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SIYOU XIAO*, ZHIXIANG LIU**, YUANJUN JIANG***,
CHENG LI*,***, CHANGNING SUN*,***, LIJUN SU***,****#

REMOTE PIPELINE PUMPING TRANSPORTATION OF CEMENTED TAILINGS BACKFILL SLURRY

PRZETŁACZANIE NA ZNACZNE ODLEGŁOŚCI ZAWIESINY ZAWIERAJĄCEJ ODPADY POFLOTACYJNE ORAZ CEMENT RUROCIĄGAMI Z WYKORZYSTANIEM POMP

For most precious metal mines, cemented tailings backfill slurry (CTBS) with different cement-sand ratio and solid concentration are transported into the gobs to keep the stability of the stope and mitigate environmental pollution by mine tailing. However, transporting several kinds of CTBS through the same pipeline will increase the risk of pipe plugging. Therefore, the joint impacts of cement-sand ratio and solid concentration on the rheological characteristics of CTBS need a more in-depth study. Based on the experiments of physical and mechanical parameters of fresh slurry, the loss of pumping pressure while transporting CTBS with different cement-sand ratio, flux and solid mass concentration were measured using pumping looping pipe experiments to investigate the joint impacts of cement-sand ratio and solid concentration on the rheological characteristics of CTBS. Meanwhile, the effect of different stopped pumping time on blockage accident was revealed and discussed by the restarting pumping experiments. Furthermore, Fluent software was applied to calculate the pressure loss and velocity distribution in the pipeline to further analysis experimental results. The overall trends of the simulation results were good agreement with the experiment results. Then, the numerical model of the pipeline in the Sanshandao gold mine was conducted to simulate the characteristics of CTBS pipeline transportation. The results show that the pumping pressure of the delivery pump can meet the transportation requirements when there is no blockage accident. This can provide a theoretical method for the parameters optimizing in the pipeline transportation system.

Keywords: strong resistance; pipe pumping; pumping looping pipe experiment; rheological characteristic; CFD

W większości kopalń metali szlachetnych zawiesina zawierająca odpady poflotacyjne wraz z cementem w różnych proporcjach cementu i piasku oraz o różnym stężeniu części stałych transportowana jest do wyrobisk i zrobów, gdzie wykorzystywana jest następnie do stabilizacji w rejonie przodka,

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* THE INSTITUTE OF MOUNTAIN HAZARDS AND ENVIRONMENT , CHINESE ACADEMY OF SCIENCES
** CENTRAL SOUTH UNIVERSITY
*** INSTITUTE OF MOUNTAIN HAZARDS AND ENVIRONMENT, CHINESE ACADEMY OF SCIENCES
**** CAS CENTER FOR EXCELLENCE IN TIBETAN PLATEAU EARTH SCIENCES

Corresponding author: sulijun1976@163.com

ponadto w ten sposób ogranicza się zanieczyszczenie środowiska odpadami poflotacyjnymi. Jednakże przetłaczanie różnych rodzajów zawiesin w tym samym układzie rurociągu zwiększa ryzyko zaczopowania rur. Zbadanie wpływu proporcji cementu do piasku w zawiesinie oraz stężenia części stałych na charakterystykę reologiczną zawiesiny wydaje się kwestią kluczową. W oparciu o badania eksperymentalne fizycznych i mechanicznych parametrów świeżej zawiesiny, dokonano pomiarów spadku ciśnienia pompowania w trakcie przetłaczania zawiesin o zawartości cementu i pisaku w różnych proporcjach, dla różnych natężeń przepływu i stężeń części stałych w eksperymentach z wykorzystaniem linii obiegowej rurociągu. Celem eksperymentu było określenie łącznego wpływu proporcji cementu do piasku oraz stężenia części stałych na właściwości reologiczne zawiesiny. Ponadto, przeanalizowano w jaki sposób długość przerw w procesie przetłaczania wpływa na zwiększenie ryzyka zatkania rur i przeprowadzono eksperymenty polegające na wznowieniu pracy pomp. Analizę wyników eksperymentów uzupełniono poprzez zastosowanie oprogramowania Fluent do obliczenia spadku ciśnienia w rurociągu oraz rozkładu prędkości. Wykazano, że wyniki symulacji pozostawały w dużej zgodności z wynikami eksperymentów. W kolejnym kroku opracowano model numeryczny rurociągu eksploatowanego w kopalni złota Sanshandao dla potrzeb symulacji procesu przetłaczania zawiesiny. Uzyskane wyniki wskazują, że ciśnienie tłoczenia w pompie jest na wymaganym poziomie gdy nie występuje zablokowanie przepływu w rurze, i wykorzystane być mogą jako uzupełnienie teoretycznych metod optymalizacji parametrów układu transportowania i przetłaczania zawiesiny.

Słowa kluczowe: opory przepływu, przetłaczanie, eksperyment z wykorzystaniem linii obiegowej rurociągu, właściwości reologiczne, CFD (Computational Fluid Dynamics)

Introduction

Mine tailing is a major source of pollution, especially when it piles up on coasts. The filling mining method is the preferred method because of its technical characteristics of high recovery rate, pro-environment, safety and so on (Wu, 2015). However, coastal mining requires a high filling quality because of its extremely complicated mining conditions. There is a series of technical problems in pipeline pumping transportation of CTBS, such as high mass concentration, long-distance transportation, high filling times line (Total length *L* divided by height difference *H*), strong resistance and so on.

It has been concluded that when CTBS with mass concentrations of 72% to 78% and cement-sand ratio of 1:4 to 1:6 under the transporting condition of a pipeline with an internal diameter of 108 mm to 133 mm and a flux of 100 ±10 m^3/h, its optimal filling times line by gravity are 4 to 6. Its extreme filling times line are 9 to 10 (Cooke, 1993; Helms, 1988; Yilmaz, 1977). In this case, the pipeline transportation of CTBS can not just rely on gravity, and it needs to have a booster pump installed in the pipeline transportation system to provide pressure (Yilmaz, 2009; Supa-Amornkul, 2005). CTBS is a typical non-Newtonian liquid, and the flowing rules in the pipeline are affected by many factors, such as the mass concentration of the slurry, flow velocity, pipe diameter, and the layout of pipe network. Furthermore, the tailing fineness and density significantly influence the dehydrating and hardening properties of paste backfill (Fall, 2005). Kaushal et al. (2005) studied the influence of particle size on pressure drop and concentration profile in pipeline flow of highly concentrated slurry. Wu (2015) et al. pointed out that the Bingham plastic model can be used to describe the rheological behavior of cemented coal gangue-fly ash (CGF) mixtures slurry with high solid concentration (78%-79.5%). Creber (2017) found there are no remarkable effect of size and shape of the backfill particles on pastefill properties. Deng (2017) found that the apparent viscosity of UCB increased consistently as the solids content was increased. Cement-sand ratios and mass concentrations are the key indexes to estimate the strength backfill body.and filling cost. At present, the joint impact of cement-sand ratios and mass concentrations on rheological characteristics of CTBS have not been widely reported. Due to the mining technology requirements, the pipeline filling system may need to deliver several kinds of CTBS.

