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# Optimization of Tailings Paste Preparation for Deep-Cone Thickeners Prone to Rake Blockage: From Particle Classification to Tailings Reconstitution

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**Abstract**

To address the high risk of rake blockage in deep-cone thickeners and the difficulty in optimizing backfill performance during paste preparation from full tailings, a paste preparation method based on particle classification, tailings dewatering, and secondary remixing and reconstruction was proposed. Sedimentation thickening tests, flowability tests, and strength tests were conducted to systematically investigate the dewatering characteristics of tailings, the flowability of backfill slurry, and the strength development of backfill. The results showed that flocculation sedimentation significantly improved the thickening efficiency of fine tailings. With increasing coarse-tailings proportion, the flowability of the slurry was enhanced, and the allowable transportable solids concentration gradually increased. The strength of the backfill was jointly affected by tailings gradation, solids concentration, and binder-to-tailings ratio, among which the binder-to-tailings ratio was the dominant factor, while an optimum tailings gradation existed. Based on the experimental results, a paste backfilling process suitable for the target mine was proposed. By separating the coarse fraction from the deep-cone thickening stage and subsequently remixing it with the thickened fine tailings, the proposed process provides a process-level basis for reducing the potential risk of rake blockage while maintaining satisfactory backfill performance. The findings provide a reference for the design of paste backfilling systems in mines utilizing full tailings.

**Keywords:** full tailings; paste backfilling; particle classification; flowability; backfill strength

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## 1. Introduction

Tailings backfill has been widely applied in both underground and open-pit mines in recent years as an important approach for the resource utilization of mine solid waste and the maintenance of stope stability [1–4]. Although conventional slurry backfill can provide stope support to a certain extent, its relatively low solids concentration makes it susceptible to sedimentation and segregation, resulting in unstable backfill strength and limited backfilling efficiency [5–9]. Such instability not only compromises stope safety but also restricts the adoption of high-efficiency mining methods, such as underhand cut-and-fill mining. Owing to its high solids concentration, low sedimentation rate, and superior mechanical performance, paste backfill can significantly improve backfill quality

and enhance the long-term stability of backfilled stopes, while also supporting safer and more efficient mining operations. Consequently, paste backfill has gradually become a preferred backfilling technology in modern mining practice [10–17].

However, the preparation of paste backfill from tailings with a wide particle size distribution and a high proportion of coarse particles remains technically challenging. In deep-cone thickeners, coarse particles tend to accumulate in the rake zone, leading to rake blockage. Once rake blockage occurs, the thickener must be shut down for cleaning and maintenance, which not only increases operational complexity and maintenance costs but also disrupts the continuity and efficiency of backfill production [18,19]. In addition, the complex particle composition of tailings gives rise to nonlinear rheological behavior, further increasing the difficulty of preparing high-concentration paste. Although extensive studies have been conducted on paste rheology, thickener parameter optimization, and pipeline transport stability, systematic investigations focusing on the coordinated treatment of coarse and fine particles, mitigation of rake blockage in deep-cone thickeners, and simultaneous improvement of paste mechanical performance remain limited.

To address these challenges, a paste preparation strategy based on particle classification, tailings dewatering, and reconstitution is proposed in this study. Specifically, the tailings are first classified into coarse and fine fractions. The fine tailings are concentrated in a deep-cone thickener to produce a high-density tailings slurry, whereas the coarse tailings are dewatered using a high-frequency vibrating screen to obtain a filter cake with an appropriate moisture content. Subsequently, the dewatered coarse tailings are mixed with the thickened fine-tailings slurry at a designed proportion in a mixing tank to achieve paste reconstitution. Unlike previous studies that mainly focus on individual aspects such as thickening optimization, slurry rheology, or particle-size regulation, the present study integrates particle classification, differentiated dewatering, and subsequent gradation reconstruction into a coordinated paste preparation route. More importantly, the effects of the reconstructed coarse-to-fine tailings ratio on slurry flowability and backfill strength are systematically evaluated, thereby clarifying the relationship between particle-size reconstruction and backfill performance. This integrated strategy reduces the exposure of coarse particles to the rake zone of the deep-cone thickener and thereby provides a process-level basis for potentially lowering the risk of rake blockage, while simultaneously balancing slurry transportability and backfill strength.

