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Experimental study on the cemented filled annular tube of ultrafine flotation phosphorus tailings from a phosphorus mine

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Introduction: Paste backfilling serves as a key approach for goaf management and mine solid waste disposal. This study investigates the rheological properties of ultra-fine flotation phosphate tailings utilized as backfill aggregates.

Methods: To investigate the pipeline transport characteristics of high-concentration ultra-fine full phosphate tailings under both pumping and gravity flow conditions, this research employed a self-designed industrial-scale paste loop testing system. The pipeline resistance loss of the backfill slurry under various working conditions was systematically measured, and the influence degree of different factors on this resistance was quantified. Furthermore, the rheological parameters of the slurry under different conditions were calculated based on the Bingham fluid model. This allowed for the determination of the slurry's flow regime and critical velocity, and ultimately enabled the back-calculation of the feasible pipeline flow gradient for gravity flow under multiple factor conditions.

Results: 1) Flow velocity had the most significant impact on pipeline resistance loss, followed by flow rate, binder-to-tailings ratio, slurry concentration, and pipe diameter. 2) The flow regime of the backfill slurry was most stable when the flow velocity ranged between 1.4 m/s and 1.8 m/s. 3) Under pumping conditions, the Reynolds number of the backfill slurry was significantly less than 2100, indicating a laminar flow regime within the pipeline. 4) A slurry with a mass concentration of 68% achieved a gravity flow gradient between 7.5 and 9.5 in a pipeline with an internal diameter of 150 mm, confirming the feasibility of gravity flow transport.

Discussion: This study demonstrates that the full phosphate tailings from the Kunyang Phosphate Mine No. 2 are ideal for backfilling due to their favorable gradation. Systematic analysis identified an appropriate pipe diameter range corresponding to economical flow velocities and revealed the weighting of factors affecting pipeline resistance. Flow regime analysis based on the Bingham model confirmed laminar flow within the pipeline, with higher-concentration slurries exhibiting more pronounced structural flow characteristics and a higher critical velocity. Semi-industrial tests finally verified that the 68% concentration slurry can be transported via gravity flow within a pipeline gradient of 10. In conclusion, this research provides crucial theoretical foundation and practical guidance for optimizing pipe diameter, reducing the binder-to-tailings ratio, and controlling flow velocity to achieve economically efficient backfilling while ensuring transport stability.

KEYWORDS

phosphorus tailings, ring pipe test, rheological properties, mechanical properties, pressure drop

1 Introduction

China is the world's largest producer of phosphate rock, with a massive phosphate chemical industry. Its phosphate rock mining output has consistently ranked first globally for many years. However, the country's phosphate resources are generally characterized by a higher proportion of low-grade and refractory ores than high-grade and easily beneficiated ores. Medium- and low-grade phosphate ores account for over 90% of the total. Approximately 10 million tons of phosphate tailings are generated annually in China. Statistics indicate that the utilization rate of solid waste from the phosphate chemical industry is 70%–80% in Japan and Brazil, whereas China's comprehensive utilization rate of phosphate tailings is only approximately 7%—significantly lower than that of other countries. Most phosphate tailings are stored as waste in tailings ponds, which severely damages aquatic ecosystems and causes substantial land and resource waste (Chen et al., 2017). Paste backfilling is an effective method for addressing goaf areas and managing mine solid waste. It facilitates the construction of green mines while minimizing interference by backfilling operations with mining activities (Wang et al., 2023). Within the backfill process pipeline, transportation is the cornerstone of paste backfill technology, determining the success of slurry delivery. The efficiency of pipeline transport largely depends on the paste's fluidity; better fluidity translates to more effective transport and higher overall backfilling efficiency (Shuai et al., 2022; Yao-hui and Chuan-ming, 2023; Dong et al., 2019).

Pipeline transportation is the primary means of transporting filling slurry from the surface to the mining area, and its safe, stable and efficient operation is the premise of normal production in a mine (Chen et al., 2016; Xu et al., 2024). For this reason, some scholars in China and elsewhere have focused on the mining pipeline transportation problem. Zhou et al. (2021; 2018) designed an L-type test to study the transportation characteristics of whole tailing paste in pipelines, deducing the calculation method of the rheological parameters of high-concentration whole tailing filling material. The results of their research provide a theoretical basis for determining the optimal transportation concentration, water-cement ratio, and limit of the concentration of pipeline autoconvection transportation. Lei et al. (2021) used a laboratory L-type pipe and pilot annulus test to study transportation. The results showed that the L-pipe and annulus tests had similar trends, but the L-pipe had higher pressure drop values at different solid and cement contents; Cheng et al. (2023) and Haiyong et al. (2023) systematically investigated the pipeline conveying flow and resistance characteristics of pastes under different pipeline arrangements and proposed quantitative characterization parameters for differences in flow regimes between different pipeline arrangements. They proposed a quantitative characterization parameters for flow patterns and determining optimal pipeline network arrangements. Li et al. (2024a) analyzed the rheological properties of slurry transportation in filling pipelines through rheological, L-pipe self-flow, and semi-industrial loop tests and investigated the relationship between pressure loss and slurry flow rate, C/T ratio, and mass concentration. Wang et al. (2023) employed a combined approach of orthogonal testing and numerical simulation to investigate the influence of five parameters—filling gradient, bend curvature radius, pipe inner diameter, paste flow rate, and paste concentration—on pipeline transportation characteristics. Zhou et al. (2013) conducted a simulation analysis of gravity flow transportation in filling slurry pipelines based on Fluent software. The results indicated that the flow velocity in the transportation system was relatively ideal, with significant variations in slurry velocity at the bends, while pressure remained uniform in other sections, enabling the realization of gravity flow transportation.