To calculate the velocity distribution and pressure loss, many methods were proposed. Turian et al. (1987) studied the critical velocity in pipeline flows of slurry based on balancing the energy. Wang et al. (2011) adopted a computational fluid dynamics (CFD) method to optimize the flow velocity of pipeline transportation of CTBS by gravity in deep mining. In addition, a CFD model was also applied to analyze dense-phase pneumatic conveyance of fine particles, including particle size distribution (Behera et al., 2013). Now CFD-DEM technology have been gradually applied to the simulation of solid-liquid two-phase flow (Yang, 2018). However, it is hard to simulate the remote pumping transportation of CTBS because of the restriction of computing ability of computer.

Due to the pipeline filling system may need to delivery several kinds of filling slurry, there are two valuable questions are worth researching: (1) Different kinds of filling slurry transported by different velocities should be simulated by what kinds type of flow model. (2) In order to ensure the stability of the filling system, the flow characteristic of CTBS after pumping had stopped should be further researched. In this work, based on a looping pipe experiment of pumping transportation, the dates of pressure loss under different pipeline transportation conditions were measured. According to the theory of non-Newtonian liquids mechanics, the rheological characteristics of the classified tailing slurry with different cement-sand ratios and mass concentrations in pipeline transportation were analyzed. On this basis, FLUENT was used for simulating the pressure loss and velocity distribution in the pipeline. Synthesizing these results provided an important basis for the parameter selection of pipeline transportation system in mines.

1. Description of filling system

The Sanshandao Gold Mine in Shandong Province, China is the first and biggest coastal metal mine in China. Presently, the majority of the mining ore body is under the Bohai Sea. The vertical elevation height between the stope in the southwest Xinli district of the Sanshandao Gold Mine and filling station is only 165 m. However, the horizontal distance is longer than 2,200 m and the highest filling timeline reaches 14.3. It is very important to control the deformation and seepage. The lower settlement frame stope hierarchical level filling mining method is used for the mining method at this mine. The ore body is mined in two steps. CTBS with cement-sand ratio of 1:4 was adopted to fill the mined-out openings after the first mining step. The filling body will be a temporary pillar because it can prevent cave-ins and roof falls and can improve pillar recovery ratio and productivity for the second mining step. In order to reduce the filling cost, a CTBS with a lower mass concentration (72%) and cement-sand ratio (1:10) is applied in the second mining step. For these reasons, several kinds of CTBS are transported by the same pipeline system.

The layout of the pipeline transportation system is as follows: The CTBS is transported from a filling station on the coast to –165 m underground through a filling hole. Then, the CTBS is transported over 2,200 m over the horizontal pipeline to the stope, as is shown in Fig. 1. The average volume filled by slurry per hour is about 45 m^3. The corresponding transportation velocity and pumping frequency are 1.0 m/s and 14 times/min, respectively. Due to the filling volume sometimes being greater than the average volume, the transportation velocity should be greater than 1.0 m/s.

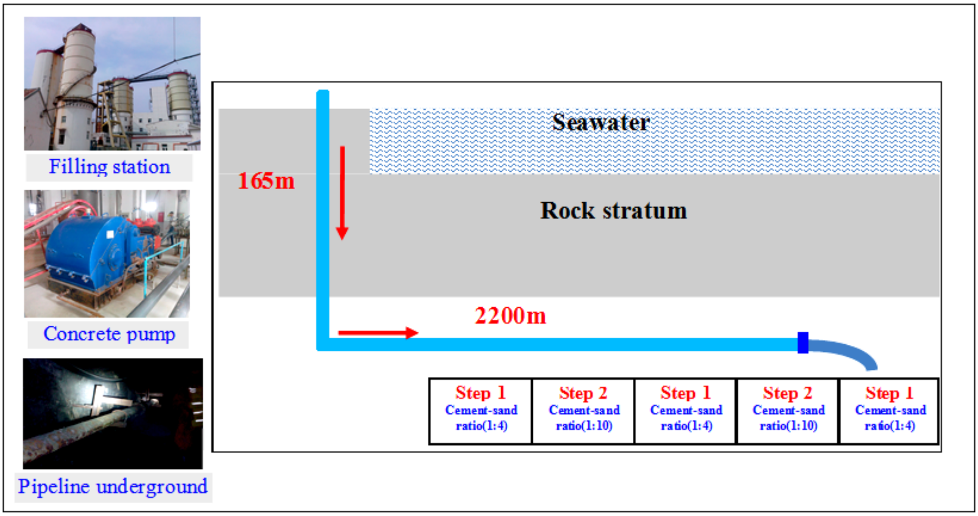
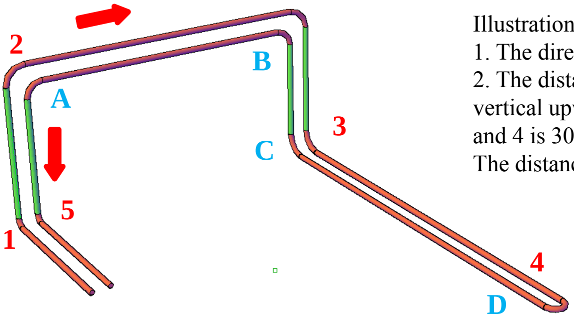


Fig. 1. The layout of pipeline transportation system

2. Experimental section

2.1. Experimental equipment and materials

The layout of the looping pumping pipeline is shown in Fig. 2. The total length of the pipeline is 150 m. The elbows are respectively marked as A, B, C, and D. In order to prepare uniform CTBS, mixing time should be appropriately extended to 8 to 10 min. A HBT90.21.200S concrete pump made by China' Zoomlion corporation, which provides a maximum pressure up to 18 MPa, was chosen as the transportation pump. Its theoretical maximum transport capacity is about 90 m^3/h. The seamless steel pipe with an inner diameter of 125 mm and a wall thickness of 8 mm was applied to the transportation pipe. In addition, some elbows, pipe clamps, and rubber gaskets were needed. Pressure loss was measured using the MultiSystem 5060 portable tester made by Germany's Hydrotechnik corporation, shown in Fig. 3.