## 2. Materials and Basic Physicochemical Properties of Tailings

### *2.1. Study Site*

A gold mine located in Shandong Province, China, was selected as the engineering case for this study. With the continuous increase in mining depth, the in-situ stress environment within the stopes has become increasingly complex, imposing higher requirements on the overall stability and load-bearing capacity of backfill bodies [20–22]. High-quality backfilling has become an essential technical measure for ensuring safe and efficient extraction under deep mining conditions, and its performance directly affects mining efficiency, operational safety, and economic benefits. Therefore, a systematic evaluation and upgrading of the existing backfill process are necessary to meet the increasingly stringent requirements for backfill quality in deep mining operations.

At present, the mine mainly employs the upward horizontal cut-and-fill mining method and the overhand drift-and-fill mining method [23]. Under the current mining system, the backfill body primarily serves as a working platform for equipment and personnel during ore extraction. Except for localized surface capping layers placed at the top of the fill, the overall mechanical performance requirements of the backfill body are relatively moderate. However, the mine plans to gradually transition to sublevel cut-

and-fill mining in the future. Under this mining method, the backfill body will directly function as an integral part of the stope roof and the sidewalls of adjacent stopes, making its stability and uniformity critical to mining safety. Consequently, the change in mining method requires the backfill body to possess higher and more stable mechanical properties, posing new technical challenges for backfill material preparation.

Currently, the mine adopts a process in which full tailings are directly used to prepare high-concentration backfill slurry. Full tailings produced by the concentrator are discharged without particle classification and sent directly to a sand silo for gravity settling and dewatering. After preliminary dewatering, the tailings are mixed with binder and make-up water in a vertical mixer to produce backfill slurry, which is subsequently pumped through pipelines to underground stopes for backfilling. The existing backfill process used at the mine is illustrated in Figure 1.