The rheological characteristics of whole tailings slurry are crucial parameters in the transportation and filling process, and many studies have experimentally investigated the rheological characteristics of the filling slurry based on rheological theory, especially the mass concentration of the slurry, the size distribution and characteristics of the tailings particles, the admixtures, the temperature and PH value, and the other external environments (Guo et al., 2024; Yang L. et al., 2024; Li X. et al., 2024; Yu et al., 2024; Cuiping et al., 2023; Sen et al., 2023). Hou et al. (2024) used an orthogonal test to analyze the influence of the sand–ash ratio, mass concentration, steel-slag dosing, and straw fiber on the rheological parameters. Wu and Fall, (2024) investigated the rheological properties of paste slurry, the combined effect of sulfate, temperature, and time through indoor tests. With the simultaneous increase of sulfate, time, and temperature, the viscosity of paste slurry increased significantly, but while the yield stress increased, the rate of increase was relatively limited. Xue et al. (2023) and Zhenlin et al. (2023) independently established an experimental platform for non-contact monitoring of the microscopic slip layer in paste slurry pipelines, analyzed the effect of slurry temperature, pipe diameter, solid phase concentration, and slurry flow rate on the paste slurry's wall slip velocity, and refined the theory of the effect of the wall-slip characteristics of pipeline conveying. Sandeep et al. (2018) established a multivariate linear regression model based on hydration age, binder content, and superplasticizer dosage to predict the yield stress, plastic viscosity, and thixotropic properties of mine backfill slurry. Sada and Fall (2019) investigated the influence of high-range water-reducing admixtures on the rheological parameters of cemented paste backfill (CPB) under varying mixing and curing temperatures through laboratory experiments. Their results indicated that elevated ambient temperature leads to increased yield stress and viscosity in CPB treated with water-reducing agents. Carnogursky et al. (2023) systematically examined the effects of salinity and binder type on the rheological properties and setting time of paste backfill from the perspective of mixing water quality. Their findings provide a theoretical basis for designing cost-effective and operationally efficient backfill schemes in mining. Creber et al. (2017) conducted simultaneous sampling at surface preparation plants and underground discharge points in two Canadian mines, demonstrating that the yield stress and temperature of paste backfill are not constant throughout the distribution system; they identified temperature as a critical factor influencing variations in yield stress. Nima et al. (2017) conducted integrated experimental and numerical studies to thoroughly investigate the flow behavior and wear patterns of paste backfill in underground pipeline systems. Constructed a loop pipeline test system with diameters of 50, 100, 150, and 250 mm to systematically study the laminar transport characteristics of non-Newtonian slurries carrying coarse particles. Their results revealed that the ratio of mean wall shear stress to mean surficial particle stress serves as a more effective indicator of particle settling tendency in laminar flow than the conventionally used frictional pressure gradient. Yang et al. (2024b) used the stress relaxation method to conduct a thixotropy test to determine the rheological parameters of paste regarding shear time. They established a resistance model for pipeline transport that accounts for the time-varying rheological parameters of paste slurry and proposed a method for estimating the thixotropic equilibrium time of the yield stress. In order to accurately analyze and predict the yield stress of paste slurry, Niu et al. (2022) and Yonghui et al. (2022), based on 136 sets of rheological test data of copper ores, applied the sprawl search algorithm to the correlation vector machine. In order to accurately analyze and predict the yield stress of the paste slurry, based on 136 sets of copper ore rheological test data, they optimized the relevance vector machine (SSA-RVM) using the sprawl search algorithm and proposed the regression prediction model of the yield stress of the SSA-RVM CPB. Chen et al. (2016) conducted three-dimensional numerical simulations using FLUENT software to model the filling of slurry into coarse tailings sand with varying slurry mass fractions. Subsequently, they obtained the rheological parameters of the slurry and used MATLAB software to regress the relationship between the pipeline transportation process of the slurry, its rheological parameters, and the slurry mass fractions. The correlation between the slurry pipeline transportation process, rheological parameters, and slurry mass fraction was established through MATLAB mathematical software.

Thus, in analyzing the conveying performance of filling slurry pipelines and their rheological characteristics, researchers have generally employ numerical simulation and physical test methods. Numerical simulation primarily relies on hydrodynamics-related software for research and is heavily dependent on the fundamental parameters of the slurry. The physical test method is based on the L-pipe test, and the small-scale annulus test is mainly used, often yielding results that deviate somewhat from actual conditions and thus providing weaker reference values. Research has predominantly focused on whole tailings from metal ores, particularly graded tailings, where the particle size composition differs significantly from that of flotation phosphorus tailings. In this study, based on the filling ring pipe test system built independently in a mine industrial site, we study the conveying characteristics of high-concentration ultrafine whole phosphorus tailings under pumping and self-flowing conditions and analyze the influences of filling slurry concentration, ash–sand ratio, pipe diameter, flow rate, and flow velocity on pipeline resistance. We also analyze the slurry flow from the perspective of the paste critical flow rate, integrating rheological parameters into our analysis. The research results provide technical support for the cementation and filling of ultrafine phosphorus tailings in Kunyang Phosphorus Mine No. 2.

2 Rheological theory

Many studies have found that pastes formulated with different materials show typical non-Newtonian fluid properties; under the action of shear force, there is a certain relationship between shear force and shear rate, known as the “flow pattern”. If the shear stress is applied to the paste, the paste is strained at a certain rate—the “shear rate”. In the absolute value of the shear stress r and the resulting shear rate, there is a certain relationship with the typical non-Newtonian fluid rheological mathematical model of the general expression for (Kwak et al., 2005)

$$\tau = f(dv/dr) = \tau_0 + \mu(dv/dr)^n \quad (1)$$

where: τ is the shear stress Pa; dv/dr is the shear rate s^{-1}; τ_0 is the yield stress Pa; μ is the plastic viscosity $pa.s$; v is the flow rate of the slurry m/s. The index of rheological propertiesτ_0,μ, and n are collectively referred to as the “rheological parameters” of the slurry.

3 Physical and chemical property analysis of filling materials

The analysis of the backfill material’s properties includes both physical and chemical aspects. Physical characterization encompasses tests for the specific gravity, density, and particle size distribution of the tailings. The chemical analysis involves determining the chemical composition of the tailings via X-ray fluorescence (XRF) spectroscopy.

3.1 Whole tail sand particle size distribution

The particle size distribution of the filling aggregate, also known as the “gradation” of the material, refers to the percentage content of different particle sizes in the granular material. The particle size distribution of the filling material is pivotal in dictating the entire filling process and has a great influence on the preparation, transportation, and quality of the filling body. In this study, the particle size composition of all tailing sands of Kunyang Phosphate Mine II (Figure 1a) was analyzed by a Malvern 3,000 (as shown in Figure 1b) laser particle size tester (Figure 1c).

The test results are presented in Table 1 and Figure 2. It is evident from Figure 2 that the particle size of all the tailing sand samples taken is within 163.2 μm, the proportion of particles with particle size less than 75 μm (−200 mesh) accounts for approximately 91.6%, the proportion of particles with particle size less than 37 μm

FIGURE 1
Particle size analysis" **(a)** phosphate tailings; **(b)** instrument appearance; **(c)** data combing.

TABLE 1 Full sand-end particle size distribution.

Particle size (μm)	−5	−10	−20	−50	−75	−100	−200
Shared yield (%)	26.763	11.925	18.532	25.156	9.210	4.630	3.784
Cumulative yield (%)	26.763	38.688	57.220	82.376	91.586	96.216	100.000

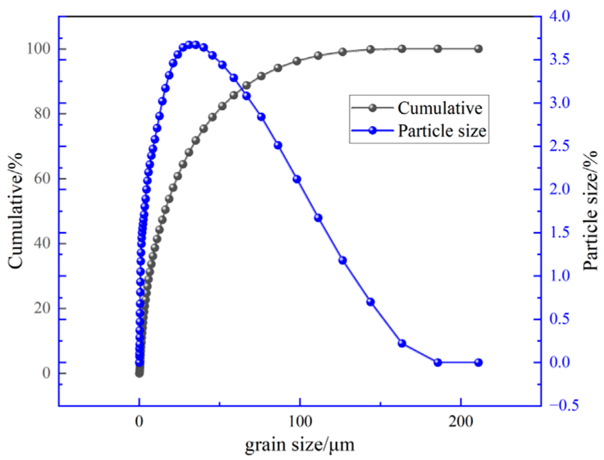

FIGURE 2
Particle size distribution of total phosphorus tailings.