Illustrations:
1. The direction of the arrow is the flow direction.
2. The distance of point 1 and 2 is 7 m, in an upward vertical upward direction. The distance of point 3 and 4 is 30 m, in a horizontal direction.
The distance of point 1 and 5 is 120 m.

Fig. 2. The layout of pipeline transportation system

Fig. 3. MultiSystem 5060 portable tester

32.5# cement was used for the cementing material. Seawater was directly used to prepare the experiment slurry. Two kinds of CTBS with mass concentrations of 72% and 78% were respectively designed for the experimental materials.

2.2. Experimental method

The tailing was the classified and deslimed by hydrocyclone to obtain the filling aggregate. The nonuniform coefficient of the filling aggregate is was 5.9, and the grain size of the tailing is shown in Fig. 3. Table 1 presents that the proportion of toxic metal elements is very small. It will not cause environmental pollution and health hazards to workers. The results of sedimentation experiment are listed in Table 1. According to the results, the CTBS with a mass fraction of 72% has larger sedimentation velocities. The sedimentation rate reached more than 10% within three minutes, therefore, some tailing particles would easily accumulate in the pipe. This maybe the cause for the pipe blockage accident. If the pump broke down or other causes led the pump to stop for more than 15 minutes during the process of pipeline transportation, it is most likely the cause of a pipe blockage accident. The results of the sedimentation experiments show that increasing the fine grain content can decrease the sedimentation in the pipe. Moreover, increasing the fine grain content will be conducive to restarting the pump after pumping has stopped. For these reasons, two groups of experiments were carried out.

In order to improve the quality of the classified tailing gradation and increase the mass concentration of slurry, it is necessary to increase the fine grain content. In the first group of the looping pipe experiment, the CTBS with the mass concentration of 78% and cement-tailing ratio of 1:4 were prepared to a paste-like consistency CTBS by the appropriate addition of fine grain content.

According to the mining requirements, CTBS with a mass concentration of 72% and a cement-tailing ratio of 1:10 was prepared as the experimental material for the second group of the pumping pipe experiment.

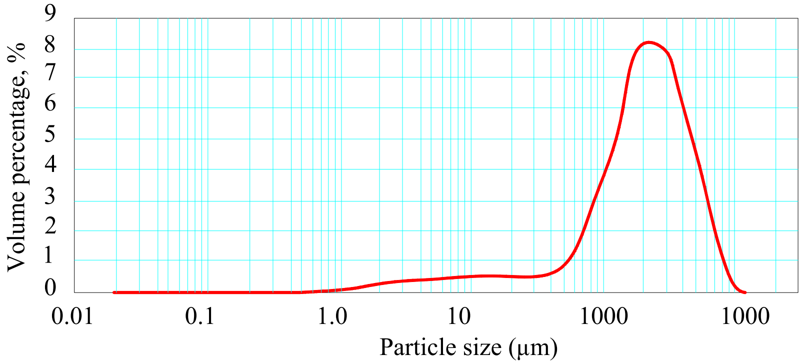


Fig. 4. Particle size distributions of the tailing used

TABLE 1

The proportion of metal elements

Element	**Al (%)**	**Fe (%)**	**K (%)**	**Ca (%)**	**Na (%)**	**Mn (%)**	**Pt (%)**	**Zn (%)**	**Ba (%)**	**Cu (%)**
Ratio	3.787	1.211	1.944	0.576	0.181	0.075	0.038	0.037	0.027	0.025

TABLE 2

Sedimentation of CTBS with cement-sand ratio of 1:4 (1000 ml)

Mass concentrations/%	**Sedimentation/ml**		
	5 min	**15 min**	**25 min**
72	35	85	95
78	17.5	45	80

Based on the daily gold ore output, the minimum transportation capacity should be greater than 45 m^3/h (the corresponding flow velocity is 1.0 m/s). In the actual production, the minimum flow velocity should increase 10% to 20% faster than the critical velocity. On this basis, the experimental flow velocity was taken as 1.0 m/s to 1.4 m/s. The total length of pipelines is 150 m.

During the experiment, the flux and flow velocity were in control of the pumping frequency. The flux (flow velocity) was increased in the order from smallest to largest. The setup of the first group experiment are was as follows:

Step 1. Check and clear debris in mixer and hopper of the concrete pump.

Step 2. Moisten the pipeline by pumping clean water,and when done do not return to the concrete pump.

Step 3. Prepare CTBS using a mixer with the maximum mixing ability of 3 m^3 per time. In the experimental process, material addition was controlled manually. A 2.5 m^3 CTBS with a mass concentration of 78% and cement-sand ratio of 1:4 was prepared in proportion as the pumping material. In order to prepare uniform slurry, a mixer should remain working while the water and materials are added. The mixing time should be longer than 8 min.

Step 4. Pour the prepared slurry into hopper of the concrete pump, then start the pump and maintain the slurry volume of 70% in the hopper of the concrete pump.

Step 5. After pumping stability has been achieved, turn the pumping frequency to 10 times per minute and measure the resistance loss in the respective parts of the pipeline. Then, turn the pumping frequency to 12, 14, 16, and 18 times per minute in sequence. Each test time lasted 5 min.

Step 6. After measuring the required data, carry out the stop pumping experiment. Stop pumping for 15 min and 30 min, then restart the pump at the same time.Then measure the resistance after restarting the pump. After those measurements have been taken, dilute the mass concentration slurry to 72% by adding water and conduct the same test as above. Finally, flush the pipe and the experimental equipment.

Slurry with a mass concentration of 72% and cement-tailing ratio of 1:10 was used for the materials of the second group experiment. When conducting the second group experiment, the pump was not stopped as in the first experiment to avoid a pipe blockage accident on account of easy tailing sedimentation.

TABLE 3

Result of flux test (m^3/h)

Pump frequencies	14	16	18
Flux	47.501	54.287	61.073

2.3. Experimental result and discussion

According to Table 3, the flux are respectively 47.5 m^3/h, 54.287 m^3/h, and 61.073 m^3/h. The flux increased linearly with the increase of pumping frequency. The first group experiment went well. The resistance was relatively small in the pipeline, so the CTBS was easy to transport. The change curves of the pressure lost with the time transporting the slurry in mass concentrations of 72% and 78% with a cement-sand ratio of 1:4 are shown in Fig. 4. In Fig. 3, dp1 is the differential pressure between point 1 and point 2, dp2 is the differential pressure between point 3 and point 4, and dp3 is the differential pressure between point 1 and point 5. The calculation law of the average of the pressure loss (dp*) is the average value of maximum pressure difference minus the minimum pressure difference during each instance of stable pumping.

