretically on the basis of grain-size distribution of the fly ash and average free fall velocities of grains of different sizes. On that basis flow of mixtures may be described by rheological models for actual liquids, what reduces amount of empirical formulas staying behind theories of flow of two-phase mixtures in conduits.

**Figure 1.** Measured relationship between velocity of flow and specific head loss for fly ash – water mixtures of density from 1447 kg/m$^3$ to 1605 kg/m$^3$, pipe diameter $D = 80$ mm [5].

Flow of liquids is described by the well-known Darcy-Weisbach formula [6], which allows to determine specific head loss in terms of velocity of flow $v_m$ and Darcy friction factor $\lambda$:

$$\frac{\Delta p}{L} = \lambda \frac{\rho_m v_m^3}{2D}$$  \hspace{1cm} (1)

where $\Delta p$ is the total head loss of flow in a pipe of length $L$ and diameter $D$. Friction factor $\lambda$ is a function of Reynolds number ($Re$), which depends again on flow velocity, pipe diameter, and density of a liquid, as well as its rheological parameters.

Due to versatility in terms of the use of different rheological models a generalized Reynolds number formula has been applied in a form [7]:

$$Re = \frac{\rho_m v_m^{2-n} D^n}{\tau_0 + K^{(3m+1)n} \frac{\varrho_m}{4m+1} g^{-n-1}}$$ \hspace{1cm} (2)

where:

$$m = \frac{nK \left( \frac{\varrho_m}{D} \right)^{n} }{\tau_0 + K \left( \frac{\varrho_m}{D} \right)^{n}}$$ \hspace{1cm} (3)

which is adequate for a wide range of rheological flow models. If taking under consideration that structure index $n$ could be equal to 1, than consistency index $K$ is adequate to Bingham dynamic viscosity $\mu_B$. A liquid or mixture, where $n = 1$ and $\tau_0 = 0$ represents properties of a Newtonian fluid.
When the value of $Re$ is below about 2300 mixtures flow is laminar and the value of friction factor $\lambda$ is [8]:

$$\lambda = \frac{64}{Re} \quad (4)$$

For turbulent flows with $Re > 4000$ exists a wide range of equations allowing determination the friction factor coefficient $\lambda$, both for hydraulically smooth and rough pipelines [9]. After statistical assessment of obtained measurement results, for the purposes of further pipe loop tests analysis, empirical equation formulated by Blasius has been chosen:

$$\lambda = \frac{0.316}{Re^{0.25}} \quad (5)$$

Which is valid for hydraulically smooth pipes, what is the case for the laboratory pipe loop used for the flow tests.

Research works have revealed that mixtures of densities up to $\rho_m = 1382 \text{ kg/m}^3$ exhibit rheological properties of Newtonian fluids, while denser mixtures with high accuracy may be considered as Bingham liquids. Values of Bingham model parameters for all mixtures, which took a part in measurements have been listed in table 2.

Values of dynamic viscosity for Newtonian mixtures range from $\mu_m = 0.010$ Pa·s for mixture of density $\rho_m = 1105 \text{ kg/m}^3$ up to $\mu_m = 0.0173$ Pa·s for the mixture of density $\rho_m = 1382 \text{ kg/m}^3$ with correlation coefficient no less than $R^2 = 0.9977$. Flow of fly ash - water mixtures of such a low viscosities does not create any substantial problems in the most of typical underground pipeline routes arrangements.

More interesting from the point of the view of mining practice are the rheological parameters of denser mixtures, where yield point appears and coefficients of viscosity (Bingham) may reach substantial values, as presented in table 2.

| Number of sample | Density $\rho_m$ [kg/m$^3$] | Yield point $\tau_0$ [Pa] | Bingham Viscosity $\mu_0$ [Pa·s] | $R^2$ [-] |
|------------------|-------------------------------|---------------------------|-------------------------------|----------|
| 1                | 1105                          | 0.000                     | 0.0101                        | 0.9982   |
| 2                | 1209                          | 0.000                     | 0.0117                        | 0.9989   |
| 3                | 1277                          | 0.000                     | 0.0149                        | 0.9991   |
| 4                | 1307                          | 0.000                     | 0.0153                        | 0.9977   |
| 5                | 1382                          | 0.000                     | 0.0173                        | 0.9992   |
| 6                | 1447                          | 0.589                     | 0.0313                        | 0.9994   |
| 7                | 1486                          | 1.994                     | 0.0469                        | 0.9954   |
| 8                | 1529                          | 3.634                     | 0.0606                        | 0.9895   |
| 9                | 1559                          | 7.644                     | 0.0807                        | 0.9913   |
| 10               | 1605                          | 24.542                    | 0.1256                        | 0.9963   |