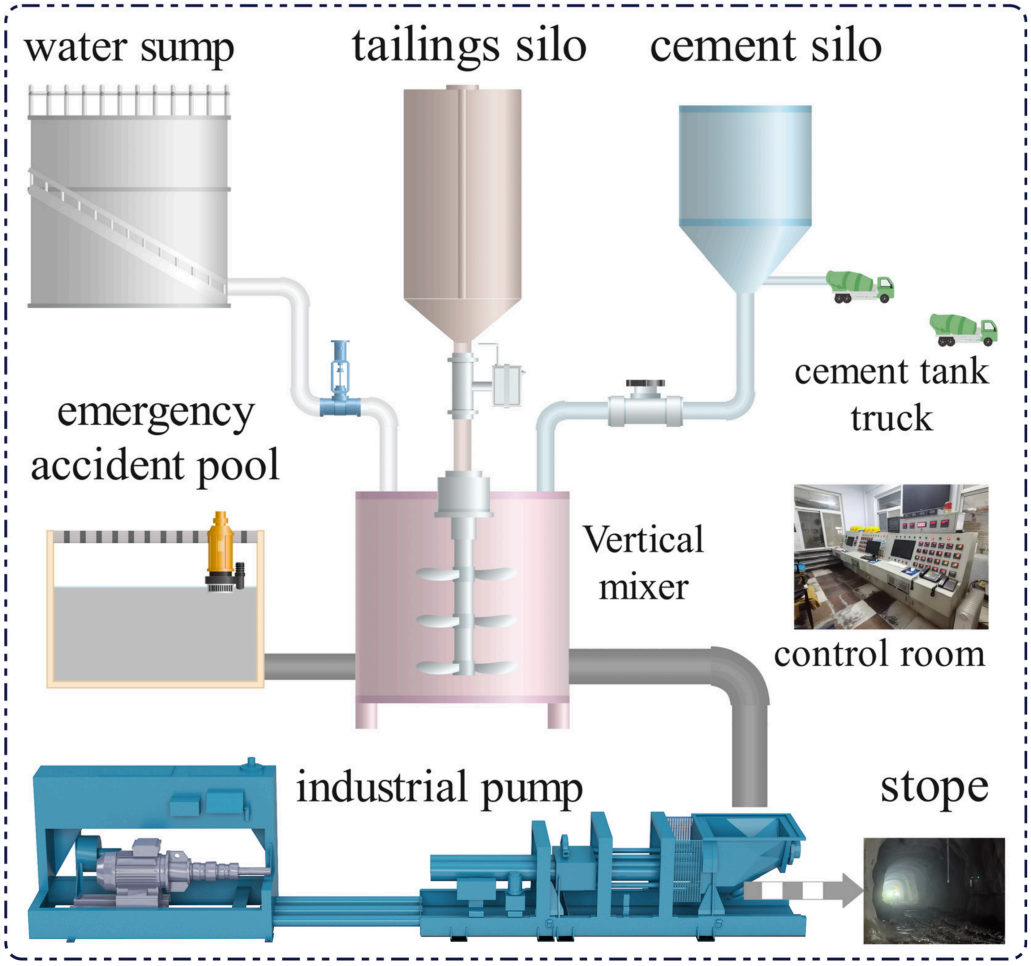



**Figure 1.** Schematic diagram of the existing backfill process at the gold mine.

Under the aforementioned process conditions, the current backfill system exhibits deficiencies in slurry stability and structural uniformity of the backfill body due to the particle size distribution of full tailings and the limitations of the dewatering process. As a result, it is difficult to reliably satisfy the requirements for the backfill body to function as a load-bearing structure for stope roofs and surrounding rock masses. This limitation, to some extent, hinders the transition toward safer and more efficient mining methods. Therefore, it is necessary to systematically investigate and optimize the backfill materials and process parameters based on the fundamental characteristics of the tailings.

### 2.2. Basic Physicochemical Characterization of Tailings

To investigate the influence of particle size composition on dewatering behavior and slurry structural characteristics, comparative physicochemical characterization was conducted on full tailings, classified fine tailings, and classified coarse tailings. The obtained results provide a basis for the subsequent investigation of settling performance, rheological behavior, and mechanical properties.

Full tailings were collected from the concentrator under normal operating conditions. The classified fine tailings and classified coarse tailings were directly collected from the fine- and coarse-fraction products of the industrial hydrocyclone classification system at the mine. Therefore, no additional laboratory classification was performed before testing. Based on the measured particle size distributions, 74 μm (200 mesh) was adopted as a nominal reference size for characterizing the separation between the fine- and coarse-dominated fractions. It should be noted that hydrocyclone classification does not provide a sharp particle-size cut, and a small proportion of particles finer than 74 μm therefore remained in the classified coarse tailings. To ensure the comparability of different tailings samples, all materials were subjected to the same pretreatment procedure. The as-received wet tailings were naturally dried to a constant mass, followed by the removal of occasional coarse impurities and thorough homogenization [24,25]. Representative samples for testing were subsequently obtained using the quartering method.

The measured specific gravity of the full tailings was 2.592 g/cm$^3$. The classified fine tailings exhibited a bulk density of 0.971 g/cm$^3$, corresponding to a porosity of 63.32%, whereas the classified coarse tailings showed a bulk density of 1.423 g/cm$^3$ and a porosity of 48.17%.

#### 2.2.1. Particle Size Distribution Test

To characterize the differences in particle composition and gradation among different tailings fractions, particle size distribution (PSD) analyses were conducted on full tailings, classified fine tailings, and classified coarse tailings.

Given the relatively high proportion of coarse particles in the tailings, direct laser particle size analysis could lead to particle settling during measurement, thereby affecting the accuracy of the results. Therefore, different testing methods were adopted according to the particle size range.

For the full tailings, a combined testing approach was employed. Particles coarser than 200 mesh were analyzed by wet sieving, whereas particles finer than 200 mesh were measured using laser particle size analysis. The PSD of the classified fine tailings was determined by laser particle size analysis, while that of the classified coarse tailings was determined by wet sieving. Each particle size measurement was performed three times using representative subsamples, and the reported particle size distributions represent the arithmetic mean of the three measurements. The corresponding results are presented in Figure 2 and Table 1.

The PSD results indicate that the full tailings contain a relatively high proportion of fine particles, with particles smaller than 74 μm and 37 μm accounting for 41.65% and 35.55%, respectively. Overall, the full tailings exhibit a non-uniform particle size distribution characterized by the simultaneous enrichment of coarse and fine fractions and a relative deficiency of intermediate-sized particles. Such a bimodal gradation structure is prone to inducing slurry segregation and particle settling during slurry preparation [26,27].

Following hydrocyclone classification, the proportion of fine particles in the classified fine tailings increased markedly. Particles smaller than 74 μm and 37 μm accounted for 71.33% and 64.43%, respectively. In contrast, the particle sizes of the classified coarse tailings were predominantly distributed within the range of 0.25–1.0 mm, exhibiting a

relatively concentrated size distribution. These results demonstrate that the classification process effectively modified the particle size composition of the tailings and achieved a satisfactory separation efficiency.

