The influence of different fly ash-cement replacement ratios on the pressure drop of a horizontal backfilling pipe

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Abstract. Fly ash (FA) is a kind of harmful by-product in thermal power generation plants, and finding a way to enhance the utility of fly ash has been widely discussed among civil engineering and mining sectors. To investigate the possible optimal ratios of replacing usually used bind agent namely Portland cement (PC) with fly ash, this paper designed different test groups with varying PC-FA replacement ratio. To identify the physical and chemical characteristics of mixing materials used to produce the backfilling slurries, a rheological experiment and X-ray diffraction test have been conducted. Rheological tests show all these three replacement ratio groups (60%, 65%, 70% respectively) are yield pseudoplastic fluid. Computational fluid dynamics as an efficient and money-saving method also has been introduced in the present research to duplicate the flow behaviors and calculate the pressure drop (PD) in the backfilling pipe circuits. The simulation results suggested that all these three RR categories experience an increasing tendency in pressure drop with increasing flow velocity, but in the velocity range of 2 m/s – 2.4 m/s, the increasing tendency is gentle until flow velocity reaches 2.6 m/s, the PD increase evidently. Furthermore, when the RR = 65%, the pressure drop is significantly lower than that of RR = 60% or RR = 70% at all the corresponding investigated flow particle sizes have significant impact on the pressure drop across a pipe and is dependent on solid fraction and flow rate and velocities. Therefore, we can conclude that a proper dosage of FA in mixing backfilling slurries can reduce pressure drop obviously and thereby decrease the expenses in bind agent. Given the FA’s significant effect on pressure drop, and comprehensive considering the backfilling capacity and backfilling cost, the combination of RR = 65% and velocity = 2.6 m/s is optimum.

1. Introduction

Fly ash (FA) is a kind of detrimental fine powder that is a by-product of burning pulverized coal in electric generation power plants [1,2]. World production of fly ash is estimated at around 1.0×10^3 million tons per year, mostly used as waste in landflling and also added to cement production to reduce the need for clinker. For the period 2020 to 2027, different sources forecast a global market between 3.5×10^3 million US dollar to 4.0×10^3 US dollar per year with a variable annual growth rate in the range of 2.6 % (Japan) to 7.6 % (China), depending on the country [3,4].

This growing production of FA has also brought some concerns in main FA producing countries. For example, in India, Government has launched the “Fly Ash Mission” to promote research and
innovation in the area of FA. So that, it can be used not only for being disposed in ash ponds, but also, to explore other areas of utilization, such for instance as a base-building product, for constructing roller compacted concrete dams, and also as stowing of mines [5,6].

Disposing FA on the surface not only occupies a large amount of area. In fact, it represents a challenging task that exposes a potential risk for the adjacent environment, mainly due to the large quantity of FA produced annually, the content of heavy metals, and the potential contamination of groundwater [7,8]. Therefore, some researchers from many industry sectors around the world conducted an intensive investigation on how to turn FA into a resource. According to Cao’s research, more than 50% of the reused fly ash was utilized for ready-mix concrete, and the second-largest application area with approximately 17% is mining and dry construction materials [8]. In civil engineering, many manufacturers introduced FA as promising alternative substances of PC, and thus many investigations were carried out to verify this hypothesis. For instance, Kozhukhova and his colleagues conducted a series tests based on the mixture of F class fly ash and Portland cement and clarified the good performance of the hybrid geopolymer binding system [9], while the research results from Sharonova declared that the high-calcium fly ash can be used as an independent cementing material in modern technologies for producing building materials [10].

Although paste or paste-like slurry backfilling mining methods is relatively new comparing other traditional excavation theories, it is getting more and more attention from mining sectors due to its unparalleled advantage in the aspects of preventing surface subsidence and providing safe working conditions for operators underground. However, for achieving a desired backfilling body strength, a large amount of PC needs to be added into the mixtures as bind agent, and this is the dominant reason why the mine owner is not willing to adopt backfill mining methods. Therefore, aiming to knock down the barricade, researchers investigated different scenarios that partly replacing PC with FA or replacing all PC with FA when producing backfilling slurries. Whether the backfilling slurries can be transferred into the goaf smoothly and efficiently mainly dependent on the pressure drop along the pipeline. And pressure drop is influenced by several factors based on some reported studies. Eesa [11] once stated that four independent variables, namely solids content, cement–tailings ratio, inlet velocity, and circuit shape show great impacts on slurry rheological states. Both Qi [12] and Bharathan [13] reported pressure drop is greatly influenced by particle concentration and the pressure drop increases with increasing velocity as well as particle concentration.