(−400 mesh) accounts for approximately 71.7%, and the range of particles less than 16.1 μm accounts for 50% of the total particle size. Much of the literature shows that, to ensure that the filling material in the pipeline for a long-distance conveying process does not stratify and segregate, the proportion of tailing sand −20 μm particle size should be greater than 15% in the formation of so-called "structural flow" (Wu et al., 2022). It is evident from the figure that the tailing sand from Kunyang Phosphate Mine II contains approximately 57.22% of particles smaller than 20 μm, thereby ensuring the feasibility of the long-distance transportation of the filling slurry.

The grading of the tailings can have a significant effect on the conveying properties of the filling slurry, and it is standard practice in the mining industry to characterize the grading of the filling aggregate using the coefficient of inhomogeneity C_u and the coefficient of curvature C_c, which can be determined from Equations 2, 3.

$$C_u = \frac{D_{60}}{D_{10}} \tag{2}$$

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \tag{3}$$

The main particle size distributions of the whole tailing sand samples are as follows.

Diameter at 10% = 1.54 μm (10% of the sample is below 1.54 μm).

Diameter at 30% = 6.28 μm (30% of the sample is below 6.28 μm).

Diameter at 50% = 16.14 μm (50% of the sample is below 16.14 μm).

Diameter at 60% = 23.46 μm (60% of the sample is below 23.46 μm).

Diameter at 90% = 70.73 μm (90% of the sample is below 70.73 μm).

In the field of backfill engineering, industry practices commonly reference the gradation theory from soil mechanics and concrete science to evaluate the suitability of aggregate materials. An ideal backfill aggregate gradation generally needs to meet the following criteria: the coefficient of uniformity (Cu) should be not less than 5, and the coefficient of curvature (Cc) should fall within the range of 1–3. Substituting the main particle size distribution data of the whole tailing sand sample into Formulas 2 and 3, we can calculate

TABLE 2 Main chemical composition of tailings.

Chemical composition	CaO	Fe_2O_3	Al_2O_3	MgO	SiO_2	K_2O	Na_2O	P_2O_5	Others	
									F	LOI
Content (wt%)	31.391	0.643	0.247	18.951	3.037	0.025	0.063	4.561	1.252	15.426

that the unevenness and curvature coefficients of the tailing sand are 15.23 and 1.09, respectively. Engineering experience shows that a well-graded material has an unevenness coefficient greater than 10, but the Cc value is small, so it may be that all the tailing sand is fine in size, and the curvature coefficient should be between 1 and 3. It can be seen that the whole tailing sand of Kunyang Phosphate Mine No.2 is well-graded and suitable for filling material.

3.2 Chemical composition analysis

The chemical composition of the tailings was analyzed using spectroscopy, and the results of the chemical composition of +400 mesh tailing sand are presented in Table 2. The test results show that the tailings are mainly CaO, MgO, and P_2O_5, accounting for 31.39%, 18.95%, and 4.56%, respectively, and that the high calcium content is beneficial for the strength of the filling body, which makes it suitable for use as a filler aggregate. The tailings exhibit low concentrations of recoverable metals (e.g., Fe and Al), and the primary constituent minerals are physically and chemically stable.

3.3 Test design

The semi-industrial conveying test of all the phosphorus tailing sand employs two methods: pumping and self-flowing. The tailing slurry conveyed from the processing plant is transported to the filling slurry preparation station through the pipeline, where the concentration of the slurry is increased from 20% to 35%, then to 65%, and finally to 71% by the thickening device. The thick slurry is transported to the mixing drum by pumping, and the gelling material is steadily fed to the mixing drum through the spiral feeder following the designed ratio. The prepared filling slurry is thence conveyed to the filling slurry conveying test area by tanker truck (self-flowing is possible if site conditions permit). Then, through the screw feeder, the gelling material is stably fed to the mixing drum according to the designated proportion, and the filling slurry is prepared by the mixing drum. Finally, the prepared filling slurry is transported to the filling slurry conveying test area via tanker truck to conduct the conveying test (the site conditions allow self-flow). The overall program design of the test is shown in Figure 3.

In the filling station, a high concentration tailing sand slurry is prepared into filling slurry according to a specific proportion. This slurry is then transported to the slurry conveying area by tanker truck. The pumping test is performed by the concrete pump truck from the pump hopper to form the loop pipe circulation pumping, which simulates long-distance pipeline transportation. For the self-flow conveying test, a commercial concrete tanker pours the filling slurry into a self-flow buffer hopper. Once the slurry reaches a certain liquid level, the self-flow manual valve is opened, allowing the slurry to flow down the pipeline on its own. The outlet of the pipeline is monitored determine whether the slurry is flowing out, and thus whether the self-flow timeline of the filling slurry can reach the target of 9. The pipeline system has a total length of approximately 250 m, with an adjustable total vertical head of 15–20 m. It is capable of simulating a pipeline gradient—a key parameter for paste backfill—of 3–9. The system is configured with pipes of nominal diameters (DN) of 125, 150, and 175 mm.

According to the actual production requirements of the mine, the design of the conveying end of the filling ring pipe involves test filling slurry with gray-to-sand ratios of 1:6, 1:8, 1:12, 1:18, and mass fractions of 68% and 71%. The filling pipes have inner diameters of 125 mm, 150 mm, 175 mm, with flow rates ranging from 50 m^3/h ~ 110 m^3/h. Ring pipe testing also uses a standard conical collapsibility cylinder to carry out the collapse test to assist in judging the flow and fluidity of the filling slurry.

3.4 Test device

At the slurry transportation test site (as shown in Figure 4a), a flow meter is used to monitor the flow rate of the slurry system, and a pressure sensor monitors differential pressure measured at various points (designed to be installed at intervals of 20 m). Communication cables transmit the monitoring data to the system operator interface for unified collection. The filling slurry is transported either through self-flow or by pumping, with variations in concentration, ash–sand ratio, and flow rate. Stress sensors are employed to record the pressure values of the slurry at each monitoring point, and other relevant parameters are calculated and summarized accordingly.

4 Analysis of factors influencing pressure drop

To study the relationship between pipeline conveying resistance and slurry concentration, industrial tests were carried out to collect the pipeline pressure and flow rate of filling different concentrations of slurry over time. The pipeline transport resistance (H, Pa/m), pipeline pressure, flow velocity (v, m/s), and flow rate (Q, m^3/h) are calculated using Equation 4.

$$\begin{cases} H = \dfrac{\Delta P}{L} = \dfrac{P_1 - P_2}{L} \\ v = \dfrac{4 \times 3600Q}{\pi R^2} \end{cases} \tag{4}$$

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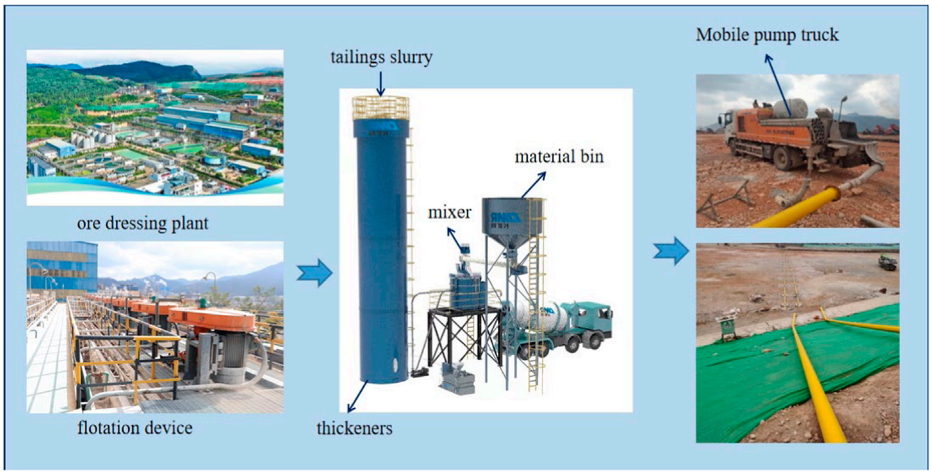

FIGURE 3
Experiment scheme design.