A paste-like CTBS is a typical non-Newtonian flow (Shaheen, 1972; Zhai, 2011; Assefa, 2015), which usually present yield-pseudoplastic rheological model and Bingham plastic rheological model. The results of the pressure loss test are listed in Table 3. Fig. 5(a) shows that the pressure loss per 100 m obviously increases with a decrease of flow velocity when the mass concentration is dropped to 72% by adding water to the slurry. The coarse particles can be suspended in the slurry to decrease the pressure loss. The rheological model of this slurry can be considered a solid-liquid mixing two-phase liquid. As seen in Fig. 5(b), the pressure loss for the slurry with a mass concentration of 78% per 100 m increases with the increasing flow velocity. Therefore, the CTBS presents the flow characteristics of the Bingham flow. The pressure loss of the vertical section was obviously greater than the horizontal section. The change curve of pressure loss with the time for the second group experiment are measured and shown in Fig. 5(c). The average pressure loss between dp1 and dp3 reached 1.65 MPa, which is greater than the result plotted in Fig. 5(a). This indicates that a part of the coarse particle can not suspended in the pipe, so those particle deposited in the pipe and increased the pressure loss. As shown in Fig. 5(c), it took a long

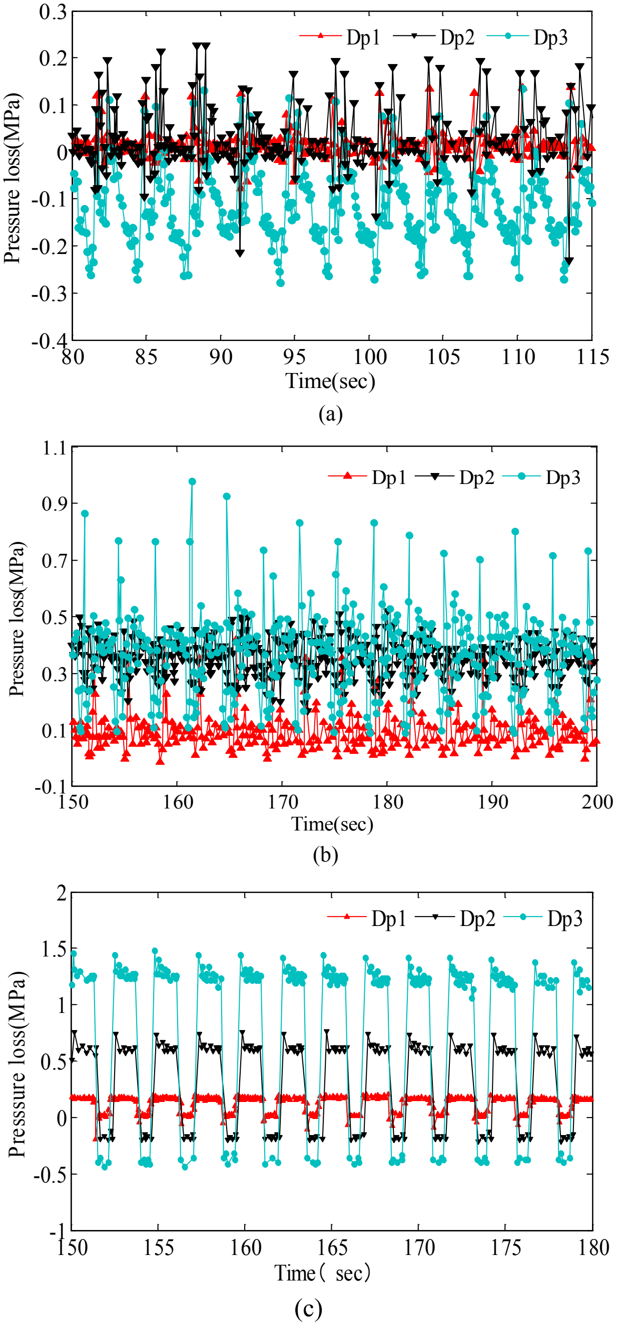


Fig. 5. Change curves of pressure loss over the time
(a) Solid mass fractions of 72%, cement-tailing ratio of 1:4, pumping frequency 18 times per minute.
(b) Solid mass fractions of 78%, cement-tailing ratio of 1:4, pumping frequency 18 times per minute.
(c) Solid mass fractions of 72%, cement-tailing ratio of 1:10, pumping frequency 18 times per minute.

time to reach pumping stability. This is different from the results of high mass concentration slurry rheological experiment,wherein slurry rheological models are the yield-pseudoplastic model and Bingham model. The flow characteristic of the CTBS with the cement-sand of 1:10 and mass concentration of 72% presented typical discrete solid-liquid mixing two-phase flow character. Increasing the cement-tailing ratio can efficiently improve the grading of the CTBS and reduce pressure loss when the cement sand ratio is relatively lower.

TABLE 4

Result of pressure loss test

Slurry with mass concentrations of 72% and 78%, cement-sand ratio of 1:4
at different pump frequencies (times/min)

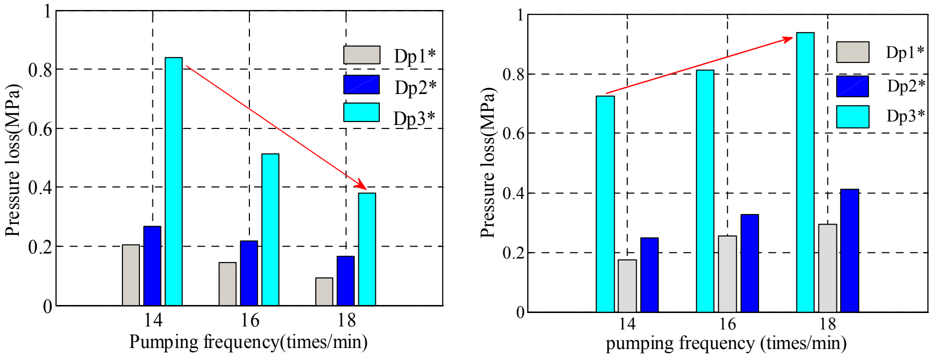
Measure point	**78% Mass concentration**			**72% Mass concentration**		
	14	**16**	**18**	**14**	**16**	**18**
dp1*	0.174	0.256	0.294	0.205	0.146	0.093
dp2*	0.249	0.328	0.413	0.267	0.219	0.165
dp3*	0.724	0.812	0.937	0.839	0.514	0.380

