Pipe pressure of mining wet shotcrete flowing in pipes

Lianjun Chen¹,², Xuekai Jiang¹,², Guoming Liu¹,², and Xiangfei Cui¹,²

¹State Key Laboratory of Mining Disaster Prevention and Control Co-founded by Shandong Province and Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao, 266590, China.
²College of Safety and Environmental Engineering, Shandong University of Science and Technology, Qingdao, 266590, China.
³National Demonstration Center for Experimental Mining Engineering Education, Shandong University of Science and Technology, Qingdao, 266590, China.

Abstract: In order to explore the pressure change law of mining wet shotcrete in pipes, the rheological model was built based on rheology principle, and the computational formula of rheological parameters of wet shotcrete was deduced with the linear regression. 100 m full-scale pipeline platform of wet shotcrete was designed and built to study the relationship of pressure and other factors including flow rate, water cement ratio, mix proportion, and pipe bends. Results show: pipe pressure increases with the increase in flow rate and declines with the increase in water-cement ratio, the pressure may fluctuate with a high water cement ratio which can cause cement overhydration and bleeding separation. It will be more beneficial to transport materials if the continuous grading and straight pipe were considered. According to the tests of mix proportion 1:1.5:2.25, the pressure drop is 0.032 MPa·m⁻¹ and the bend pressure drop is 1.3 times higher than in the straight line. We also conclude that solid phase pressure is bigger than liquid phase pressure and they both decline along the pipe based on FLUENT simulation. Finally, the formula of on-way resistance used in mine production was deduced.

1 Introduction

The application of wet shotcrete technology in mine support is of great importance in some aspects such as decrease of aggregate rebound and dust, as well as improvement of supporting quality. However, a series of problem still exist. For example, the pipe blockage caused by the large resistance is often occurred and significantly affects the development of...
wet shotcrete[1, 2]. Hence, it is imperative to study the rheological behavior and pumpability in order to ensure that the pipage of wet shotcrete is safe and effective. In term of pumpability, most research so far has focused on both rheology of fresh concrete and the lubrication layer formed at the interface between the concrete and the wall of the pipe that is the dominant factor to facilitate the pump[1, 3-6]. From the point of view of forecasting and controlling pumpability, it is crucial to measure the rheological parameters of wet-mix shotcrete[7-15]. Since the lubrication layer was first suggested by Alekseev and Weber[16, 17], numerous attempts has been done to estimate lubrication layer thickness based on measuring the velocity profile frontier between concrete bulk and lubrication layer through using various advanced technology[1, 4, 18-21]. However, it is difficult to measure precisely the velocity profile of the flow of concrete in the entire cross section of pipes and there is few accurate and reliable practical method to obtain the real thickness of lubrication layer. In addition, the composition of this layer is still a hot discussion, although several approaches for extracting lubricating materials were reported to study this layer, such as indirectly through wet-screening of fresh concrete[22], or by applying a high pressure filter press[23], or by collecting it after the completion of a tribometer test[22], or directly from the pumping pipeline[24], and some people thought that this layer behaves similarly to the constitutive mortar of the pumped concrete[25-27]. Based on the tribology properties of lubrication layer, the pressure models along pipes of fresh concrete were proposed in Kaplan’ reports[28, 29]. The theoretical model of predicting pumping pressure can be divided into two types: one is for the concrete bulk that does not undergo any shear, the other is the case where both concrete and lubrication layer undergo some shearing in pipes. However, these two models are complicated. In addition, there is not an evaluation standard related to rheology and tribology because those rheometer developed are different ranging from work principle to calculating method, leading to significant quantitative differences between rheological parameters (yield stress and plastic viscosity) measured by various rheometer. In the paper, the rheology property of wet shotcrete was analyzed. The circuit pipe test system of pump wet shotcrete was built to analyze the relationship between pressure and flow rate, mix proportion, pipe shape. The change law of solid and liquid phase pressure was explored by FLUENT. Finally, the formula of on-way resistance used in mine production was proposed to predict the pipe pressure.

2 Rheological behavior of mining wet shotcrete

It has been found that rheological behavior of mining wet shotcrete plays a important role in the pumping process and the construction quality. Hence, it is necessary to study rheological property of fresh shotcrete which is a kind of heterogeneous material in the pumping pipes, especially the mechanical behavior between the pipes and shotcrete.