So based on the above literature review, and without further analysis of other factors like for instance economic feasibility or influence of fly ash abrasiveness on pipelines and other underground mining equipment, we can draw the following conclusion that the fly ash as a backfill material [2], not only can replace Portland cement as the cementitious material in mine filling, but also, has a positive effect on the fluidity of the coal ganger cemented backfill slurry [14,15]. Particularly, because during mining operations a mining company may easily consume around 1×10^1 million tons of cement per year [16].

However, traditional research methodology relies heavily on experimental tests to acquire data. And running a large-scale or industrial experiment to test the pressure drop and flow characters usually cost a large amount of money and time. Hence, nowadays more and more scholars turn to increasingly powerful computer simulation [17,18]. Many application results have approved the implemented CFD simulations were capable of reproducing the experimental results [19], and the Herschel-Bulkley model is more applicable to duplicate the rheological behaviors of high concentration fluid [20,21].

In the present study, three groups of different cement-fly ash replacement ratio slurries with varying flow velocity has been investigated. A commercial computational fluid dynamics code FLUENT has been employed to conduct the simulation.
2. Materials and replacement ratios

2.1. Materials preparation

In this study, coal fly ash and Portland cement were used as the binding agent for producing backfill slurries, and the milled coal gangue is the aggregate. Raw materials being adopted were shown in figure 1 and figure 2. The gangue used in this paper comes from a coal mine in Jining City, Shandong Province, China, and the original gangue size is too large, in order to achieve the size requirements for making the filling slurry, a two-stages crushing was carried out using a jaw crusher. And the used fly ash was collected from a thermal power plant in Qingdao city, Shandong province, China.

![Figure 1. Portland cement](image)

![Figure 2. Fly ash](image)

As the above literature review show, the materials’ chemical composition and size grading have a great influence on the backfill slurry’s rheological features [22]. The particle size distribution of fly ash and Portland cement and crushed gangue were obtained by laser analyzer, and the analysis results were depicted in figure 3 and figure 4. respectively. The chemical composition of gangue and fly ash is significantly influenced by the production area, and even from the same mine different coal seams can produce great differences. For this reason, it is necessary to test the chemical composition of the filling material in advance. The chemical compositions of the three main filling materials measured using X-ray diffraction techniques are recorded in table 1.

Particle distribution curves show that most of the fly ash and Portland cement are in the diameter range 140 – 450 μm and 1.5 – 9 μm respectively. While around 90 % of the gangue particles located in the diameter range of 0.2 – 20 mm.

![Table 1. Main chemical composition of raw materials (weight%)](table)

| Raw material | CaO | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | Burning loss |
|--------------|-----|------|-------|-------|-----|--------------|
| Fly ash      | 5.78| 56.91| 30.28 | 4.61  | 0.98| 5.96         |
| Cement       | 24.05| 9.42 | 2.87  | 51.03 | 5.53| 4.08         |
| Gangue       | 3.35| 57.64| 19.77 | 6.08  | 1.09| 24.81        |
2.2. Different replacement ratios

In order to find out how the different Portland cement-fly ash replacement ratios affect the pressure drop and flow characteristics, we prepared three groups of slurries replacing 60%, 65%, 70% of Portland cement by weight with fly ash respectively.

After weighing the raw materials according to the planned proportion, the desired slurry was mixed for 1 min at the speed of 100 r/min, then immediately transferred to the rheometer, and the shear stress and shear rate relationship was demonstrated in figure 5. However, the rheological curve shows a significant different from that of Newtonian flow, it is a non-linear curve and needs a critical stress to start the moving of the slurry flow.

Using the shear stress vs shear rate data, the non-Newtonian rheological constants can be obtained by curve fitting methods to the Herschel-Bulkley rheology equation (see equation 1).
\[ \tau = \tau_0 + kr^n \]  \hspace{1cm} (1)

Where \( \tau \) is the shear stress, \( r \) is the shear rate, \( \tau_0 \) is the yield stress, \( k \) is the consistency index, and \( n \) is the flow index.