TABLE 5

Result of pressure loss per unit length (MPa · 100 m^{-1})

slurry with mass concentrations of 72% and 78%, cement-sand ratio of 1:4 at different pump frequencies

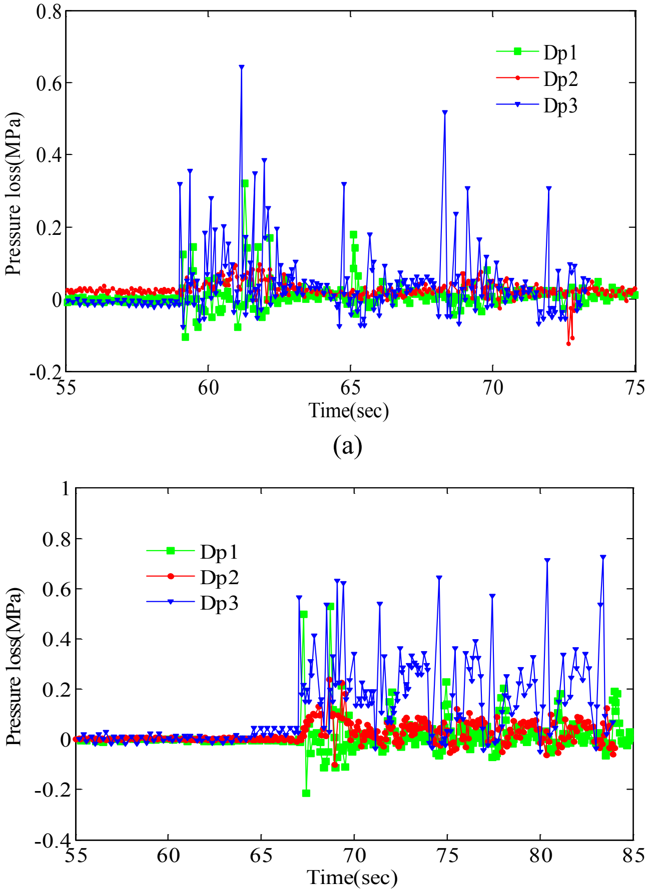
Mass concentration	**Pump frequencies (times/min)**			**Stop pump for 15 min and restart**	**Stop pump for 30 min and restart**
	14	**16**	**18**		
72%	0.449	0.428	0.400	0.550	0.912
78%	0.603	0.677	0.781	0.766	1.543



(a) mass concentrations of 72% (b) mass concentrations of 78%

Fig. 6. The relationship of pumping frequency and pressure loss

Fig. 7 is the change curves of pressure loss over time after pumping was stopped. Table 5 indicates that the pressure loss of slurry with a solid mass concentration of 72% and a cement-tailing ratio of 1:4 was 0.550 (MPa/100 m) after stopping pumping for 15 min. As the stop time



(a)

(b)

Fig. 7. Change curves of pressure loss with the time after stopping pumping
(a) Solid mass fractions of 72%, cement-tailing ratio of 1:4, restart pump after stopping for 15 min.
(b) Solid mass fractions of 78%, cement-tailing ratio of 1:4, restart pump after stopping for 15 min.

extended to 30 min, the pressure loss was 0.912 (MPa/100 m). The pressure loss respectively increased to 0.766 (MPa/100 m) and 1.543 (MPa/100 m) with the solid mass fractions increasing to 78%. If the CTBS was well-graded (reasonable cement-sand ratio), then the mass concentration had an obvious influence on the pressure loss after restarting pumping because the viscosity increased with the improvement of the mass concentration. Instead, if the CTBS has a lower cement sand ratio, then the main reason for the increase in pressure loss is particle sedimentation.

3. Numerical simulation application

CFD has been widely used in the mining industry to simulate the fluid flowing behavior in underground mine works (Aminossadati, 2008; Gopaliya, 2014). Based on the results of the looping pipe experiment, FLUENT was applied to simulate the flowing characteristics of the slurry with mass concentrations of 72% and 78%. The results provide proof of the results of the looping pipe experiment.

3.1. Calculation parameters and solution settings

The numerical model was built based on Figure 1. The model was divided into five parts: inlet, outlet, vertical section, elbow section, and horizontal section. The model was meshed into 186,440 elements and 237,762 nodes. The inlet was defined to be a velocity-inlet. The velocities are,respectively, 1.0 m/s, 1.2 m/s, and 1.4m/s. Wall was defined to be a wall that adopts the default wall boundary. Outlet was defined to be outflow. A second order implicit transient equation was selected to be the governing equation.

(1) Mass concentration of 78%, cement-sand ratio of 1:4

The Herschel-Bulkley model was used to as the rheological models because it has high precision and reliability to predict pressure losses of fluid modeled (Wu, 2018). The rheological characteristics and parameters of the filling slurries can be tested with a four-bladed vane rotary rheometer. The rheological equation of Herschel-Bulkley fluid is given by (Frank, 2006; Belem & Benzaazoua, 2007; Vassilios, 2011):

$$\tau = \tau_0 + K\gamma^n \tag{1}$$

Where τ is shear stress, τ_0 is yield stress, 52.83 Pa; γ is shear rate, s^{-1}; K is plastic viscosity coefficient, 2.134 Pa·s; n is flow performance index, 1. The definition of Reynolds number is based on the Herschel-Bulkley viscosity formula:

$$\mathrm{Re} = \frac{\rho \mathrm{v} D}{\mu} \tag{2}$$

Where ρ is density of CTBS, 1950kg/m^3; μ is effective viscosity, the formula is given by:

$$\mu = K\left(1 + \frac{\tau_0 D}{6K\mathrm{v}}\right) \tag{3}$$

According to Eq. (2) and Eq. (3), the Reynolds number is 115.6, meaning the flow regime is lamina flow.

(2) Mass concentration of 72%, cement-sand ratio of 1:4

DPM (Discrete Phase model) and Realizable k-ε turbulence model were applied to the solving model (Wang, 2017; Kharoua, 2017; Singh, 2018). The fine particles (<200 μm) and the water mixed in a homogeneous suspension are seen as a continuous phase. Coarse particles are seen as a discrete phase. Erosion/Accretion was chosen for the physical models (Messa, 2015). The mass fraction of the discrete particle is 0.21. The rheological equation of Herschel-Bulkley was applied to continuous the phase viscosity model, where τ_0 is 28.14, K is 0.91, n is 0.76. The fluid phase continuity equation and momentum equation are respectively:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla\left(\alpha_k \rho_k u_k\right) = 0, \qquad \sum_{k=1}^{3} \alpha_k = 1 \tag{4}$$

$$\frac{\partial(\alpha_k \rho_k \mu_k)}{\partial t} + \nabla \alpha_k \rho_k u_k^2 = -\alpha_k \nabla P + \nabla(\alpha_k \tau_k) + \rho_k \alpha_k g - f_k \tag{5}$$

Where α_k is the volume fraction of phase k; ρ_k is the density of phase k, kg/m^3; μ_k is the velocity of phase k, m/s; P is the pressure of the fluid phase, Pa; g is the gravitational acceleration, 9.8 m/s^2; τ_k is Stress tensor of the fluid phase; f_k is the average resistance of the fluid phase, N.

