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Pipeline Transportation Characteristics of Different Cementing Materials in CPB Slurry

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ABSTRACT

Research on the underground filling mining of Cemented Paste Backfilling (CPB) slurry shows that it alleviates the underground subsidence and environmental problems caused by mining, making a strong contribution to the realization of green mining. To optimize performance, cost reductions, and the recycling of agricultural solid waste, some researchers have studied using volcanic fly ash (FA) to replace part of cement. Corn straw fly ash (CSFA) may be used to replace the same amount of part of cement or FA, as corn straw can improve the mechanical properties of FA to make the CPB slurry for filling goaf. On this basis, in order to ensure a good flow of the CPB slurry in the pipeline, we need to conduct pipeline tests on the slurry of these different cement materials to verify their feasibility. In this article, Fluent has been used to study the CPB slurry transport properties in the two cases mentioned above through numerical simulation. Comparing the velocity distribution and pressure loss changes of the CPB slurry with different proportions in the horizontal pipeline provides a reference for future CPB slurry research. The results show that: (1) FA forms a lubricating layer in the pipe wall due to its "ball effect", which effectively reduces the yield stress and pressure loss of the CPB slurry in the pipe, and plays a positive role in the transportation of CPB in the pipe; and (2) CSFA increases the CPB slurry transport pressure loss due to its irregular particle size, increasing the risk of pipe wear. The results are helpful for better understanding and designing paste filling material for mine.

1. Introduction

Security of energy supply is an important goal of energy policy all over the world [1]. In 2020, global coal output was about 7.438 billion tons, and China's coal output is 3.84 billion tons; that is, China's coal production accounts for 51% of the world’s output [2]. According to the National Bureau of Statistics, China's total energy consumption in 2020 was 4.98 billion tons of standard coal, of which coal consumption accounted for 56.8% of the total energy consumption [3]. The sheer scale of production and consumption means coal remains an important source of energy for China and the world. The consumption of energy will produce a large number of by-products, such as coal gangue,

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fly ash and so on. A large amount of mine waste is accumulated and discharged on the ground, which not only occupies and pollute the surrounding land, but also may cause spontaneous combustion and lead to significant hidden dangers to the surrounding residents. In addition, coal mines leave behind numerous holes or cavities, known as goaf. The ground collapse and environmental damage caused by goaf are also worthy of attention [4].

Cemented paste backfilling (CPB) slurry, a toothpaste-like material mixed by mine waste, cement, and water which is pumped by pipe into goaf, is a good solution to the above problems. It makes a significant contribution to the realization of green mining and sustainable development of resources. With the development of filling materials, in order to further reduce the cost of original materials and improve its mechanical properties, researchers have used various materials to replace the raw materials in CPB. Chen *et al.,* [5] used red mud to replace cement in filling materials and studied its influence on the strength, microstructure and cost of filling slurry. Yılmaz *et al.,* [6] investigated the short- and long-term strength, durability and microstructural properties of CPB using pulverized construction waste (CDW) as a partial substitute for sulphide tailings. Liu *et al.,* [7] investigated the relationship between slurry curing time and ice water ratio by introducing ice into CPB to address high-temperature workplaces. Zheng *et al.,* [8] used calcined hard kaolin instead of cement to improve the strength of CPB. Additionally, Ordinary Portland Cement (OPC) has been used as the primary binder for concrete and other cementing materials since its inception. Due to is extensive use in OPC, limestone overexploitation and greenhouse gas emissions have caused adverse effects on the environment [9,10]. Thomas *et al.,* [11] proposed to replace part of OPC with volcanic ash material to reduce greenhouse gas emissions [12]. Furthermore, biomass byproducts contain high silica content and exhibit strong volcanic ash properties, as an alternative to cementing materials, which are increasingly being introduced into backfilling materials to also reduce one of the most important environmental problems caused by biomass burning: worsening air quality [13]. Sandhu and Siddique [14] studied rice husk ash (RHA) as an alternative cementitious material in concrete and showed that it can effectively improve the strength and compactness of concrete at a substitution rate of 10% to 15%. Fořt *et al.,* [15] believes that the content of harmful elements in biomass fly ash is significantly lower than coal fly ash, and can be used as a substitute for coal fly ash to replace 30% Portland cement in the mixture. Qudoos e*t al.,* [16] studied the effect of wheat straw ash replacing cement in cement composite, and the results showed that although the addition of fiber reduced the compressive strength and other capabilities of the material, its bending and indirect tensile strength were significantly improved. Wang *et al.,* [17] showed that replacing the same amount of fly ash with the same amount of corn straw fly ash can effectively improve the compressive strength of backfill. Qi *et al.,* [18] investigated the substitution of corn straw fly ash for part of cement in the slurry and concluded that the compressive strength and drying shrinkage ratio of the filling body were the best when the replacement rate was 20%.