O the basis of data listed in tables 1 and 2, a relation between volume concentration of a mixture and its rheological parameters may be formulated. Graphs on figure 2 shows that linear increasing of mixture’s concentration is accompanying by exponential growth of viscosity and yield point, especially when the concentration of mixture exceeds a value of about 0.47. Above this value the yield point and Bingham viscosity is growing proportionally to the mixtures concentration by the power of 7 and even by the power of 15 for higher concentrations in case of viscosity coefficient. The use of such mixtures in gravitational pipelines in coal mines is debatable and must be very carefully considered.

For given values of mixture’s density, viscosity coefficient, yield point, and pipe diameter, flow velocity can be replaced by adequate Reynolds number ($Re$) value, which generally describes actual flow regime which governs the movement of mixtures in the pipe.
Figure 2. Influence of volume concentration of fly ash – water mixtures under test conditions on coefficient viscosity $\mu_B$ on the left and the yield point $\tau_0$ on the right [5].

Range of $Re$ values from round 2100 to 4000 represents a gap between laminar and turbulent flow [10, 11] where the head loss cannot be described using friction factor values derived from equations (4) and (5). Some part of data points have been collected under flow conditions of transient regime, enabling the assessment of friction factor variability in the accessible range of mixtures concentrations and flow rates.

Measurements results obtained for mixtures of density in a range of $1486 \text{ kg/m}^3 \div 1559 \text{ kg/m}^3$ show that within the gap of transient flow regime, part of the data points with higher values of $Re$ does still follow the turbulent flow dependence, while the rest of the data points measured closer to laminar range of flow follow other, more steep function. This function connects highest data points of laminar flow conditions with lowest data points which fit into the turbulent flow conditions. This observation is clearly visible in measurement results for the mixture of density 1559 kg/m$^3$, which has been selected as an example plotted in figure 3 for the purposes of this paper.

After statistical analysis of the usefulness of a number of equations available in literature, equation of Blasius (5) has been selected as a basic relation, which was finally rebuild to a form:

$$\lambda = \frac{0.011(\rho_m - \rho_w)}{\rho_w Re^{0.25}}$$

Range of application of dependence (6) is limited to an area of $Re$ values from round 2000 to 2400. Precisely range of this area within transient zone limits has been determined using maximum of correlation coefficients calculated for dependences (4 – 6) for different ranges of measurement points.

Similar impact of Reynolds number value on specific head loss have been observed by the flow of mixtures of lower density (down to 1486 kg/m$^3$), however area where equation (6) fits the best into the experimental data becomes narrower with decreasing density of a mixture and is gradually replaced by the turbulent flow approximation. In case of mixture of density 1605 kg/m$^3$, which was the highest in the range of research, full range of measured flows was laminar, so there is no evidence about suspected extent of transient area and the validity range of equation (6).
Figure 3. Specific head loss in a function of Reynolds number for mixture of density 1555 kg/m$^3$, approximated with equations (4) for laminar flow, (5) for turbulent flow regime, and (6) for the transient area of flow [5].

4. Practical application of the research results in gravitational pipeline transport of fly ash – water mixtures

In gravitational hydraulic transport systems the only source of energy is the maximum head of mixture resulted from difference in height between inlet ($H_i$) and outlet of a pipeline ($H_o$). If the mixture preparation device is able to keep the mixture level at the top of the pipeline inlet, than the pressure, which converts into head loss during flow of a mixture equals:

$$\Delta p = \rho_m g \Delta(H_i - H_o)$$

(7)

Taking under considerations the relationship between properties of mixture and geometrical shape of pipeline described in equations (1) and (7), a mixture of certain density and rheological parameters is able to flow at a determined flow rate for a limited distance.

While the depth of a mine, which corresponds to the pipeline height difference is more or less constant, thus the horizontal distances between mine shafts and places of operations can be substantial, frequently even more than twenty times longer as the length of vertical part of a pipeline.

Large number of analyses of underground voids fill processes show that in most cases the flow occurs in the range of Reynolds number values from round 2000 up to about 12000, so the flow tests in laboratory test loop reflect directly the conditions governing operation of industrial pipelines, with respect to the difference in pipe diameters (80 mm in the laboratory loop and 100 – 150 mm in underground pipeline systems in coal mines).