The diameter of the solids was set to the average grain size, 0.00038 m. The phase transition in two-phase flow is not considered. The particle stochastic trajectory model was applied to simulate the motion of particle because the the particle stochastic trajectory can accurately predict the diffusion and deposition of particles. The equilibrium equation of discrete phase particles can be expressed as (ANSYS, 2011):

$$\frac{du_d}{dt} = \frac{3\mu C_D R_e(\mu_i - \mu_d)}{4\rho_d d_d^2} + \frac{g(\rho_d - \rho_i)}{\rho_d} + F \tag{6}$$

Where, μ_i and μ_d are respectively the velocity of fluid phase and the velocity of particle phase. C_D is the drag coefficient; R_e is the relative Reynolds number; ρ_d and ρ_i are respectively the density of fluid phase and the velocity of particle phase; d_d is the diameter of particle. F mainly include additional mass force and lift force. The mass force is very small when the particle density is greater than the fluid density, so the effect of lift on the fine particles is usually negligible. In order to simplify the calculation process, the influence of F is not considered. The displacement of particles at t can be expressed as (ANSYS, 2011):

$$r(t) = \int_{t_0}^{t} \left[\int_{t_0}^{t} \left(\frac{3\mu C_D R_e(\mu_i - \mu_d)}{4\rho_d d_d^2} + g(\rho_p - \rho)\rho_p \right) dt \right] dt \tag{7}$$

As the diffusion of particles by turbulence, the velocity of fluid can be expressed:

$$\mu_i = \bar{\mu} + \hat{\mu} \tag{8}$$

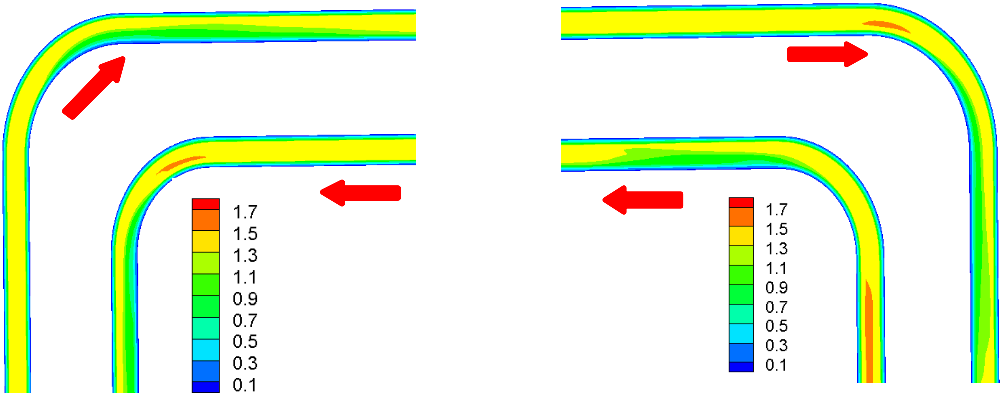
Where, $\bar{\mu}$ is the averaged velocity of fluid, $\hat{\mu}$ is the stochastic fluctuating velocity of fluid. Using random walk model to determine $\bar{\mu}$ for standard k-ε turbulence mode:

$$\bar{\mu} = \xi \sqrt{\frac{2k}{3}} \tag{9}$$

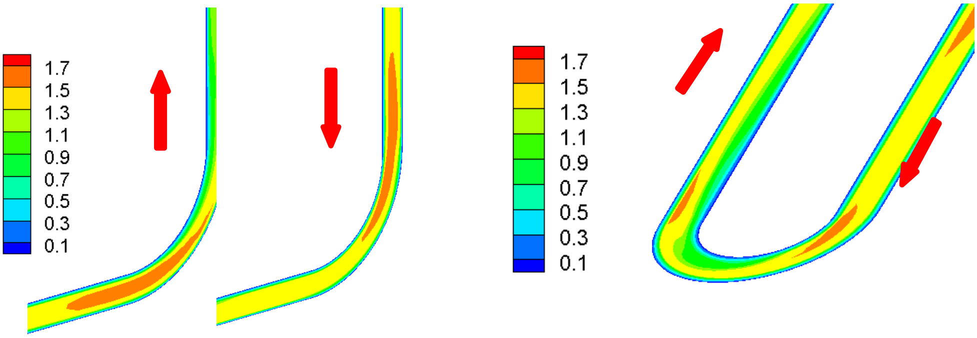
Where, k is turbulent kinetic energy, ξ is Random numbers obeying normal distribution. The boundary conditions of the wall roughness coefficient was defined to be 0.12 and the roughness height was defined as 0.0003. The wall also was defined to be a elastic reflect boundary. The intensity of the turbulence was defined as 10% and the hydraulic diameter was defined as 0.125 m.

4. Engineering application

Based on the physical properties experiment of CTBS and the pumping looping pipe experiment of CTBS, the transportation characteristics of the pipeline were studied in order to

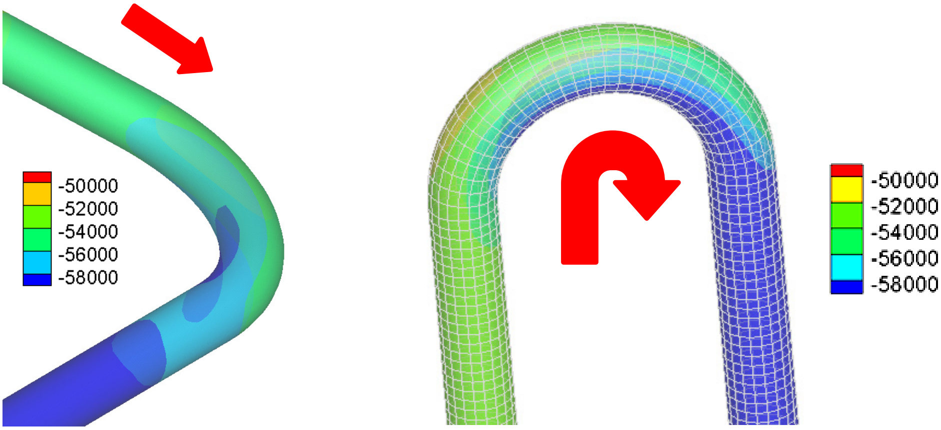


(a) Elbow A (b) Elbow B



(c) Elbow C (d) Elbow D

Fig. 8. Distribution of velocity at elbow



(a) Elbow A (b) Elbow D

Fig. 9. Distribution of pressure at elbow (pa)