During the entire backfilling process, CPB slurry needs to meet the following conditions: good liquidity, ability to reach the filling position through the pipe and wear the pipe as little as possible; good backfilling strength and the ability to support the surrounding rock pressure well after curing. Reviewed and summarized from relevant of literature on the CPB slurry, studies on CPB have mainly been in terms of the following three aspects [19,29]

i. Study on material ratio of CPB
ii. Study on rheology and pipeline transportation of CPB
iii. Study the influence of CPB strength after curing on surrounding rock of underground goaf.

Most researchers mainly focus on substitution ratio, compressive strength, shear strength and other aspects when studying CPB slurry substitute materials [17,18,30]. Nevertheless, the rheological characteristics and pipeline transport characteristics have not been well studied. Slurry pipeline transportation research is influenced by the whole process of the experiment because of the high cost of initial investment and the consumption of a lot of time for laying. Computational fluid dynamics, as a numerical simulation technique, are widely used by modern researchers to study complex fluid behavior [24]. Because of the uncertainty and difficulty in viewing slurry flow in a working pipeline, combining CFD simulation with rheological experiment is an effective way to study pipeline transportation [31]. For example, Chen *et al.,* [32] numerically simulated the pipeline performance of slurry in an L-type pipeline, while Capecelatro *et al.,* [33] used a CFD model to study the settlement law of slurry in a horizontal pipeline.

In this study, on the basis of other researchers' studies using corn stalk fly ash to replace part of fly ash or cement in slurry, rheological experiments and pipeline simulations on the CPB slurry with different cemented materials tests are conducted to verify the feasibility of alternative cementing materials. This study provides more selective and theoretical reference for backfilling materials and transportation in goaf.

2. Materials and Methodology

2.1 Materials

The materials used in the test include coal gangue, fly ash, corn straw fly ash, cement and water, and their physical and chemical properties can be referred to [17,18,34]. According to the previous research results and other researchers' work, coal gangue is mainly composed of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) [35-37]. The broken coal gangue shows irregular lump or granular shape under the microscope. Fly ash is a gray white powder mainly derived from power plant coal combustion products, with particle size less than 45μm content reaching about 90% of its content [34]. Fly ash is spherical under a microscope, and it is mainly composed of silicon dioxide (SiO_2). With a primary chemical composition, the same as fly ash, corn straw fly ash comes from biomass power plants. Under a microscope, it appears as fine strips with particle size larger than cement and fly ash. The cement particles are dominated by calcium oxide (CaO) and have an irregular shape under a microscope. Specific physical and chemical properties are shown in Table 1.

Table 1
Comparison of physico-chemical property of backfilling materials

Materials	Main chemical composition	Physical shape	Particle size
Coal gangue	SiO_2 Al_2O_3	Irregularly granular	Biggest
Fly ash	SiO_2	spherical	Smallest
Corn straw fly ash	SiO_2	fine strip	Second
cement	CaO	irregular shape	Third

2.2 Experimental Methods

Three groups of CPB slurry samples were included in this study. The first group was the original CPB slurry samples mainly composed of coal gangue, fly ash, cement and water, specific experimental data for which can be found in the literature [34]. The subsequent two groups of samples used corn stalk fly ash to replace fly ash and cement with different ratios, whose replacement ratios were derived from the research results of Wang *et al.,* [17] and Qi *et al.,* [18]. Specific data are contained in Table 2.