2.1 Rheological model

The wet shotcrete that has the property of elasticity, plasticity and viscosity at the same time belongs to rheological body. The big particles, cement paste and framework constructed by aggregates are treated as elastic body, viscous body and St. Venant body. The elastic particles evenly distribute in the viscous cement paste and framework. If the viscous body and St. Venant body were treated as a construction of parallel connection, then the construction and elastic body were treated as series connection, the rheological model of Bingham body will be formed[8], as shown in Fig.1.
Fig. 1. Model and construction of Bingham body

The deformation of Bingham body is the deformation sum of elastic and viscous (or St. Venant). According to Maxwell principle, the deformation equation caused by the series connection can be describe as:

\[ d\gamma = \frac{1}{G} d\tau + \frac{\tau}{\eta} dt, \quad (1) \]

\[ \tau + \eta \frac{d\tau}{dt} = \eta \frac{d\gamma}{dt}, \quad (2) \]

Where \( G, \tau, \eta \) and \( \gamma \) denote elastic coefficient, shear stress, viscous coefficient and deformation respectively, set \( T = \frac{\eta}{G}, \quad y \frac{d\gamma}{dt} = \frac{dx}{dt} = \nu, \) where \( T \) is called relaxation period related to body property and \( \nu \) denotes deformation velocity. When \( t = t_0, \tau = \tau_0, \) we obtain

\[ \tau = \eta \frac{d\nu}{dy} + \tau_0 e^{-\frac{t}{T}}, \quad (3) \]

For Bingham body including a number of colloidal solution and supernatant solution and can form structure, \( \eta \neq 0, \tau_0 \neq 0, \) but \( T = \infty, \) its rheological equation is

\[ \tau = \tau_0 + \eta \frac{d\nu}{dy}, \quad (4) \]

When \( \tau_0 = 0, \) it is suitable for Newtonian fluid. Rheological cure and the flow of Bingham body is shown in Fig.2[10]. There is no flow in the pipe shown at the stage O-A when \( \tau < \tau_0, \) the fluid begins to overcome resistance of pipe and breaks the initial construction, which belongs to the “plug flow” at the stage A-B, the phenomenon of “plug flow” disappears gradually when the shear stress \( \tau \) accelerates increase at the stage B-C; the velocity gradient which is direct proportion to the shear stress \( \tau < \tau_0 \) is close to the parabola that reflects full size flow at the stage C-D. The line of C-D is extended reversely to the point E (i.e. yield shear stress \( \tau_0 \)).
2.2 Rheological behavior of wet shotcrete

The rheological behavior of fresh shotcrete conforms to the characteristic of general Bingham body, so the wet shotcrete slips along the pipe under the push of pump. To take a small cylinder of flow concrete in the pipe and make force analysis in Fig.3

According to static equilibrium theory, we have

\[
\pi r^2 \cdot \Delta p = 2\pi r \cdot \tau \cdot l
\]

(5)

\[
\tau = r \cdot \frac{\Delta p}{2l}
\]

(6)

The rheological equation of Bingham body is analogous to that of Buckingham Eq.(7) when the lubrication is ignored and the “plug flow” is simplified into laminar flow.

\[
\tau = \frac{4}{3} \tau_0 + \eta \cdot \left(\frac{8v}{D}\right)
\]

(7)

Based on Eq.(6), to set the internal diameter of wet shotcrete pipe D=64mm, the pressure drop \( j = \frac{\Delta p}{l} \), we obtain

\[
 j = 83.3\tau_0 + 7812.5\eta \cdot v
\]

(8)

The Eq.(7) is analyzed by linear regression with \( \tau = a + bv \) to obtain the line relationship between yield shear stress and plastic viscosity coefficient

\[
\begin{align*}
\tau_0 &= \frac{3a}{4} \\
\eta &= \frac{rb}{4}
\end{align*}
\]

(9)
3 Circuit experiment of mining wet shotcrete pipage

The experimental plat of 100 m full scale circuit which can carry out a number of pumping circuit tests was designed and established based on the environmental requires of mining shotcreting support. The pressure change and the flow law of shotcrete in the middle and small pipeline can be analysed by experiments as follow.

3.1 Pipe test system

The circuit was built with 64 mm-diameter high-pressure steel pipes. This circuit included four 90° bends. The horizontal total length was 100 m. The system of data acquisition was sheltered in a hut installed nearby. A double-plunger pump was used for the experimental campaign. The filling rate of the pump cylinder, which directly affects flow rate, was calibrated from specific experiments prior to the actual concrete pumping.