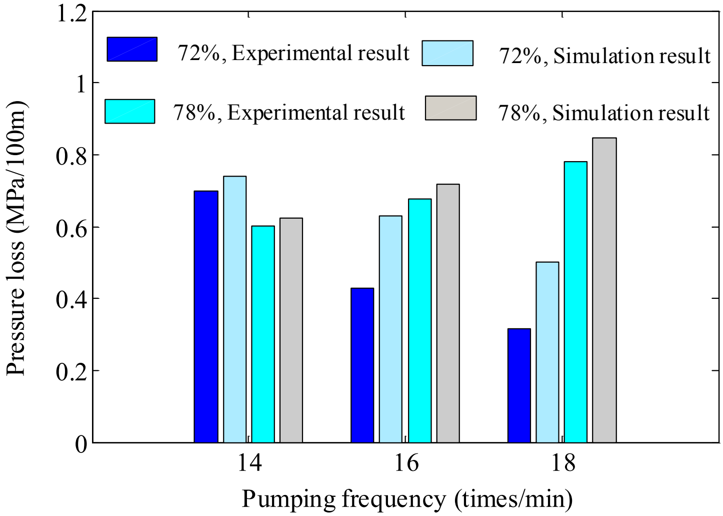
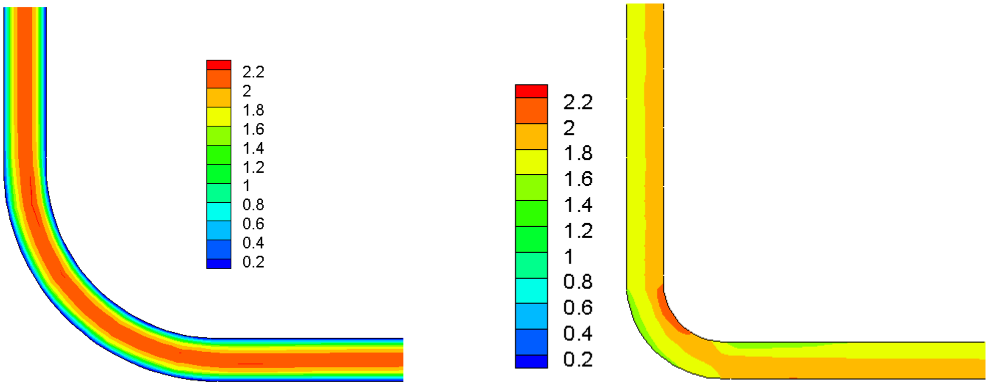


Fig. 10. The relationship of transportation velocity and pressure loss

ascertain the optimal transportation parameters. The layout of pipeline transportation system was shown in Fig. 1. As shown in Fig. 11 the maximum flow velocity along the pipeline is 2.29 m/s, which is located at the elbow of the pipe. The maximum velocity has a larger increase than the inlet velocity. Outlet velocity gradually decreases from the pipe central to the wall. It indicates that slurry transportation in the pipeline is relatively stable. The maximum and minimum static pressures are 0.11 MPa and –10.02 MPa, respectively. The total pressure lost is 10.13 MPa. The elbow is prone to abrasion because the pressure and the maximum flow velocity are located at the elbow. The pressure generated by gravity is 2.571 MPa as the level difference is 165m. In order to guarantee the stability of the pipeline transportation system, the pump should provide more than 7.559 MP of pumping pressure. A combination of both results can reflect the flow characteristic of CTBS in pipeline. By analyzing the pressure loss, the experimental results showed that the slurry with a mass concentration of 72% and a cement-sand ratio of 1:10 does not have the flow characteristics of yield-pseudoplastic and Bingham fluid, which is a non-linear discrete solid-liquid mixed in a two-phase flow. Therefore, it is appropriate to use the DPM model to analyze the flow characteristics of this slurry. Based on the 2D geometry model built, the simulation results show that the maximum static pressure is 0.74 MPa and the minimum static pressure is −10.45 MPa. The total pressure lost is 11.19 MPa and the maximum flow velocity along the pipeline is 2.38 m/s, which is located on the inside of the elbow. Accretion distribution on the elbow is shown in Fig. 11(b). The results show that in the case of no blockage accidents, the pumping pressure of the delivery pump can meet the transportation requirements. The restarting pumping pressure loss (P_{re}) of the pipeline is estimated according to table 4. The restarting pumping pressure loss can be expressed as:

$$P_{re} = LP_{av}/10 \tag{11}$$

Where, L is the total length of the pipeline which is about 2400 m; P_{av} is the pressure loss of per one hundred meters. The restarted pumping pressure loss of CTBS with mass concentrations of 72% and 78%, cement-sand ratio of 1:4 are respectively 13.2 MPa and 18.38 MPa after the stopped pumping time reach to 15 min. If the stopped pumping time reach to 30 min, the restarted pumping pressure loss are respectively 21.9 MPa and 37 MPa. Under this circumstances, it is impossible to restart transportation only relied by the delivery pump so that it is easy to cause blockage accident.



a) mass concentration of 78%, cement-sand ratio of 1:4

b) mass concentration of 72%, cement-sand ratio of 1:10

Fig. 11. Distribution of velocity

5. Conclusion

(1) During the process of CTBS pipeline transportation, the flow characteristics are significantly influenced by solid mass concentration and sand-cement ratio. When the CTBS has the same cement-sand ratio (1:4), its rheological model transforms the yield-pseudoplastic flow or solid-liquid mixing two-phase flow into a Bingham flow with improvement in mass concentration. The flow characteristics of the CTBS with a mass concentration of 72% and a cement-sand ratio of 1:10 presents a typical discrete solid-liquid mixing two-phase liquid character because of the low cement content and high coarse grains content.

(2) The pumping pressure loss after restarting pumping increases with an increasing mass concentration if the cement-sand ratio is 1:4 because viscosity increases with the improvement of mass concentration. If the mass concentration is 72%, then the transportation pressure loss of the CTBS with a lower cement ratio will be greater than the CTBS with a higher cement-sand ratio, as the particles more easily sediment in the pipeline. If the stopped pumping time reach to 30 min, it is easy to cause blockage accident.