Table 2
Mixture proportions (80wt%)

Sample	Substitution Amount (wt%)	Coal Gangue (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	CSFA (kg/m^3)	Water (kg/m^3)
S0	0	950	190	380	0	380
S1	40	950	190	228	152	380
S2	20	950	152	380	38	380

In order to realize pipeline transportation of CPB slurry in filling engineering, it is very necessary to study its rheological parameters, which is of great significance to better understand the motion state and change characteristics of slurry in pipeline, determine slurry pipeline transportation parameters, and guide filling engineering system design and industrial production. In this experiment, an ICAR rheometer (shown in Figure 1) was used to measure the rheological parameters of three samples: yield stress and plastic viscosity. Each sample was measured three times and averaged to ensure the accuracy of the test. For detailed testing principles and procedures, refer to Dong [34].

Fig. 1. ICAR rheometer

3. Numerical Simulation

With the rapid development of computer technology, numerical simulation analysis method can be used to simulate backfilling slurry pipeline transportation. The numerical simulation method has the advantages of low cost, less time consuming and reliable calculation [38,39]. Aiming at the slurry pipeline transportation problem, a numerical simulation can not only be used to determine the law of resistance loss along the pipeline, but also to observe the slurry flow state inside the pipeline, and find the slurry pressure and velocity distribution in the pipeline. In this study, FLUENT software was used to provide more intuitive exploration for our research.

The initial conditions were set up as shown in Table 3. As slurry is transported in the pipeline, its transportation velocity must exceed its critical velocity to produce flow. According to a study by Wang *et al.,* [31], when the slurry concentration is 80% and the pipeline diameter is 150mm, the critical velocity of slurry is 1.2m/s. Therefore, the velocities in this study were set to 1.3m/s, 1.6m/s and 2m/s, respectively, in simulation to observe the operation of CPB slurry at different flow rates.

Table 3
Data set of simulation

Pipe diameter		150mm
Pipe length		10,000mm
Plastic viscosity		7.71Pa·S, 5.36Pa·S, 6.93Pa·S
Density		1,900kg/m^3
Boundary conditions	Velocity-inlet	1.3m/s, 1.6m/s, 2.0m/s
	wall	No-slip
	outlet	Pressure-out

A horizontal pipe with an inner diameter of 150 mm and a length of 10,000 mm was modeled. The pipe length was much greater 50 times its diameter, which satisfies the requirement for flow to be considered fully mobile [40]. The flow domain, surrounded by an inlet, outlet, and pipe wall, was discretized as a structured quadrilateral network in the pre-processing software Space Claim. The boundary conditions of velocity-inlet, wall, and pressure-out were used at the inlet, wall, and outlet, respectively, as shown in Figure 2. In order to investigate the sensitivity of simulation results to mesh numbers, preliminary simulations were carried out. To achieve a balance between high calculation accuracy and low computational cost, the physical model with total cells of 12,000 was selected in this study. The residual target was set to 10^{-8} to check the convergence for all equations to be solved.

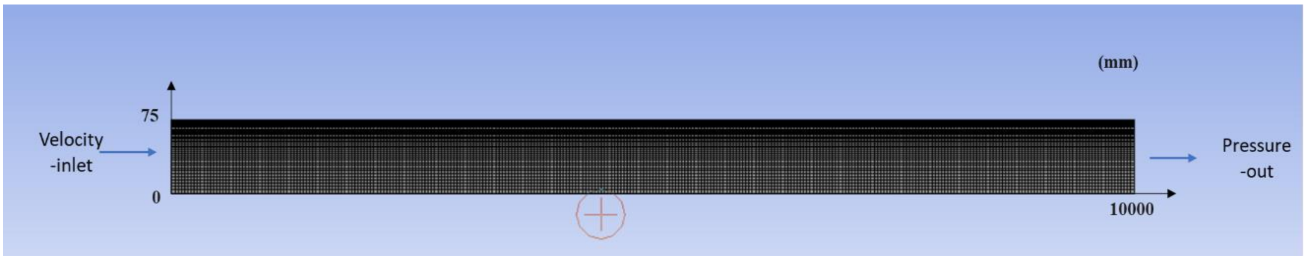

Fig. 2. The grid and size of pipe model

4. Results and Discussion of Rheology of CPB
4.1 Rheological Analysis of CPB

According to the rheological experiment, the rheological curve of paste slurry can be obtained as shown in Figure 3. It can be seen that the slurry we are studying belongs to Bingham fluid [41]. The Eq. (1) of rheological relational expression is as follows

$$\tau = \tau_0 + \eta \cdot \frac{du}{dy} \tag{1}$$

where τ_0 is the yield stress and η is the plastic viscosity.