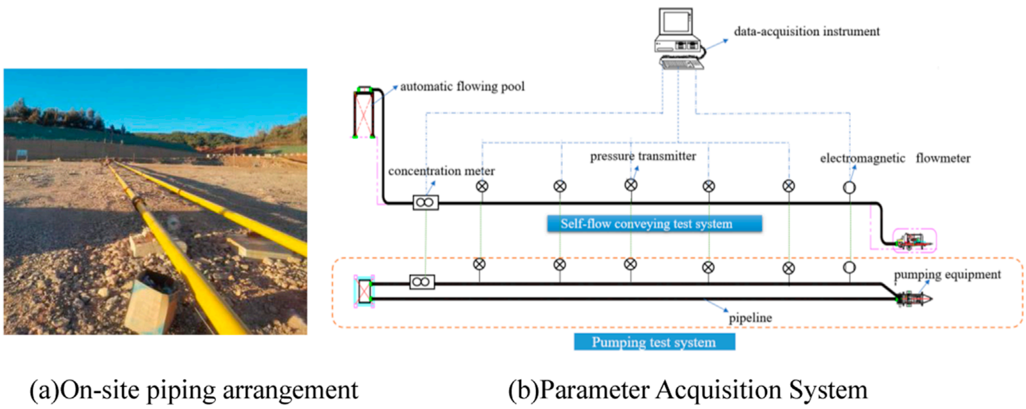

FIGURE 4
Schematic diagram of pipe loop test system for paste slurry rheological parameters. **(a)** On-site piping arrangement. **(b)** Parameter acquisition system.

where: ΔP is the pressure difference between two pressure points, measured in MPa; L is the distance between the two pressure points, m; P_1 and P_2 represent the pressure values at pressure points 1 and 2, respectively, also measured in MPa; R is the diameter of the pipeline, measured in meters. Pipeline resistance is based on Formula 1 for the calculation to analyze the filling slurry mortar and sand ratio, the pipeline diameter, and the flow rate of the pipeline resistance to the impact.

4.1 Yield stress and rheological parameters

Much research from the perspective of rheology on the relationship between shear stress and shear rate has found that high concentration tailings or paste-filling slurry exhibits rheological characteristics consistent with those of a Bingham's plastic body and a yield pseudo-plastic body (H-B). Its constitutive equation can be represented by Equation 5 (Wang et al., 2023):

$$\tau_w = \tau_0 + \mu.\gamma \tag{5}$$

where τ_w is the slurry in the pipe flow with the wall of the shear stress, Pa, and γ is the shear rate of the slurry, s. Due to their high concentration, significant yield stress, and viscosity, cemented backfill slurries are typically transported in a laminar flow regime. Under laminar flow conditions, the rheological relationship of a Bingham plastic fluid in a circular pipe is described by the Buckingham equation, where the shear rate γ is equal to the flow velocity v along the direction of the pipe diameter of the gradient dv/dy. The rheological equation is represented by Equation 6 (Wang et al., 2023):

$$\tau_w = \frac{4\tau_0}{3} + \mu.\frac{8v}{D} \tag{6}$$

where v is the flow rate of slurry, m/s, and D is the inner diameter of the filling pipe, m. The filling slurry can be filled into the pipe with friction equal to the resistance.

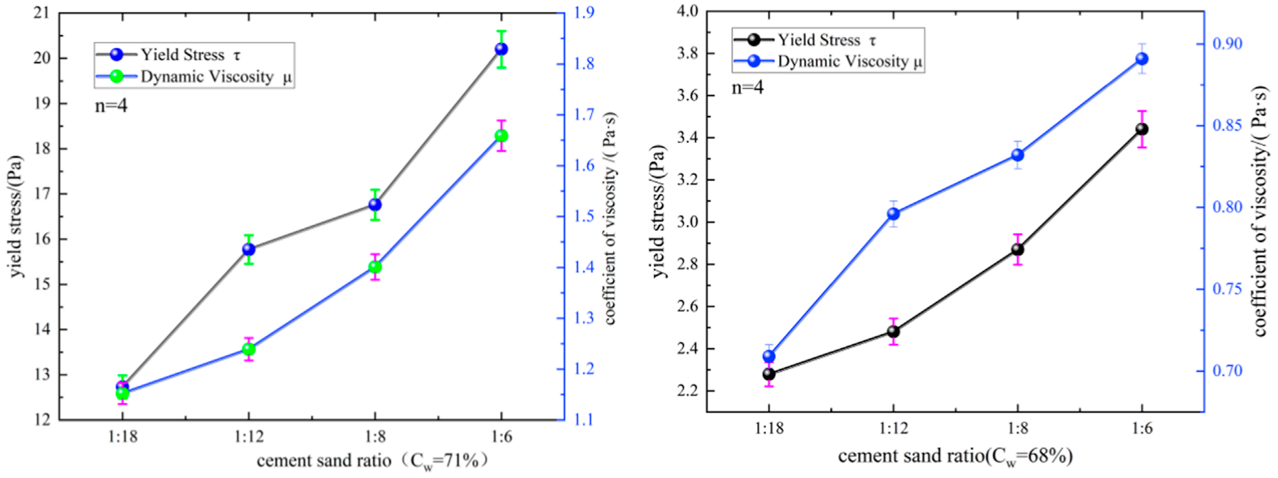

FIGURE 5
Variation curves of yield stress and viscosity coefficient of unclassified tailings slurry under different cement–sand ratios.

According to hydrostatic equilibrium theory, the friction between the filling slurry in the pipe and the wall is equal to resistance along the pipe; therefore, the wall shear stress,τw, can also be expressed by Equation 7.

$$\tau_w = \frac{D}{4} \times \frac{\Delta p}{L} \quad (7)$$

Based on Equation 6, the rheological parameters of the filling slurry for different working conditions can be obtained using MATLAB custom function fitting (Figure 5). The rheological properties of the slurry exhibit a high sensitivity to variations in its compositional parameters. Both the yield stress and plastic viscosity demonstrate a significantly increasing trend with the rise of solid mass fraction and binder-to-sand ratio. The underlying micro-mechanism is an increase in solid mass fraction directly leading to a higher number of particles per unit volume. This not only intensifies the hydrodynamic interactions among particles, causing the slurry to experience greater viscous resistance during flow—macroscopically observed as an elevation in plastic viscosity—but, more importantly, the reduced inter-particle spacing markedly increases the probability of their collision and contact. This promotes the development of a more extensive three-dimensional network structure facilitated by inter-particle forces such as electrostatic attraction, van der Waals forces, and flocculation. This spatial network structure imparts a solid characteristic to the slurry, requiring the application of a critical stress sufficient to break this structure (i.e., the yield stress) to initiate flow. Consequently, the yield stress increases accordingly.