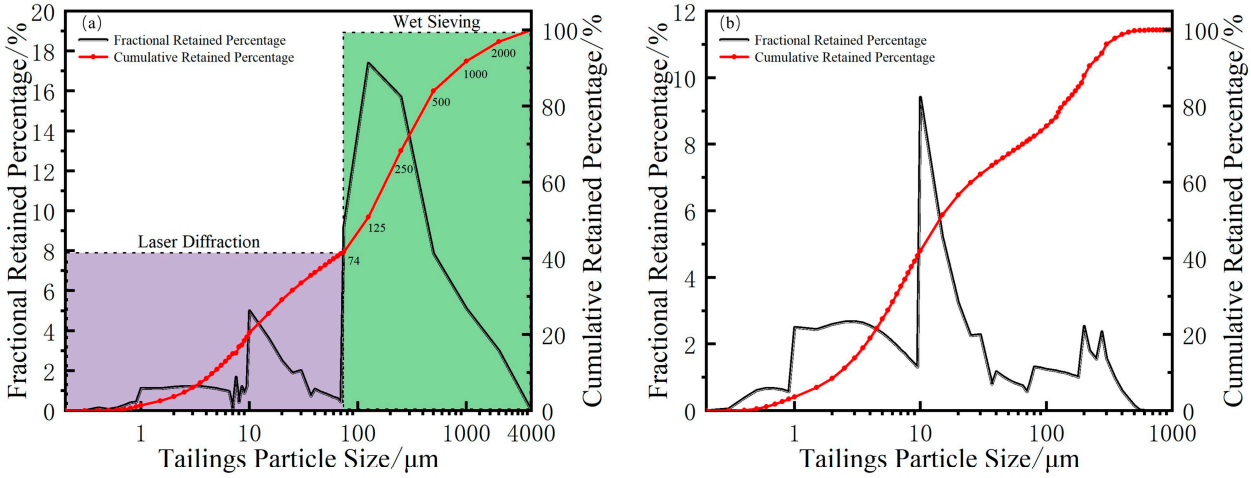



**Figure 2.** Particle size distribution curves of the tailings: (**a**) full tailings; (**b**) classified fine tailings.

**Table 1.** Particle size distribution results of classified coarse tailings.

| **Particle size/mm** | >2 | 1~2 | 0.5~1.0 | 0.25~0.5 | 0.125~0.25 | 0.074~0.125 | <0.074 |
|---|---|---|---|---|---|---|---|
| **Percentage/%** | 0.26 | 1.31 | 24.18 | 53.41 | 13.23 | 2.4 | 5.21 |

The distinct gradation characteristics of the three tailings fractions provide an important basis for the subsequent investigation of dewatering behavior, slurry flowability, and backfill performance.

### 2.2.2. Chemical Composition Analysis

To characterize the chemical composition of the tailings and evaluate their suitability for backfill applications, chemical composition analysis was conducted on the tailings samples. Quantitative determination of the major elemental constituents provides essential information for assessing the compatibility of cementitious binders, evaluating the mechanical performance of backfill materials, and discussing potential environmental implications. The elemental composition of the tailings was determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) [28,29]. The analytical results are presented in Table 2.

**Table 2.** Chemical composition of the tailings.

| **Chemical Elements** | **Testing Result/%** | **Chemical Elements** | **Testing Result/%** |
|---|---|---|---|
| Ca | 0.96 | P | 0.019 |
| Si | 36.24 | K | 3.59 |
| Al | 6.78 | Na | 0.41 |
| Fe | 1.91 | S | 0.27 |
| Ti | 0.059 | / | / |

The chemical composition analysis indicates that the tailings are primarily composed of Si, Al, and Ca, which is consistent with the chemical characteristics commonly observed in metal mine tailings. No abnormal enrichment of potentially harmful elements was

identified in the tested samples, indicating that the tailings meet the fundamental chemical requirements for application as aggregate material in paste backfill systems.

## 3. Sedimentation Tests of Tailings

The sedimentation and thickening process is a critical stage in paste backfill systems, as its dewatering performance directly determines the underflow concentration and influences the operating conditions of the backfill system. Insufficient sedimentation efficiency not only limits the achievable solids concentration of the backfill slurry but also adversely affects the stability of subsequent pipeline transportation and backfilling operations. As demonstrated by the particle size distribution analysis, the full tailings from the studied mine exhibit a wide particle size distribution with a relatively high proportion of coarse particles. These particle-size characteristics may increase the potential for rake resistance and blockage if the full tailings are directly treated in a deep-cone thickener. Accordingly, the sedimentation and dewatering experiments in this study were conducted exclusively on the classified fine tailings.