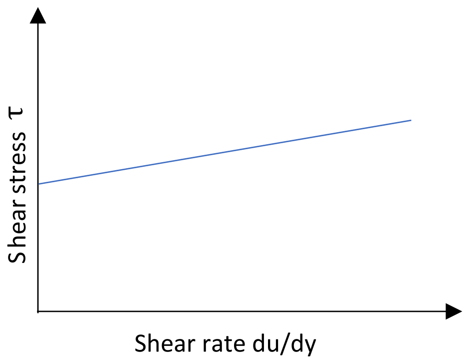

Fig. 3. Schematic diagram of shear stress and shear rate

4.2 Flow State of CPB

Before numerical simulation, the flow state of slurry needs to be analyzed in terms of its Reynolds number(Re). If the Reynolds number is greater than the critical Reynolds number（Re_c）, the flow state is considered as turbulent, otherwise it is considered laminar flow. The CPB Reynolds number（Re）and critical Reynolds number（Re_c）can be calculated from Eq. (2) to Eq. (5) as follows

$$R_e = \frac{\rho u D}{\eta} \tag{2}$$

$$R_{e_c} = \frac{2100}{1-\frac{4}{3}a_c+\frac{1}{3}a_c^4} \tag{3}$$

$$a_c = \frac{\tau_0}{\tau_w} \tag{4}$$

$$\tau_w = \eta\left(\frac{8u}{D}\right) + \frac{4}{3}\tau_0 \tag{5}$$

where u denotes the average transport velocity, D denotes the inner diameter of the pipeline, ρ denotes the slurry density, τ_w denotes the shear stress near the pipeline, and τ_0 denotes the yield stress.

Table 4 below shows that the CPB flow state is laminar flow.

Table 4
The rheological data of CPB

Sample	ρ(kg/m^3)	u(m/s)	D(mm)	$\eta(Pa\cdot s)$	τ_0 (Pa)	R_e	R_{e_c}
S0	1900	1.3	150	7.71	229.8	48.05	3281.25
		1.6				59.14	3088.24
		2.0				73.93	2876.71
S1	1900	1.3	150	5.36	357.9	69.12	4666.67
		1.6				85.07	4200
		2.0				106.34	3818.18
S2	1900	1.3	150	6.93	237.5	53.46	3500
		1.6				65.80	3230.77
		2.0				82.25	2957.75

4.3 Discussion on the CPB Rheological Parameters of Different Cemented Materials

Plastic viscosity is one of the important parameters in evaluating the transport properties of CPB slurry. It significantly affects the transport capacity of CPB slurry, and thus further affects pipeline design [42]. Figure 4 shows that the plastic viscosity of S0 is the highest, S2 is the second, and S1 is the lowest, because the plastic viscosity is mainly affected by fine aggregate [34]. In this study, the content of coal gangue remains unchanged, so its influence is not considered. Among the three samples, S0 has the highest content of fine grain, so the plastic viscosity is the highest, which is consistent with the measured value in the experiment. S1 has the lowest fine grain content, and therefore the lowest measured plastic viscosity.