Combined with the results of the statistical analysis of the particle size distribution of all the phosphorus tailings, it was found that 50% of the particle size of the flotation phosphorus tailings is below 16.14 μm and, compared with the traditional low-concentration two-phase flow filling slurry, the paste contains a higher proportion of fine particles This is due to the strong surface physicochemical effect of the fine particles of phosphorus tailings in water and the addition of the gelling material to enhance the tailings of the "flocculation effect." Due to the strong surface physicochemical effect of fine particles of phosphorus tailings in water, the addition of gelling material enhances the "self-flocculation" between the tailings, which leads to the generation of a stable network structure between the solid particles. The viscosity of the paste increases with the increase of the ratio of gray sand.

4.2 Influence of cement–sand ratio on pressure drop

An appropriate cement–sand ratio can ensure that the cementitious material is fully hydrated to form a strong filling body. According to the filling station slurry design ratio, we analyze the pipe resistance under pipe diameters of 125 mm/150 mm/175 mm and slurry concentrations of 68%/ 71% using a gray-to-sand ratio of 1:18; 1:12:1:8; 1:6. As shown in Figure 6, under the same slurry mass concentration, the flow resistance showed an increasing trend as the cement–sand ratio increased. Taking the example of a slurry concentration of 68% and pipe diameter D = 125 mm, when the cement–sand ratio increased from 1:18 to 1:6, the flow resistance increased from 2.087 Kpa/m to 2.67 Kpa/m. When comparing the slurry conveying pipeline with diameters of 125, 150, and 175 mm, it is evident that the larger the diameter, the slower the growth of pipe resistance under the influence of the cement–sand ratio.

4.3 Influence of slurry concentration and flow velocity on pressure drop

The filling ring pipe test shows that the effect of flow velocity on pressure drop follows the same law. The flow resistance and flow velocity have a linearly positive correlation, indicating that the filling material is in a laminar conveying state within the scope of this research. The higher flow rate of the filling slurry indicates that its

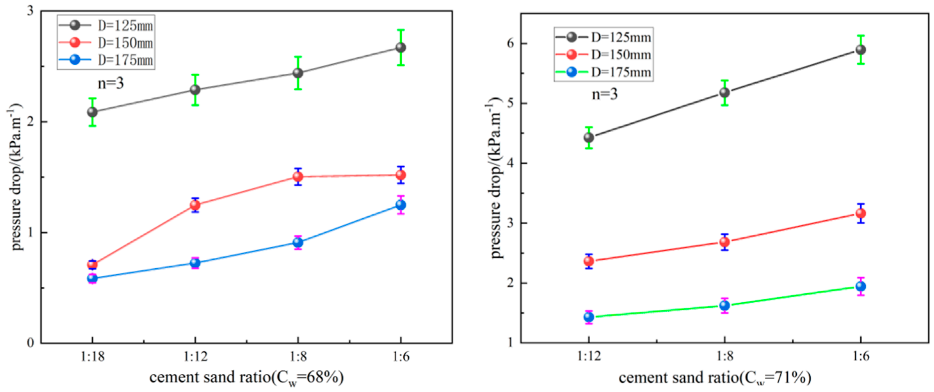

FIGURE 6
Influence of cement–sand ratio of slurry on pressure drop.

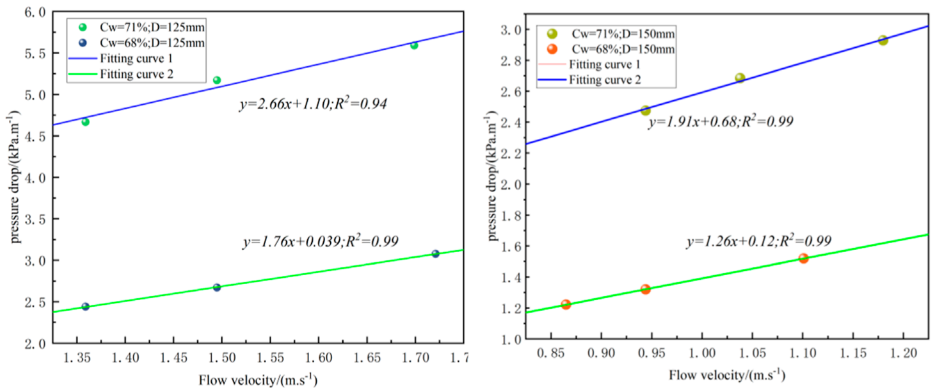

FIGURE 7
Influence of slurry velocity on pressure drop.

energy is also higher, which means that the friction and resistance in the pipeline will also increase. Taking the example of the filling slurry with concentrations of 68% and 71% used in this test, a linear correlation between flow rate and pressure drop was observed when the pipe diameter was 125 mm.

Due to the existence of "self-flocculation" between the particles of ultrafine phosphorus tailings, the higher the concentration of the filling slurry, the smaller the average distance of the particles, the higher the probability of collision, and the stronger the flocculation effect. The particles in the flocculation will be linked into flocs; when the number of flocs reaches a certain number, the flocs begin to be connected and eventually form a loose floc structure. In the process of slurry transportation, due to the existence of the floc structure, the friction resistance between the flow layer and the pipeline increases; the higher the concentration, the more obvious the increase in resistance. As shown in Figure 7, the experimental investigation was conducted under a constant flow rate, Q. Backfill slurries with concentrations of 68% and 71% were compared based on the fitted parameter curves. The pipeline resistance growth rate of the 71% concentration slurry was 2.66, while that of the 68% concentration slurry was 1.76, corresponding to a relative increase of 51.14%. This indicates that higher slurry concentrations result in a more significant increase in pipeline resistance.

As shown in Figure 7, for backfill slurries with identical mass concentrations, a comparison was made between two operating conditions with pipeline diameters of 125 mm and 150 mm. The pipeline resistance growth rate for the 71% concentration slurry decreased from 2.66 to 1.91, and for the 68% concentration slurry it decreased from 1.76 to 1.26. The reduction magnitude was approximately 28.41%, with largely consistent decreases observed across both concentrations. In mining practice, selecting a larger-diameter filling pipeline is advantageous for reducing pipeline resistance.

4.4 Multi-factor sensitivity analysis

Gray relational analysis (GRA) (Muddineni et al., 2020) is an analytical method that assesses the degree of approximation between factors based on data. This method uses the relational grade to quantify the closeness of the relationship between two factors. It determines the strength of the connection by analyzing

TABLE 3 Calculation results of the correlation degree.