To evaluate the feasibility of applying high-efficiency thickening technology to the classified fine tailings and to establish appropriate operating parameters, a series of experiments was carried out following a progressive approach from static to dynamic conditions. Specifically, natural sedimentation tests, flocculation sedimentation tests, and process parameter optimization tests were conducted sequentially to systematically investigate the sedimentation behavior of the classified fine tailings under different operating conditions (Figure 3).

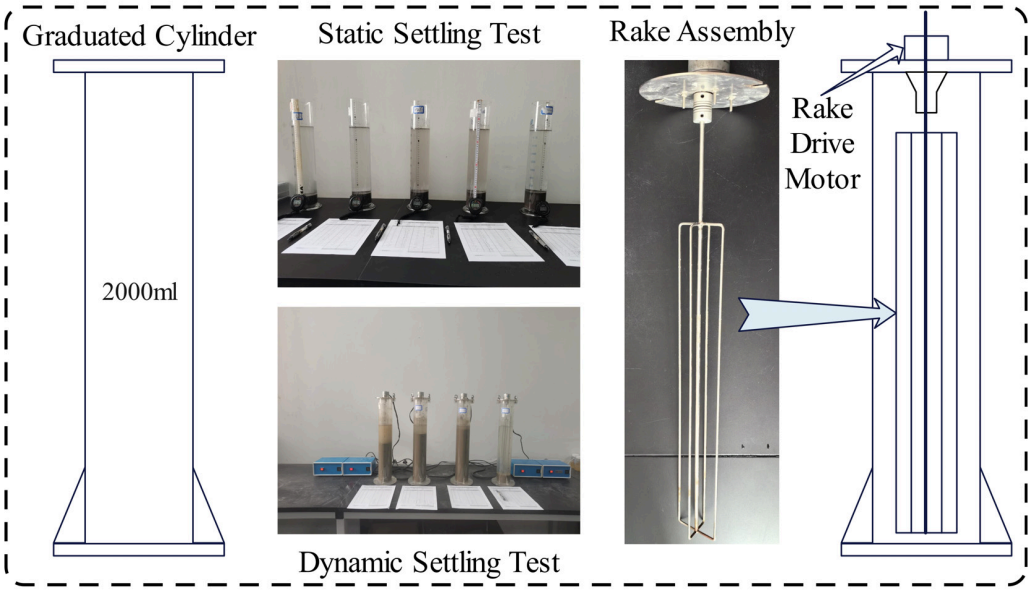



**Figure 3.** Sedimentation tests of tailings.

### 3.1. Natural Sedimentation Test

To characterize the fundamental sedimentation behavior of the classified fine tailings in the absence of flocculants and to provide a reference for the subsequent flocculation sedimentation and process parameter optimization tests, natural sedimentation tests were conducted. Classified fine tailings slurries with predetermined initial solids concentrations were first thoroughly mixed and then allowed to settle under static conditions. The variation in the solid–liquid interface height was continuously recorded over time to analyze the sedimentation rate and the formation of the clarified zone during the natural sedimentation

process. The initial solids concentrations of the classified fine tailings slurry were set at 26 wt%, 28 wt%, and 30 wt%, respectively.

The experimental results indicate that, in the absence of flocculants, the classified fine tailings exhibited a relatively low sedimentation rate, with the solid–liquid interface descending slowly throughout the sedimentation process. Sedimentation was governed primarily by gravitational settling of individual particles, making it difficult to achieve effective thickening within a practical time frame (Figure 4). As the settling time increased, the clarified zone developed gradually, while the increase in underflow solids concentration remained limited. After 150 min of settling, the maximum underflow solids concentration reached only 58 wt%, which was insufficient to meet the requirements of high-concentration paste backfill preparation.