The circuit was equipped with 8 pressure sensor. The detailed locations of the sensor and the general view of the circuit are shown in Fig.4. The first sensor was located 1 m after the beginning of the circuit whereas the last one was located 100 m.

![Fig. 4. Pipeline system and installation of pressure sensors](image)

3.2 Materials and mix proportions

The cement was from the local cement factory. Its composition and property is shown in Table 1. The sand was a natural river sand with a density of 2560 kg·m⁻³ and fineness modulus of 2.75. The maximum coarse aggregate size was 10 mm. It was a limestone aggregate with density of 2670 kg·m⁻³. The amount of mixing water was corrected to take into account the water absorbed by sand and coarse aggregates.

<table>
<thead>
<tr>
<th>Strength grade (MPa)</th>
<th>BET (m²·kg⁻¹)</th>
<th>Main composition /%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>tricalcium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tricalcium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>free calcium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>alkali</td>
</tr>
</tbody>
</table>

Table 1. The composition and property of cement
Three different mix proportions of shotcrete were studied in this work. Their mix proportions are given in Table 2. One mix proportion is corresponding to four group water-cement ratio and one water-cement ratio is corresponding to four group flow rate.

**Table 2. Experimental scheme**

<table>
<thead>
<tr>
<th>Mix proportion (mass ratio)</th>
<th>Water-cement ratio</th>
<th>Flow rate (m³·h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1.5:2.25 or 1:1.7:2 or 1:2:2</td>
<td>0.45</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>4</td>
</tr>
</tbody>
</table>

4 Results and discussion

4.1 Influence of flow rate on pressure

Because the pressure data fluctuated largely caused by the alternatively working of double-plunger pump, the average pressure was adopted. The pressure data shown in first sensor was treated as the pumping pressure. The pressure data of different flow rate under the condition of different mix proportion is plotted in Fig.5. The linear regression was done to analyse the relationship between pressure and flow rate.
No matter what the mix proportion is, the relationship of pressure and flow rate is nearly linear within the proper scope of water-cement ratio (i.e. 0.45, 0.5, 0.55). The pressure increases with increasing flow rate. The imitative effect shown in figures is good and the fitting variance $R^2$ is close to 1. However, the data fluctuation occurs when the water-cement ratio is 0.6 in the three group mix proportion, the fitting variance $R^2$ is close to 0.8. To analyse the reason: even though the flow shotcrete has a good liquidity under the situation of high water-cement ratio, the separation and bleeding that make flow shotcrete lose the cohesion and water retention often take place in the pumping process. So the shotcrete is changed to be the discontinuous flow that may cause the abnormal pressure along pipes.

**Fig. 5.** The relationship of pressure and flow rate in the 100 m full-scale test
4.2 Influence of water-cement ratio and mix proportion on pressure

![Graphs showing the relationship of pressure and water-cement ratio for different flow rates.]

Fig. 6. The relationship of pressure and water-cement ratio in the 100 m full-scale test

Fig. 6 shows the pressure change trend which decreases with the increase of water-cement ratio. From the opinion of chemical analysis, we can know the experimental cement consists of much tricalcium silicate whose hydration product is mainly tobermorite (i.e., gel, its skeleton symbol C-S-H), chemical reaction equations as follows

\[
2(3\text{CaO} \cdot \text{SiO}_2) + 6\text{H}_2\text{O} \rightarrow 3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 3\text{Ca(OH)}_2
\]

Cement particles dissolve quickly in the water. When the concentration of calcium ion and hydroxyl reach a critical value, hydration products \(\text{Ca} (\text{OH})_2\) and C-S-H seed out from the mix solution and C-S-H grows on the surface of tricalcium silicate to form a bundle layer that can prevent the cement hydration. With increasing water-cement ratio, relative volume of each constituent is shown in Fig. 7 [30, 31]. The volume of hydration products (i.e., gel) and gel pore change very little while the number of capillary porosity increase
gradually. These capillary porosity distributing between particles act as a kind of elastic fine aggregate that can reduce the friction of particles. At the same time, the free water lubricates the particles as the form of water film. So the flow shotcrete gains a good mobility with the enough water, which lower the pressure along pipes.