Serial number	$\zeta_1(k)$	$\zeta_2(k)$	$\zeta_3(k)$	$\zeta_4(k)$	$\zeta_5(k)$
1	0.44	0.51	0.41	0.45	0.52
2	0.77	0.99	0.76	0.80	0.77
3	0.88	0.70	0.80	0.84	0.93
…	…	…	…	…	…
63	0.63	0.84	0.57	0.69	0.80
Relational coefficient	0.742	0.747	0.705	0.749	0.779

the geometric similarity between the curves of a reference sequence and comparative sequences within a system. A key advantage of GRA is its ability to overcome the limitation of traditional single-factor analysis, which cannot simultaneously consider the influence of all factors. This study employed GRA to investigate the primary and secondary order of influence of the following parameters on pipeline resistance: slurry concentration (X_1), binder-to-sand ratio (X_2), pipe diameter (X_3), flow rate (X_4), and flow velocity (X_5). The pressure drop is designated as the reference sequence, while the factors influencing the pressure drop serve as the comparative sequences. The procedural steps are as follows.

Step 1: Based on the 63 sets of experimental data obtained, the data was nondimensionalized using Equation 8.

$$x_i(k) = \frac{X_i(k)}{X_i(1)}, i = 1,2...n; k = 1,2...m \tag{8}$$

Step 2: Derive the difference series and calculate the maximum absolute difference M and minimum absolute difference m.

Difference series: $\Delta_i(\mathrm{k}) = |X_0(k) - X_i(k)|, i = 1,2...n; k = 1,2...m;$
Maximum absolute difference: $M = \max_{i=1}^{n} \max_{k=1}^{m} |X_0(k) - X_i(k)|$
Minimum absolute difference: $m = \min_{i=1}^{n} \min_{k=1}^{m} |X_0(k) - X_i(k)|$

Step 3: Calculate the correlation coefficient: It was calculated based on Equation 9.

$$R(X_0(k), X_i(k)) = \frac{m + \rho M}{\Delta_i(k) + \rho M} \tag{9}$$

Where ρ is the resolution coefficient, the smaller ρ is, the larger the resolution. Generally, ρ takes the value range of (0,1); when $\rho \le 0.5463$, the discriminative power is the best, so take $\rho = 0.5$.

Step 4: Calculate the gray correlation and sorting. It is calculated based on Equation 10.

$$r(X_0, X_\mathrm{i}) = \frac{1}{n} \sum_{ki=1}^{n} (r(X_0(k), X_i(k))) \tag{10}$$

When the gray correlation is between 0 and 1, a higher value indicates a stronger the correlation with the reference sequence. The 63 sets of annular pipe test data were processed according to the above steps, and the results are shown in Table 1. According to Table 3, the average correlation of slurry concentration X1, ash-to-sand ratio X2, pipe diameter X3, flow rate X4, and flow rate X5 are 0.742, 0.747, 0.705, 0.749, and 0.779, respectively. Based on the calculation results, it is evident that for the ultrafine phosphorus tailings filling material, the flow rate has the most significant impact on pressure drop, followed by flow rate, ash-to-sand ratio, and slurry concentration, and the pipe diameter has the least influence on the pressure drop, which can be used as the mine filling material. The influence of pipe diameter on pressure drop is the smallest, which can be used as the basis of mine filling parameters. In light of the results from this semi-industrial test, to ensure the stable transportation of the phosphorus tailings slurry, it is advisable to select a larger diameter filling pipe and appropriately reduce the ash-to-sand ratio and flow rate.

5 Filling slurry flow characteristics analysis

5.1 Analysis of the flow state of paste ring pipe test

Many studies have concluded that the paste used to fill the downhole airspace typically belongs to a non-Newtonian body. Under the condition of high speed, the slurry flow state is turbulent, and there is a resistance loss of the flow in the tube $\Delta P/L$ increases sharply with flow velocity v; when v decreases to a certain point, the flow transitions from turbulent to laminar, the flow velocity of the point, or "critical flow velocity." When v decreases to a certain point, the flow rate at this point is the "critical flow rate," which is recorded as V_D; when $v < V_D$, the increase of $\Delta P/L$ with v is relatively slow (Wu et al., 2013; Xibing et al., 2018). Therefore, in the process of conveying paste slurry through pipelines, it is important to determine the fluid flow state and critical flow rate in order to avoid resistance loss.

The analysis of the transition velocity generally begins with the Reynolds number of the fluid flow. For clear water pipe flow, the condition for its transition from turbulent to laminar flow is when the Reynolds number reaches a critical value of approximately 2,100 to 2,300. The corresponding velocity at this point is termed the transition velocity. However, for a paste backfill slurry, which behaves as a Bingham fluid, the calculation of the Reynolds number becomes more complex because the apparent viscosity μ_A in its expression varies with flow velocity. Typically, the plastic viscosity μ_B of the slurry is used to calculate the Reynolds number, which is then referred to as the Bingham Reynolds number R_{eB}. The expression is given by Equation 11.

$$R_{eB} = \frac{D_V \rho_m}{\mu_\mathrm{p}} \tag{11}$$

For Bingham fluid, according to the Buckingham flow equation, the relationship between the flow rate in the pipe and the resistance and fluid properties is:

$$\frac{4v}{R} = \frac{\tau_w}{\mu_p}\left[1 - \frac{4}{3}\left(\frac{\tau_w}{\mu_p}\right) + \frac{1}{3}\left(\frac{\tau_w}{\mu_p}\right)^4\right] \tag{12}$$

Omitting the higher power terms in Equation 12, the transformation yields the following equation:

$$\frac{4v}{R} = \frac{\tau_w}{\mu_p} - \frac{4}{3}\frac{\tau_w}{\mu_p} \tag{13}$$

Carrying Equation 7 into Equation 13 gives

$$i = \frac{\nabla p}{L} = \frac{2\tau_w}{R} = \frac{16}{3D}\tau_y + \frac{D^2}{32}\cdot\mu_p \tag{14}$$

The above formula represents the resistance of the paste in tube flow when the wall slip effect is not considered. To calculate its Reynolds number, the above formula is transformed into the form of Fanning's resistance formula:

$$\Delta P = 4f\frac{L}{D}\frac{\rho_m v^2}{2} \tag{15}$$

In Equation 15, f is the Fanning drag coefficient:

$$f = 16/R_{es} \tag{16}$$

Where R_{es} is the effective Reynolds number, joining Equations 15 and 16 gives

$$R_{es} = \frac{8\rho_m v^2}{\tau_w} \tag{17}$$

We define the effective viscosity μ_e from Equation 14:

$$\mu_e = \tau_w D/8v = \mu_p\left(1 + \frac{\tau_y D}{6v\mu_p}\right) \tag{18}$$

Joining Equations 17, 18 gives

$$R_{es} = Dv\rho_m/\mu_e \tag{19}$$

R_{es} is the Reynolds number of the paste in the tube flow. When the Reynolds coefficient reaches 2,100, the paste from the laminar to the turbulent flow is the paste slurry flow state of the discriminatory criteria.

$$R_{es} = \frac{D_V\rho_m}{\mu_e} \geq 2100 \tag{20}$$

By combining Equations 11, 18, Equation 20 can be transformed as

$$\mathrm{Re}_B = \frac{Dv\rho_m}{\mu_p} \geq 2100\left(1 + \frac{\tau_y D}{6v\mu_p}\right) \tag{21}$$

The formula for the critical flow rate is solved from Equation 21:

$$V_D = \frac{1050\mu_p}{D\rho_m}\left[1 + \sqrt{1 + \frac{D^2\tau_y\rho_m}{3150\mu_p^2}}\right] \tag{22}$$

Samples of several representative paste slurries from the loop-pipe tests were collected and their fundamental parameters were characterized. Subsequently, based on the aforementioned research, the flow regime of the slurry within the pipeline was analyzed. The effective Reynolds number (Res) was calculated using Equation 19, and the critical velocity was determined with Equation 22. The corresponding results are summarized in Tables 4, 5.