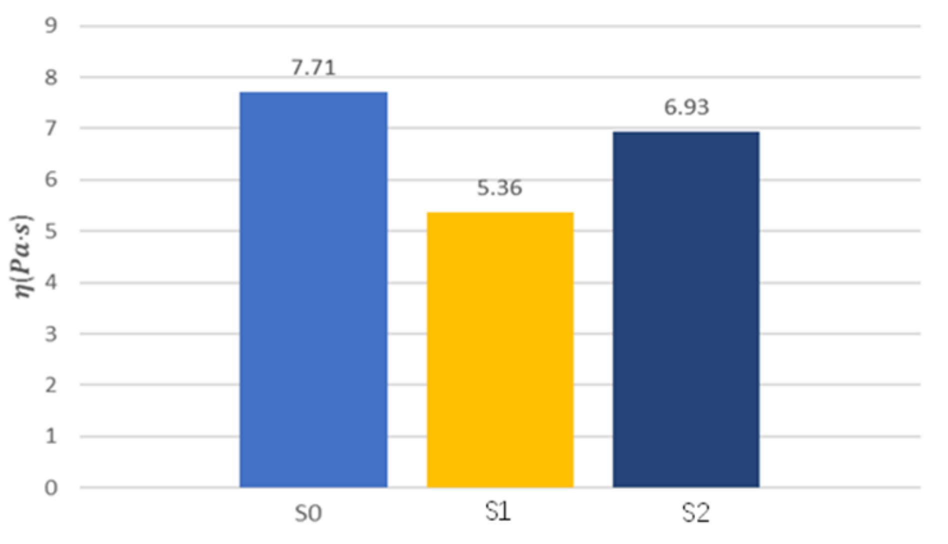

Fig. 4. Plastic viscosity of CPB of different cementing materials

Yield stress is generally used to measure and quantify the fluidity and stability of slurry, which are of great significance in slurry containing cementing materials [38,39]. It can be seen from Figure 5 that the yield stress of S1 is the highest, S2 is the second and S0 is the lowest, because the yield stress is related to slurry concentration, grain size distribution, particle shape and particle spacing and so on [42-45]. At the same concentration, the finer particles in the slurry, the denser the slurry, and its yield stress will increase accordingly. However, as the particles of fly ash are spherical, the lubrication degree between particles is increased, which can greatly reduce the friction between particles. Therefore, the yield stress of slurry with high content of fly ash particles will decrease correspondingly. In addition, the strip shape of corn straw particles will increase the space between particles and increase the friction between particles. Thus, increasing the content of corn straw will increase the yield stress of slurry, which explains the low yield stress growth in S2.

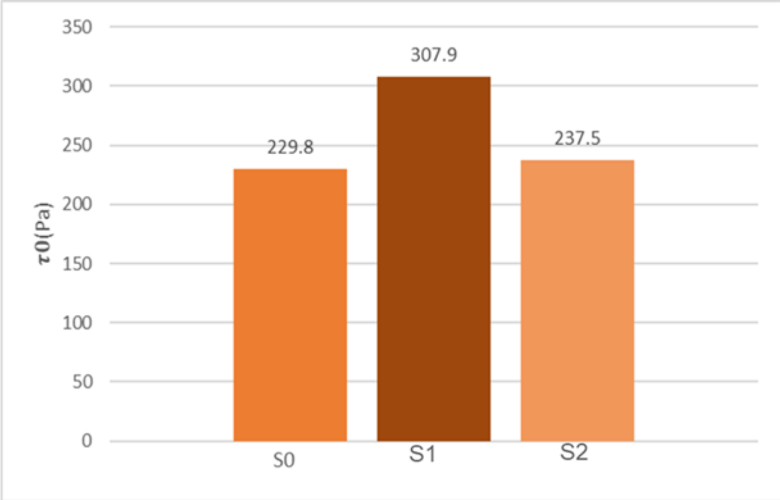

Fig. 5. Yield stress of CPB of different cementing materials

5. Result and Discussion of Pipeline Transportation Simulation of CPB

CPB slurry at different velocities was simulated at laminar flow state according to the initial setting, and the simulation results were sorted out as shown in in Table 5 below.