(3) Based on the tailing property experiment and the looping pipe experiment, FLUENT was applied to simulate the long distance and strong resistance pipeline transportation by pumping. The results show that in the case of no blockage accidents, the pumping pressure of the delivery pump can meet the transportation requirements. However, if the stopped pumping time exceed 15 min, the risk of blockage accident will be very great.

It can provide a theoretical basis for the parameters optimizing the pipeline transportation system.

(4) Cementing slurries are know for having thixotropic behaviour, an aspect which is not discussed, nor the potential effect of looping on the progressive thinning of the fluid with time. Moreover, The impacts of particle shape and particle gradation on the pressure loss and velocity distribution are worth further study.

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References

Aminossadati S.M., Hooman K., 2008. *Numerical simulation of ventilation air flow in underground mine workings*. 12th North American Mine Ventilation Symposium – Wallace (ed): 253-259.

ANSYS Inc., 2011. ANSYS FLUENT Release 14.0 User Manual. ANSYS Consulting Group Inc.

Assefa K.M., Kaushal D.R., 2015. *Experimental study on the rheological behaviour of coal ash slurries*. Journal of Hydrology & Hydromechanicsm **63** (4), 303-310.

Behera N., Agarwal V.K., Jones M.G., Williamsl K.C., 2013. *CFD modeling and analysis of dense phase pneumatic conveying of fine particles including particle size distribution* [J]. Powder Technology **244** (4), 30-37.

Belem T, Benzaazoua M., 2008. *Design and application of underground mine paste backfill technology*. Geotechnical & Geological Engineering **26** (2), 175-175.

Creber K.J., Mcguinness M., Kermani M.F., Hassani F.P., 2017. *Investigation into changes in pastefill properties during pipeline transport*. International Journal of Mineral Processing **163**, 35-44.

Cooke R., Lazarous J.H., 1993. *Hydraulic transport systems for the backfilling of deep mines* [J]. Journal-South African Institute of Mining and Metallurgy **93** (2), 25-30.

Deng X., Klein B., Tong L., Wit B.D., Deng X., Klein B. et al., 2017. *Experimental study on the rheological behavior of ultra-fine cemented backfill*. Construction & Building Materials. (https://doi.org/10.1016/j.conbuildmat.2017.05.085)

Fall M., Benzaazoua M., Ouellet S., 2005. *Experimental characterization of the influence of tailing fineness and density on the quality of cemented paste backfill*. Minerals Engineering **18**, 41-44.

Frank M.W., 2006. *Fluid Mechanics*. New York: McGraw Hill Higher Education.

Gopaliya M.K., Kaushal D.R., 2014. *Analysis of Effect of Grain Size on Various Parameters of Slurry Flow through Pipeline Using CFD*. Particulate Science & Technology **33**, 369-384.

Helms W., 1988. *Preparation and transportation systems for cemented backfill* [J]. International Journal of Rock Mechanics & Mining Science & Geomechanics Abstracts **7** (2),183-193.

Kaushal D.R., Thinglas T., Tomita Y., Kuchii S., Tsukamoto H., 2012. *CFD modeling for pipeline flow of fine particles at high concentration* [J]. International Journal of Multiphase Flow **43**, 85-100.

Kharoua N., Alshehhi M., Khezzar L., Filali A., (2017). *CFD prediction of black powder particles' deposition in vertical and horizontal gas pipelines.* Journal of Petroleum Science & Engineering **149**, 822-833.

Messa G.V., Malavasi S., 2015. *Improvements in the numerical prediction of fully-suspended slurry flow in horizontal pipes*. Powder Technology **270**, 358-367.

Shaheen E.I., 1972. *Rheological study of viscosities and pipeline flow of concentrated slurries*. Powder Technology **5** (4), 245-256.

Singh J., Kumar S., Singh J.P., Kumar P., Mohapatra S.K., 2018. CFD modeling of erosion wear in pipe bend for the flow of bottom ash suspension. Particulate Science & Technology. Doi:https://doi.org/10.1080/02726351.2017.1364816

Supa Amornkul S., Steward F.R., Lister D.H., 2005. *Modeling two-phase flow in pipe bends*. Journal of Pressure Vessel Technology **127** (2), 204-209.

Turian R.M., Hsu F.L., Ma T.W., 1987. *Estimation of the critical velocity in pipeline flow of slurries*. Powder Technology **51** (1), 35-47.

Vassilios C., Kelessidis, Panagiotis Dalamarinis, 2011. *Experimental study and predictions of pressure losses of fluids modeled as Herschel-Bulkley in concentric and eccentric annuli in laminar, transitional and turbulent flows*. Journal of Petroleum Science and Engineering (77), 305-312.

Wang X.M., Zhao J.W., Xue J.H., Yu G.F., 2011. *Features of pipe transportation of paste-like backfilling in deep mine*. Journal of Central South University of Technology **18**, 1413-1417.

Wang K., Li X.F., Wang Y.F., He R.Y., 2017. *Numerical investigation of the erosion behavior in elbows of petroleum pipelines*. Powder Technology **314**, 490-499.

Wu A.X., Ruan Z.E., Wang Y.M., Yin S.H., Wang S.Y., Wang Y., W J.Z., 2018. *Simulation of long-distance pipeline transportation properties of whole-tailings paste with high sliming*. Journal of Central South University **25** (1), 141-150.

Wu D., Yang B., Liu Y., 2015. *Transport ability and pressure drop of fresh cemented coal gangue-fly ash backfill (CGFB) slurry in pipe loop*. Powder Technology **284**, 218-224.

Wu D., Yang B., Liu Y., 2015. *Pressure drop in loop pipe flow of fresh cemented coal gangue-fly ash slurry: experiment and simulation*. Advanced Powder Technology **26** (3), 920-927.

Yang D., Xia Y., Wu D., Chen P., Zeng G., Zhao X., 2018. *Numerical investigation of pipeline transport characteristics of slurry shield under gravel stratum*. Tunnelling & Underground Space Technology **71**, 223-230.

Yilmaz E., Benzaazour M., Belem T., Bussiere B., 2009. *Effect of curing under pressure on compressive strength development of cemented paste backfill*. Miner Eng. **22** (9), 772-785.

Zhai Y.G., Wu A.X., Wang H.J., Chen Q.R., Xiao Y.T., Shou Z.Y. 2011. *Threshold mass fraction of unclassified-tailing paste for backfill mining* [J]. Journal of University of Science and Technology Beijing **33** (7), 795-799 (In Chinese).