Based on the analysis of data presented in the table, the Reynolds number of the backfill slurry during the pumping process in this circulating pipeline test was significantly less than 2,100, indicating that the flow regime of the paste within the pipeline was laminar. A comprehensive comparison between the 68% and 71% concentration backfill slurries reveals that higher concentrations result in more pronounced structural flow characteristics and greater critical flow velocity. As the flow velocity increases, both the pipeline resistance and Reynolds number rise correspondingly, leading to a reduction in the flow stability of the backfill slurry. Further macroscopic observations from semi-industrial loop tests and comprehensive engineering evaluations demonstrate that within the flow velocity range of 1.4–1.8 m/s, the backfill slurry not only meets the operational requirements for mine backfilling capacity but also exhibits high flow stability and operational reliability.

5.2 Filling slurry collapse and coagulation properties

The fluidity of the filling slurry indicates how smoothly the slurry flows under the influence of its own weight or external forces, as well as the ease or difficulty of filling the quarry. As an ideal structural fluid, the fluidity of ultrafine phosphorus tailings filling slurry is an important characteristic index in the process of slurry conveyance. In the actual production process, the fluidity of the filling slurry is primarily characterized by its slump and diffusivity. The primary factors influencing these characteristics include the slurry's mass concentration, ash–sand ratio, physical properties of the tailing sand, and other relevant factors. Combined with the field semi-industrial test to carry out the slump and setting time measurement test, the results of the tests are shown in Table 5.

Analyzing the data in the table, it is observed that as the concentration of the filling slurry increases, its fluidity decreases, corresponding to lower values for collapse and diffusivity. For the filling slurry under the same concentration conditions, with the increase of the ash–sand ratio, the yield stress and viscosity of the slurry increase, and the fluidity of the filling slurry decreases. When comparing the setting time of filling slurries of two different mass concentrations, it is evident that high concentration and a high ash–sand ratio are conducive to reducing the setting time of the slurries.

5.3 Filling slurry self-flow times line

For mine backfill pipeline networks under gravity flow conditions, let the vertical pipe height be H and the horizontal pipe length be L. According to the principle of energy conservation, the following relationship can be established:

$$\gamma H = i(H + L) + \sum_{i=1}^{n}\xi_i\cdot\gamma\frac{V^2}{2g} + \gamma\frac{V^2}{2g} \tag{23}$$

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TABLE 4 Slurry flow pattern analysis related parameters calculation results.

Serial number	Consistency/ C_w	Pipe diameter/ mm	Flow rates/m/s	Densities $\rho_m/t.m^{-3}$	Gray sand ratio	Yield stress τ_y/Pa	Plastic viscosity $u\mu_p/pa.s^{-1}$	Effective viscosity $\mu_e/pa.s^{-1}$	Reynolds factor $/R_{es}$	Critical flow rates V_D/s
1	68%	125	1.495	1.827	1:6	3.440	0.891	0.93	368.33	8.19
2	68%	150	0.944	1.827	1:8	2.870	0.832	0.89	291.00	6.38
3	68%	150	1.022	1.827	1:12	2.481	0.796	0.84	332.83	6.10
4	68%	175	0.589	1.827	1:18	2.279	0.709	0.79	237.28	4.66
5	68%	150	1.300	1.827	1:8	15.77	0.832	0.87	407.91	6.38
6	68%	150	1.800	1.827	1:8	15.77	0.832	0.86	572.33	6.38
7	68%	150	2.000	1.827	1:8	15.77	0.832	0.85	638.14	6.38
8	68%	150	2.500	1.827	1:8	15.77	0.832	0.82	802.70	6.38
9	71%	125	1.585	1.896	1:6	20.20	1.659	1.86	202.16	14.70
10	71%	150	0.944	1.896	1:8	16.76	1.401	1.73	154.84	10.35
11	71%	175	0.67	1.896	1:12	15.77	1.239	1.75	126.75	7.84

TABLE 5 Test results of fluidity and setting time of filling slurry.

Concentration/%	Concentration	Slump/cm	Diffusivity/cm	Initial condensation point/h	Time of final coagulation/h
71	1:6	26.9	84	24	36
71	1:8	27.2	89	32	45
71	1:12	27.5	100	42	52
68	1:6	27.7	97.8	39	68
68	1:8	28.1	100	62	80
68	1:12	28.2	100.5	89	105