Table 5
Simulation result

Sample	u (m/s)	$Maxu_r$ (m/s)	Δp (kPa)	Δpv (kPa)	Relative error (%)
S0	1.3	2.6	144.89	142.55	1.64
	1.6	3.2	178.92	175.45	1.98
	2.0	4.0	224.62	219.31	2.42
S1	1.3	2.6	101.36	99.10	2.28
	1.6	3.2	125.34	121.97	2.76
	2.0	4.0	157.64	152.46	3.40
S2	1.3	2.6	130.44	128.13	1.80
	1.6	3.2	161.13	157.70	2.18
	2.0	4.0	202.39	197.12	2.67

According to Eq. (6), the pressure loss can be calculated for CPB slurry during pipeline transportation. The error between the simulated value and the calculated value is less than 4%. Thus, the simulation setup may be considered to be reliable and confirmed.

$$\Delta p_v = \frac{32\eta L u}{D^2} \tag{6}$$

5.1 Velocity Distribution of CPB Slurry in Pipeline

According to the simulation results as shown in Figure 6, the slurry is transported stably in the pipeline, and the cross-sectional velocity gradually decreases from the axis to the pipe wall, which is consistent with the description of "plunger flow" in the literature [40].

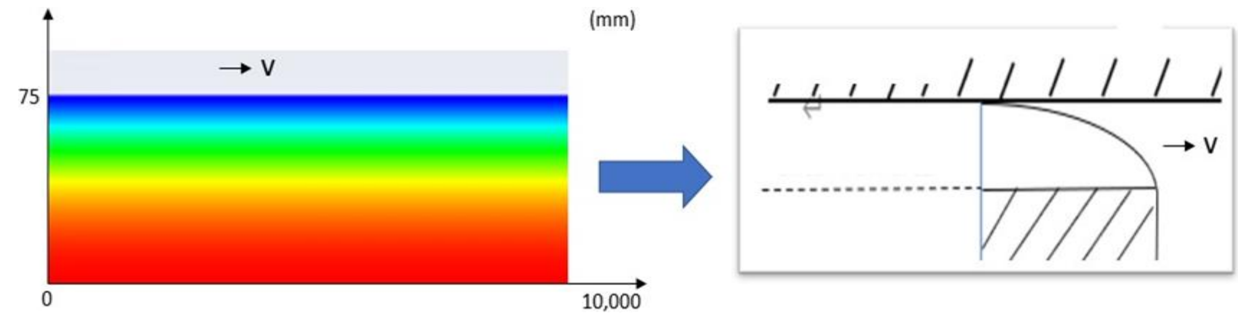

Fig. 6. Flow pattern of CPB slurry in pipeline

The cross-sectional velocity of the same pipe position at different flow rates is compared in Figure 7. The cross-sectional velocity distribution in the pipe is arched, consistent with the "plunger flow" description in the figure below. By comparing the cross-section velocity of the pipeline at the same position under different flow velocity, it is found that the cross-section velocity increases with the increase of flow velocity. The cross-sectional velocity of slurry with different proportions is basically the same under the same conditions. It can be seen that the cross-section velocity distribution is mainly related to the transport velocity of slurry.

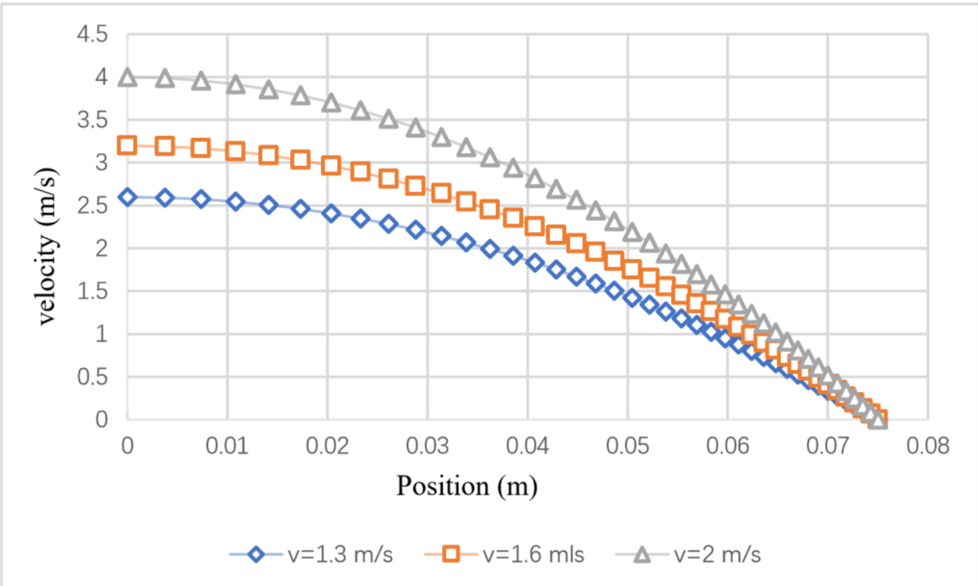

Fig. 7. The cross-sectional velocity distribution in the pipe under different velocity