**Fig. 7.** Relative volume relation of each component in hydrated cement paste

Under the same condition of flow rate, as is shown in Fig.6, the pressure that changes smoothly in the mix proportion 1:1.5:2.25 is smaller than the other two and the relation between pressure and water-cement ratio obeys to power exponent which has a better goodness of fit. The pressure measured of other mix proportions do not have a obvious function relationship with flow rate. To analyze the cause: different mix proportion forms different aggregate grading that can leading the big change on the pressure, the aggregate grading curve of mix proportion 1:1.5:2.25 is nearly close to the continuous grading that can help the fresh shotcrete pipe while the other mix proportions is slightly close to gap grading that may cause the abnormal pressure.

**4.3 Influence of bend pipe on pressure**

Given that the pressure in the mix proportion 1:1.7:2 and 1:2:2 is not smooth, in order to study the influence of bend pipe on pipe pressure accurately, the pressure value in mix proportion 1:1.5:2.25 is adopted and plotted in Fig.8.

**Fig. 8.** Pressure trend of circuit pipe

Obviously, the profiles of pressure are quite linear along the circuit for the mixtures pumped
in the project and its linear fitting formula and variance is respectively \( y = -0.032x + 3.337 \), \( R^2 = 0.982 \). So we can obtain that the pressure drop is 0.032 MPa·m\(^{-1}\). The points at P2, P3, P5 and P7 diverge from the fitting line relatively. To review the piping layout, the pressure sensors at P2, P3 and P5 approach to the bend pipes that may cause the pressure change. Hence, the study on pressure was divided into two parts: straight pipes part including P3-P4-P5 and P7-P8 and bend pipes including P2-P3 and P5-P6.

### 4.3.1 Straight pipe

The pressure measured at the straight points of P3-P4-P5 and P7-P8 is analysed in Table 3.

<table>
<thead>
<tr>
<th>Item</th>
<th>P3-P4-P5</th>
<th>P7-P8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear fitting formula</td>
<td>( y = -0.028x + 3.160 )</td>
<td>( y = -0.028x + 2.92 )</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.999</td>
<td>1</td>
</tr>
<tr>
<td>Pressure drop (MPa·m(^{-1}))</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>Average value</td>
<td>0.028</td>
<td>0.028</td>
</tr>
</tbody>
</table>

The fitting slope of two straight pipe section is same (i.e, the pressure drop is 0.028 MPa·m\(^{-1}\)). Different intercept of two sections means that initial pressure value of each straight pipe is different while the pressure drop is same. Comparing to the fitting slope 0.032 shown in entire circuit including bend pipes, the fitting slope of straight pipe section decreases by 0.004. It can be seen that pressure drop of wet shotcrete along the pipes is tend to linear relation from overall trend.

### 4.3.2 Bend pipe

The pressure measured at the bend points of P2-P3 and P5-P6 is analysed in Table 4.

<table>
<thead>
<tr>
<th>Item</th>
<th>P2-P3</th>
<th>P5-P6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure drop (MPa·m(^{-1}))</td>
<td>0.0367</td>
<td>0.0367</td>
</tr>
<tr>
<td>Average value</td>
<td></td>
<td>0.0367</td>
</tr>
</tbody>
</table>

Two bend pipes who have same characteristic were installed within 50 m and there was no cement hygration in the short distance, so two pressure drop measured is same. According to the analysis from Table 3 and Table 4, the bend pressure drop is 1.3 times higher than straight. Bend pipes influence the pipage of wet shotcrete, especially pressure change. This result above is different from Kaplan [28] and Guptil [32]. Kaplan [28] thought bend pipes did not effect the pressure change while Guptil et al. thought the bend pressure drop is 3 times higher than straight. To analyze the reason: this experiment that adopts small-sized pipe in coal mine is different from Kaplan and Guptil’ s experiment using large diameter pipes who have various radius of curvature on ground buildings. Factors such as the radius of curvature, pipe diameter and pipe material probably effect pressure drop, so the pressure drop should be confirmed by the specific work environment and the application of bend pipes should be avoided in the practical engineering.
4.4 Pressure of solid-liquid phase

The interaction between aggregates and between aggregates and mortar in wet shotcrete is extremely complex, so the flow of fresh shotcrete in pipes was treated as a kind of a continuous “paste-like”. It is different to measure the pressure of solid-liquid phase, hence the finite element simulation FLUENT was adopted to analyse the pressure change of solid-liquid phase in the pipes[4]. Firstly, the real model should be simplified: the interaction between particles was neglected; the cement paste and particles were assumed as liquid and solid phase respectively; the wet shotcrete was treated as a kind of incompressible fluid. The pressure nephogram at entrance as follow,

Fig. 9. Pressure nephogram at entrance

In Fig. 9, the attenuation of mixed static pressure is clear at the axis direction while the pressure change of solid phase is clear at the radial direction. But the pressure change of liquid phase is clear at two directions. In other words, the energy of materials per unit volume decreases with the increasing of conveying distance and the contribution of solid phase is larger than that of liquid phase on the mixed static pressure. In order to more intuitively analyse the pressure change in the pipes, the data of a diameter in different cross-section at 5m, 10m and 20m is plotted in Fig.10.