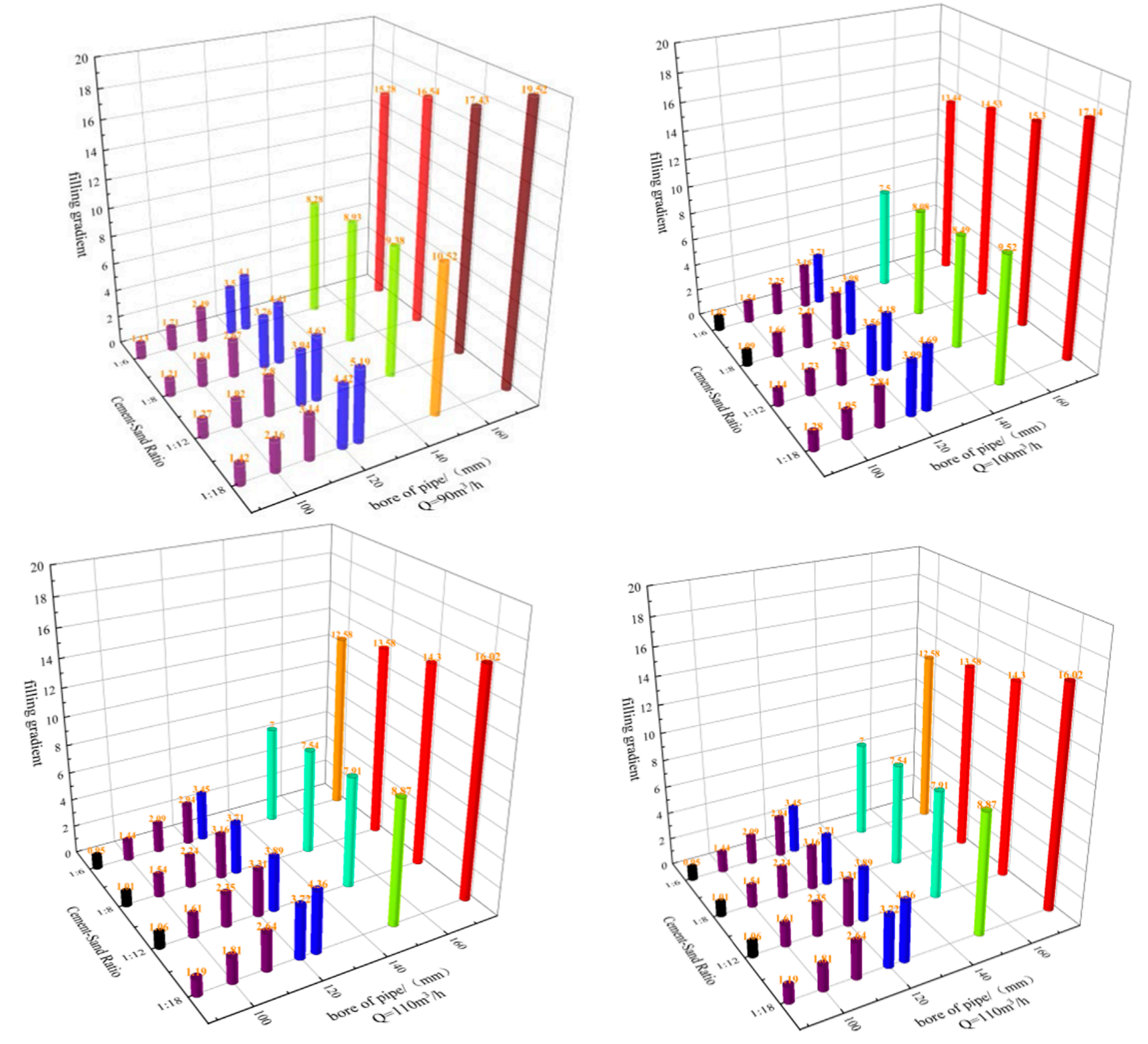

FIGURE 8
Self-flowing double line of filling slurry.

Considering the unevenness of pipeline layout and other unforeseen factors, if the sum of local resistance and exit loss is taken as 1.1 times the frictional resistance along the pipeline, then Equation 23 can be written as:

$$\gamma H = 1.1i(H + L) \tag{24}$$

Equation 24 is transformed as follows:

$$\frac{H + L}{H} = \frac{\gamma}{1.1i} \tag{25}$$

The total pipeline length ($H + L$) divided by the vertical height (H) —$(H + L)/H$—represents the paste line (or flow gradient) in backfilling.

Based on the slump test results, gravity flow transportation becomes unachievable when the backfill concentration exceeds 70%. Therefore, the pipeline flow gradient for the 68% concentration backfill slurry in this gravity flow test was calculated using Equation 25. Figure 8 presents the allowable paste line values that enable smooth transportation under different slurry concentrations, flow rates, and pipe diameters. Values in the table less than 1 indicate that gravity flow is not feasible, while calculated paste line values greater than 10 is considered practically meaningless.

As can be seen from Figure 8, when the filling flow rate is 100 m^3/h, the gravity flow paste line (self-flow gradient) for the 68% concentration backfill slurry in a pipeline with an inner diameter of 150 mm can reach 7.5–9.5. Combined with field observations from the self-flow transportation tests, slurries with different cement-to-sand ratios at 68% concentration all achieved smooth gravity flow within a paste line range of up to 10, which is generally consistent with theoretical calculations.

The total pipeline length for the field self-flow transportation test system was 125 m, with pipe inner diameters of 125 mm, 150 mm, and 175 mm, and a vertical height difference of approximately 15 m. A self-flow storage bin measuring 3.0 m (length)×2.0 m (width)×1.8 m (height) was installed at the test site. The tests were conducted outdoors at an average ambient temperature of approximately 22 °C. Calculations show that the static pressure head generated by the gravity of the 68% concentration backfill slurry in this system is approximately 268.569 kPa. Under these conditions, the measured slurry flow velocity range was 0.8–1.2 m/s.

Based on the semi-industrial test results, it can be concluded that under the conditions of this study, backfill slurry can be transported by gravity flow when the paste line is less than 10; when the paste line exceeds 10, pumping is required to overcome the increased pipeline resistance.

6 Conclusion

1. The content of −20 μm particles in the whole phosphorus tailing sand of Kunyang Phosphorus Mine No.2 is approximately 57.22%, and the coefficient of inhomogeneity and coefficient of curvature are 15.23 and 1.09, respectively; all the tailing sand has good gradation and is suitable for use as filling material.
2. When the filling flow rate is 90–120 m3/h, according to the economic flow rate, the inner diameter of the pipe is 125–175 mm; the flow rate of the slurry is then 1.04–2.72 m/s; 71% of the slurry pressure drop is 1.67–10 Kpa/m; 68% of the slurry pressure drop is 0.84–5.1 Kpa/m.
3. For ultrafine phosphorus tailings filling material, the flow rate has the greatest influence on pressure drop, followed by flow rate, ash–sand ratio, and slurry concentration; the pipe diameter has the least influence on pressure drop. Under the condition of ensuring stable transportation of whole phosphorus tailings slurry, a larger diameter filling pipe can be selected, and the ash–sand ratio and flow rate can be appropriately reduced.
4. Based on the Bingham fluid model to analyze and calculate the flow state and critical flow rate of the filling slurry, the Reynolds coefficient of the filling slurry ranges from 126.75 to 368.33 under the condition of pumping in the pipe, and the flow of the slurry in the pipe is a laminar flow state. When comparing the filling slurry with 68% and 71%, the higher the concentration, the more significant the structural flow state of the slurry, and the higher the critical flow rate.
5. The filling slurry of 68% concentration with different ash–sand ratios can flow through the multiplication line within 10, which is consistent with the theoretical calculation value; according to the filling semi-industrial test situation, the filling slurry can be transported by self-flow.

7 Discussion

This study investigates the flow characteristics of ultra-fine flotation phosphate tailings through loop-pipe experiments and theoretical analysis. The tailings contain a high proportion of fine particles, and the prepared slurry exhibits structural fluid behavior, maintaining a laminar flow state within the pipeline. As the mass fraction and binder-to-tailings ratio of the slurry increase, the yield shear stress and plastic viscosity rise correspondingly. Due to the pronounced surface physicochemical interactions of fine phosphate tailings particles in water, the incorporation of cementitious materials enhances “self-flocculation” among tailings particles, promoting the formation of a stable network structure between solid particles. The viscosity of this structure increases with a higher binder-to-tailings ratio. The pipeline resistance of the full phosphate tailings backfill slurry shows a positive correlation with flow velocity, concentration, binder-to-tailings ratio, and flow rate. Among these factors, flow velocity exerts the most significant influence on pipeline resistance, followed by flow rate, binder-to-tailings ratio, and slurry concentration. In practical mining operations, selecting larger-diameter pipelines and appropriately reducing flow velocity and binder-to-tailings ratio contributes to more stable transport of backfill slurry. Current research on the rheological properties of cemented phosphate tailings backfill primarily consists of theoretical analyses based on established assumptions. Future work should focus on elucidating the intrinsic evolution mechanisms of the rheological behavior of backfill slurries and advancing the application of rheological theory in engineering practice to address practical transport challenges.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SL: Funding acquisition, Resources, Writing – review and editing. JY: Investigation, Software, Writing – review and editing. MW: Supervision, Writing – review and editing. JP: Supervision, Writing – review and editing. JY: Writing – review and editing. YZ: Writing – review and editing. CP: Writing – review and editing. DZ: Writing – review and editing. MY: Data curation, Project administration, Writing – original draft, Writing – review and editing.

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Conflict of interest

Authors SL, JY, MW, JP, and MY were employed by Yunnan Phosphate Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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