5.2 Pressure Loss of CPB Slurry in Pipeline

Figure 8 illustrates that the pressure loss of slurry in pipeline under different ratios increases with the increase of velocity, showing a linear increase. That is, under the condition of constant concentration, the pressure loss of pipeline is mainly affected by velocity, which is consistent with the conclusion of circular pipe test conducted by *Qi et al.,* [46].

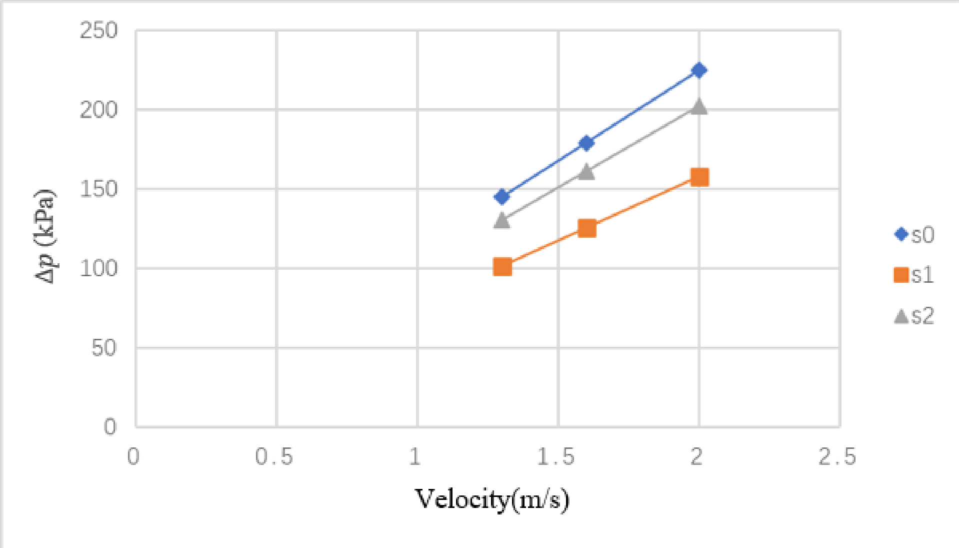

Fig. 8. Pressure loss of CPB slurry with different cementing materials during transportation

At the same speed, the S0 has the largest pressure loss, followed by S2, while S1 has the smallest pressure loss. This is because the pressure loss is mainly affected by pipe length, velocity, pipe diameter and plastic viscosity in horizontal pipeline [47]. When pipe length, pipe diameter and flow rate are constant, the pressure loss is mainly affected by plastic viscosity [48].

6. Conclusion

In this paper, the rheological properties of CPB slurry containing different cementitious materials and the transportation characteristics of CPB slurry in pipeline at different velocities have been studied. This study provides preliminary insight into the application research of biomass cementing materials in CPB slurry, and also confirms the feasibility and accuracy of CFD research on CPB slurry. Through the study of CPB slurry with different proportions, the following conclusions can be drawn

i. Plastic viscosity is mainly affected by the content of fine particles
ii. The spherical characteristics of fly ash can reduce the yield stress of slurry, and correspondingly, corn straw increases the yield stress of slurry
iii. CPB slurry is transported in the pipeline in a "plunger shape", and the velocity distribution of the cross-section of the pipeline presents an axially symmetric arch distribution
iv. With the increase of flow velocity, the radial velocity of CPB slurry in a pipeline cross-section increases correspondingly
v. The pressure loss of CPB slurry in a pipeline is positively correlated with velocity and plastic viscosity when other variables remain unchanged and
vi. Although corn stalk increases the yield stress of CPB slurry, the influence of fly ash on transportation in pipeline can be greatly neutralized due to the existence of fly ash. Therefore, the ratio of the two should be carefully considered.

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