![Shear Stress and Shear Rate for different RR](image)

**Figure 5.** Shear Stress and Shear Rate for different RR

### 3. Simulation model

In order to reproduce the flow characteristics of the filling fluid in the horizontal pipe and the evolution of the slurry pressure, Model Designer was used to develop a 3D fluid domain model. The geometry of the 3D model is 1000 cm in length and 20 cm in diameter. Since it takes some distance for the fluid to develop a steady structural flow from the inlet into the horizontal pipe, hence, two observation planes were set at 7 m and 8 m from the pipe inlet respectively. The pressure difference between the two observation planes thus represents the average pressure loss of the backfill slurry as it flows through the horizontal pipe.

An appropriate discretization is the foundation for the subsequent simulation, therefore, it is vital to have a suitable mesh for the targeted computational domain. And for saving computing resources and achieving a good simulation accuracy, in the core part of the computing domain, triangular-prisms is applied in this paper, in addition, considering the more complex flow near the pipe wall, inflation was inserted to create five layers with an increasing ratio of 1.2 (see figure 6).

Due to the high agreement between the Herschel-Bulkley model and the rheological characteristics of the filling slurry depicted in figure 5, the Herschel-Bulkley model is deployed for all simulations to calculate the fluid pressure loss.

Before running the simulation, the boundary conditions also need to be specified. The inlet was set to be velocity inlet while the outlet was pressure outflow, and no-slip condition was applied at the wall.

After all the above settings are completed, all the partial differential equations for the discrete units are solved in Fluent software and the results can be displayed in the form of contour graphs or charts.
Table 2. Simulation scheme

| Replacement ratio | Solid concentration | Velocity (m/s) |
|-------------------|---------------------|----------------|
| 60 %              |                     | 2.0            |
|                   |                     | 2.2            |
|                   |                     | 2.4            |
|                   |                     | 2.6            |
|                   |                     | 2.8            |
| 65 %              | 76 %                | 2.0            |
|                   |                     | 2.2            |
|                   |                     | 2.4            |
|                   |                     | 2.6            |
|                   |                     | 2.8            |
| 70 %              |                     | 2.0            |
|                   |                     | 2.2            |
|                   |                     | 2.4            |
|                   |                     | 2.6            |
|                   |                     | 2.8            |

Figure 6. Meshing of the fluid domain

For analyzing the best Portland cement and fly ash replacement ratio, we keep the solid concentration constant in all simulation combinations and each slurry group corresponds to five speed levels. The detailed simulation schemes are listed in table 2.

4. Results and discussion

When the backfill slurry is transported through the pipe, the collision between the particles inside the slurry and the friction between the slurry and the pipe will lead to a reduction in the total energy of the slurry, which is visually shown by a reduction in pressure. The pressure loss of the slurry is influenced by several factors, the most important of which include the friction factor of the inner wall of the pipe, the transport speed of the slurry, the composition and concentration of slurry, et al. And in this paper,
in order to simplify the analysis, the influence of other variables is removed to focus the effect of replacing different portion of cement with fly ash on the slurry pressure.

After all the simulation scenario was done in FLUENT code, the pressure drop data was obtained. And the processed data was demonstrated in graphics.

Figure 7. Pressure Drop and Velocity with different RR

Figure 7 plots how the pressure drop changes with the slurries flow velocity. From Figure 7 we can see the PD tendency of all the three cement-fly ash replacement ratio categories in respect of flow velocity is generally the same. When the slurries’ flow velocity is below 2.4 m/s, the pressure drop of all the three slurries almost keep stable, this phenomenon denotes that at the velocity of 2–2.4 m/s velocity has a gentle impact on the slurries’ pressure drop. While when the slurries move faster than 2.4 m/s the differences among those three Portland cement and fly ash replacement ratio slurries come to distinguish, comparing with the pressure loss at 2.4 m/s, the slurry with a 60% Portland cement and fly ash replacement ratio increase prominently and the other two counterpart slurries remain stable still. However, when the slurries’ velocity exceeds 2.6 m/s the pressure drop of all the slurries experiences a rapid growth. The reasons that dominate this dramatic change can attribute to mechanical friction. The pressure drop lead by friction between the transporting pipe and the backfill slurries, the relatively high value of inlet velocity resulted in a relatively high value of slip velocity between particle–particle and particle–pipe, leading to a significant increase in interactions and collisions [12] [23]. Hence, if the backfill slurry is conveyed to the goaf at a velocity of more than 2.6 m/s, the energy required will be soaring, therefore, from the financial point of view, when the backfill efficiency requirement can be met we should avoid transporting velocity too high.
Figure 8. Pressure Drop and RR with different Velocities