Fig. 10. The total and static pressure at different positional cross-section (sand means solid)

As is shown in Fig.10, the pressure of solid-liquid phase and mixed static pressure decrease
along the pipes and the total pressure of solid phase is larger than that of liquid phase. Although the change of same phase pressure is not same at different cross-sections, the distribution trend is similar. The phenomenon that mixed static pressure is always same at the a cross-section indicates the dynamic pressure plays a more importance role on the contribution to total pressure and indirectly validates that the distribution of dynamic pressure is same to that of total pressure at the radial direction. The dynamic pressure distribution meets the “plug flow” of A-B section in Fig.2. The maximum pressure wavers at the centre of the pipe, which indicates the phenomenon that the abrasion of inner pipe wall is not always at the same side of pipes.

5 On-way resistance of wet shotcrete pippage

Some research institution has mainly discussed the basic theory and computing method of pipeline resistance in the process of past filling. There are several empirical formulas such as Jinchuan formula, Fushun formula and Xinwen formula[33]. The multifarious nature of wet shotcrete caused different mix proportion leads to the boundedness of paste filling formula. There will be higher error if the past filling formula was directly adopted. Hence, the pumping experiments of wet shotcrete was used to deduce the partial formula of mining wet shotcrete with fluid mechanics and rheology.

The regression analysis of yield shear stress and plastic viscosity of wet shotcrete was done by using Eq.(9) with test data. The computed result as follows.

<table>
<thead>
<tr>
<th>Mix proportion (mass ratio)</th>
<th>Water-cement ratio</th>
<th>( \tau_0 / \text{Pa} )</th>
<th>( \eta / (\text{Pa} \cdot \text{s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1.5:2.25</td>
<td>0.45</td>
<td>322.0050</td>
<td>1.194408</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>3.842483</td>
<td>0.040986</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>165.0030</td>
<td>0.591823</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>75.04200</td>
<td>1.299832</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>245.5510</td>
<td>10.41210</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>220.5000</td>
<td>4.801130</td>
</tr>
<tr>
<td>1:1.7:2</td>
<td>0.45</td>
<td>198.2115</td>
<td>4.404320</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>89.32200</td>
<td>17.12210</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>271.1505</td>
<td>0.331140</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>299.6550</td>
<td>0.155417</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>224.2920</td>
<td>1.024608</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>115.6178</td>
<td>3.034792</td>
</tr>
</tbody>
</table>

The data shown in Table 5 reveals the law that yield shear stress presents the decreasing trend with the increasing of water-cement ratio, especially in the mix proportion 1:1.7:2 and 1:2:2, while the plastic viscosity coefficient has no obvious rule. To analyze the cause: the rheological parameters are often effected by the numerous factors such as aggregate grading, water-cement ratio and the shape of aggregates. In the experiences, the fractal dimension about the shape of aggregates was not carried out, the plastic viscosity coefficient may be effected by material composition. The future study should pay more attention on the influence of shape of aggregates on the rheological behaviours. Hence, the statistical regression was used to deduce the on-way resistance formula in the appropriate mix proportion in the following section.

5.1 The general formula of on-way resistance formula

The specific computing formula of on-way resistance used for different mix proportion and
water-cement ratio can be gained when the yield shear stress and plastic viscosity coefficient are put in Eq.(8). But the formula that changes with the change of mix proportion and water-cement ratio cannot be used expediently in coal mine. In the process of pumping wet shotcrete, slump is an important index of pumpability and the water-cement ratio directly effects the slump. Water-cement ratio exerts a tremendous influence on rheological parameter and the slight change of mix proportion probably influences the change of pipe pressure. Hence, Rheological parameters was treated as the function of water-cement ratio and mix proportion. The general formula of on-way resistance used in suitable range can be obtained by multiple linear regression.