The main risk for the effective and safe operation of pipeline systems for filling of voids is blocking of the flow in pipe resulting from too long transport way. In practice mine pipelines must reach certain, often relatively distant areas in an underground mine and deliver fill mixture of expected parameters with acceptable flow rate. Flow rate value requirements may be resulting from technical limitations like time of mining cycle or properties of mixture, i.e. time of hydration (binding process). From the other side, eventual underestimation of hydraulic transport capacity may compromise safety issues and generate increase of mining operations costs.

Diagram on figure 4 anticipates distance of effective transport with a flow rate $Q = 100$ m$^3$/h in a pipe of diameter of $D = 100$ mm depending on density of mixture and flow regime. In the first place is
to be seen how the transport distance varies with changing mixture’s density. Increase of density leads to less intensive decrease of transport distance in turbulent than in laminar flow zone. Unavoidable is the threshold between turbulent and laminar flow zone, so in case depicted in Fig. 4 would be advantageous to omit densities of mixture in the range of about 1600 kg/m$^3$ up to 1615 kg/m$^3$.

Although basically increasing density/decreasing transport distance relation is trivial one, attention should be given to an effect of mixture preparation inaccuracies on the flow distance change. Considering situation shown in figure 4, it can be found that for example change of mixture’s density from 1486 kg/m$^3$ to 1529 kg/m$^3$ (by only 2.89%), what may be referred to about 5.6% mass concentration volatility in mixture preparation plant, finally leads to about 12.6% reduction of transport length (by 174 m). In laminar flow zone this correlation is even stronger and for example, in case of 1.23% increase of density from 1630 to 1650 kg/m$^3$ (round 2% increase of mass concentration) results in almost 24% reduction of transport length from 1150 down to 876 m. Such a variability of critical parameter, which is the range of effective transport may not only reduce significantly the flow rate at which a fill mixture is being delivered to the place of application, but also may lead to a failure of hydraulic transport system. There is a need to keep precisely the composition of fly ash – water mixture, what may be a challenge for the mixture preparation plant.

Figure 4. Maximal transport distance in relation to the density of mixture in a pipeline of height difference 300 m and pipe diameter 100 mm.

5. Conclusion
Measurements of flow properties of fly ash – water mixtures used in underground mine operations has been conducted on a laboratory test loop, however achieved flow parameters are very close to actual conditions occurring in hydraulic pipeline transport systems in coal mines.

Results of research and their analysis discussed in the paper represent only a part of the whole research work. The attention has been given to one of the priority goals in design of underground filling of voids, namely range of transport of fly ash – water mixtures and the impact of flow conditions and rheological properties of mixtures on its variability.

References
[1] Popczyk M 2017 IOP Conf. Ser.: Mater. Sci. Eng. 268 012012
[2] Palarski J and Zając A 2017 The future of backfill in underground coal mines - underground placement of fill material based on fly ash and coal processing waste 12th International Conference on Mining with Backfill 2017 Englewood: Society for Mining, Metallurgy and Exploration (Colorado: Denver) pp 254–61
[3] Pierzyna P and Popczyk M 2014 Odzysk odpadu energetycznego z metody mokrego odsiarczania spalin do likwicacji zbędnych wyrobisk korytarzowych Polityka Energetyczna – Energy Policy Journal 17(3) pp 341–354

[4] Plewa F, Popczyk M and Pierzyna P 2013 Możliwości wykorzystania wybranych odpadów energetycznych z udziałem środka wiążącego do podsadzki zestalanej w podziemiu kopalń Polityka Energetyczna – Energy Policy Journa 16(4) pp 257–270

[5] Strozik G 2018 Wybrane zagadnienia transportu i zastosowania hydromieszzanin drobnorakcyjnych produktów spalania węgla kamiennego w górnictwie podziemnym (Gliwice: Wydawnictwo Politechniki Śląskiej)

[6] Albrigth L 2008 Albrigh’s Chemical Engineering Handbook (Boca Raton: CRC Press)

[7] Madlener K, Frey B and Ciezki H K 2009 Generalized Reynolds Number for Non-Newtonian Fluids Progress in Propulsion Physics 1 pp 237-250

[8] Puzyrewski J and Sawicki J 2016 Podstawy mechaniki płynów i hydrauliki (Warszawa: Wydawnictwo Naukowe PWN)

[9] Mays L W 2004 Hydraulic design handbook (New York: The McGraw-Hill Companies)

[10] Eckhardt B 2012 Turbulence transition in shear flows: chaos in high-dimensional spaces. Procedia IUTAM 5 pp 165–168

[11] Kernswell R R 2005 Recent Progress in Understanding The Transition Threshold to Turbulence in a Pipe Phys. Rev. Lett. 91 pp 17–44