Figure 8 is about the comparisons of slurries with different Portland cement and fly ash replacement ratio at various flow velocities. It is obvious in this graphic that no matter which replacement ratio of Portland cement and fly ash the slurry has, the pressure drop of the slurry at a velocity of 2.8 m/s is obviously higher than the corresponding counterpart. And all the curves shape in Figure 8 are a saddle, which means the slurry with 65% Portland cement has been replaced by fly ash has a much lower pressure drop than the slurry of RR=60 % or RR=70%. And this tendency of the pressure drops consistent with what was illustrated in Figure 7. The significant difference of pressure drop between slurries with various Portland cement and fly ash replacement ratio indicates the great effect of fly ash on pressure drop reduction. And maybe the particle size distribution can offer this phenomenon a reasonable explanation. Firstly, in the present study, the diameter of the fly ash is relatively larger than Portland cement, and that makes the mixture have a better grading and slurries more homogeneous. Therefore, a proper Portland cement and fly ash replacement ratio can achieve a reduction in pressure drop. Furthermore, the fly ash works as a lubricant as its shape is normally round. 

From figure 9 it is easier to figure out how large the pressure drop gap is among those slurries with different PCFARR. The disparity of the pressure drop between RR3 slurry and RR2 slurry (namely 70 % and 65 %) just gently increased with the flow velocity increase. While the gap of pressure drop between RR1 slurry and RR2 slurry gets larger when the slurry flows faster. Therefore, the reduction effect of fly ash on pressure drop becomes more significant with an increasing flow velocity.
5. Conclusions
The PD along the transportation pipeline is prominently affected by the bind agents added in the backfilling slurries, different binders have a different effect on slurry flowability, thereby, choosing a proper bind agent can not only enhance the backfill efficiency but also reduce the expenses. And based on the present study, for a horizontal pipe with a 20 cm diameter, we can draw the following conclusions:

- FA is a promising alternative bind agent instead of PC, and an appropriate amount of FA can effectively reduce pressure loss.
- Fly ash definitely has an obvious effect on pressure drop during transporting slurries along a horizontal pipe, however, not means the more fly ash added the better, according to the present mixing scenario the recommend Portland cement and fly ash replacement ratio is 65%.
- The transportation velocity of slurry also plays a significant role in pressure drop, when the flow velocity exceeds a certain value, the pressure drop will increase rapidly.
- The best combination of the Portland cement and fly ash replacement ratio and velocity is 65% and 2.6 m/s.
- The reduction effect of fly ash on pressure drop becomes more significant with an increasing flow velocity.

This research paper tried to make a first analysis on the influence of using different percentages of FA for replacing PC and reducing pressure loss in paste-like backfilling slurries. Results obtained are very promising as an innovative solution to alleviate the side effect of pressure loss in pipelines and the negative environmental consequences linked to the increasing FA world production.

The door was left open to further research and analysis of the economic, environmental and technical aspects that may affect the promising results obtained for Portland cement and fly ash replacement ratio and velocity, 65% and 2.6 m/s respectively. Quantification of the economic and environmental impact of using PC instead of FA would be recommendable to have a holistic understanding of the full potential of using FA in paste-like slurry backfilling mining methods. Testing solid concentrations different than 76%, analyzing also the influence of FA’s abrasiveness in pipelines and mining equipment maintenance costs due to its high content of SiO₂ (56.91%) and Al₂O₃ (30.28%).
in comparison with PC, and how to ensure long-lasting stability of backfilled stopes would be highly beneficial for the research community, energy and mining companies, and the society at large.

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