Based on the data in Table 5, water-cement ratio and mix proportion were treated as independent variable \( x_1 \) and \( x_2 \), the yield shear stress and plastic viscosity coefficient were treated as dependent variable \( y_1 \) and \( y_2 \). The formula can be gained by multiple linear regression as follows,

\[
\begin{align*}
\begin{cases}
  y_1 &= 1148.88981 - 1422.90431 * x_1 - 1075.11006 * x_2 \\
  y_2 &= -28.5793 + 78.22996 * x_1 + 19.74084 * x_2
\end{cases}
\end{align*}
\]

Therefore, the general formula of on-way resistance is obtained when yield shear stress and plastic viscosity coefficient calculated from formulas(11) above are put in Eq.(8), which is suitable for different water-cement ratio and different mix proportion in the studying range of this paper.

### 5.2 Validation of general formula

In order to verify the applicability of general formula, the comparison between calculated value and experimental data and these two error in mix proportion 1:1.5:2.25 are displayed in the Table 6.

**Table 6. Comparison between computational value and experimental value**

<table>
<thead>
<tr>
<th>Water-cement ratio</th>
<th>Flow rate ( m^3 \cdot h^{-1} )</th>
<th>Experiment (MPa·m(^{-1}))</th>
<th>Calculation (MPa·m(^{-1}))</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7</td>
<td>0.03270</td>
<td>0.036609</td>
<td>0.119541</td>
</tr>
<tr>
<td>0.45</td>
<td>6</td>
<td>0.03111</td>
<td>0.034378</td>
<td>0.105047</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.03105</td>
<td>0.031984</td>
<td>0.030081</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.02987</td>
<td>0.030127</td>
<td>0.008604</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.03083</td>
<td>0.036758</td>
<td>0.19228</td>
</tr>
<tr>
<td>0.5</td>
<td>6</td>
<td>0.02834</td>
<td>0.033895</td>
<td>0.196013</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.02209</td>
<td>0.030822</td>
<td>0.395292</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.01856</td>
<td>0.017689</td>
<td>-0.04693</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.01655</td>
<td>0.026907</td>
<td>0.625801</td>
</tr>
<tr>
<td>0.55</td>
<td>6</td>
<td>0.01608</td>
<td>0.033411</td>
<td>1.077799</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.01575</td>
<td>0.029664</td>
<td>0.883429</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.15468</td>
<td>0.025469</td>
<td>-0.83534</td>
</tr>
</tbody>
</table>

According to the comparison, the calculated value is slightly bigger than experimental data.
In the range of medium and low water-cement ratio, relative error is within 20%, while in high water-cement ratio it is relatively large. It indicates that fresh shotcrete in pipe is changed to be a kind of rarefied flow which probably causes aggregate hierarchy and separation and leads to the abnormal pressure. Hence, the general formula deduced in the paper was only applied to the materials in medium and low water-cement ratio. If a project need seriously a kind of fresh concrete of high water-cement ratio, in order to gain the accurate data, conveying speed should be improved to make the particles obtain the enough upper lifting force that can avoid separation and hierarchy, or taking the average value from four pressure sensors installed at four direction (i.e. up, down, left, right) of pipe cross-section.

6 Conclusions

(1) Rheological behavior of wet shotcrete consisted of elastomer, viscous body and St. Venant body was analysed based on the rheological principle. The flow behavior was described in pipes by establishing rheological model. Wet shotcrete fully develops flow when \( \dot{\gamma}_\text{r} \geq \dot{\gamma}_0 \). The calculated formula of yield shear stress and plastic viscosity coefficient was deduced with linear regression.

(2) 100 m full-scale circuit platform of wet shotcrete was designed and built, the experimental results shows that pipe pressure increases toward to line with increasing flow rate, the linear relationship in medium and low water-cement ratio is stronger than others. Pipe pressure decreases with increasing water-cement ratio. Continuous grading and straight pipe are more advantageous to pipeline transportation. According to the test of mix proportion 1:1.5:2.25, the pressure drop is 0.032 MPa·m\(^{-1}\) and the bend pressure is 1.3 times higher than straight. Simulations shows that at a same cross-section, the pressure of solid phase is larger than that of liquid phase, maximum pressure wavers at the centre of the pipe and dynamic pressure plays a more importance role on the contribution to total pressure.

(3) The formula of on-way resistance for mining wet shotcrete was deduced:

\[
\jmath = 83.3\tau_0 + 7812.5\eta \cdot \nu .
\]

The general formula of yield shear stress and plastic viscosity coefficient which are suitable for different water-cement ratio and different mix proportion was obtained by multiple linear regression.

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