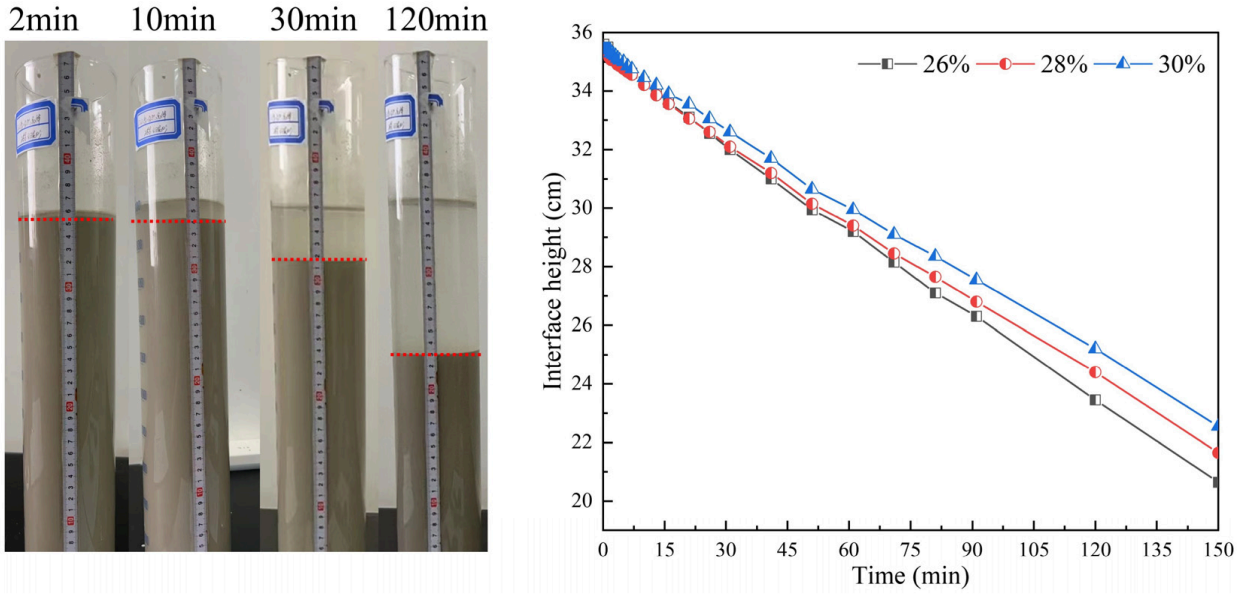



**Figure 4.** Natural sedimentation test of classified fine tailings.

The results of the natural sedimentation tests provide a baseline for the subsequent flocculation sedimentation and process parameter optimization experiments. They also demonstrate that natural sedimentation alone is inadequate for achieving efficient thickening of the classified fine tailings, highlighting the necessity of introducing flocculants to improve the dewatering performance.

### *3.2. Flocculant Selection Test*

Given the limited dewatering efficiency of classified fine tailings under natural sedimentation conditions, the introduction of flocculants is necessary to enhance sedimentation and achieve efficient thickening. Because different flocculants vary in molecular structure, flocculation mechanism, and floc formation characteristics, their effectiveness in improving tailings sedimentation may differ significantly. Therefore, a flocculant selection test was conducted under identical operating conditions.

In this test, classified fine tailings were used as the experimental material, and comparative static flocculation–sedimentation tests were carried out at a constant feed concentration. Ten commercially available flocculants supplied by SNF and other manufacturers were selected and denoted as Flocculants A–J for comparative evaluation. Before each test, the powdered flocculants were separately prepared as aqueous stock solutions at a concentration of 0.5 g/L. The flocculant and water were continuously mixed using a magnetic stirrer for approximately 24 h until the flocculant was completely dissolved.

To minimize the influence of other process variables, the feed solids concentration of the classified fine tailings was fixed at 12 wt%, and the flocculant dosage was maintained at 25 g/t on a dry-tailings mass basis. Static flocculation–sedimentation tests were conducted in 2000 mL graduated cylinders. Under these conditions, 10 different flocculant types were evaluated to comprehensively compare their sedimentation enhancement performance.

The experimental results show that flocculation significantly promoted the aggregation of fine tailings particles into larger flocs during the free-settling stage, resulting in a rapid downward movement of the solid–liquid interface in the initial stage of sedimentation (Figure 5). This accelerated settling period was relatively short, generally lasting less than 5 min, indicating the pronounced enhancement of the initial settling process by the flocculants. As sedimentation proceeded, the tailings slurry gradually entered the compression settling stage, during which the particle network continuously rearranged and became more compact. Consequently, the settling height decreased at a progressively lower rate until a stable state was reached.

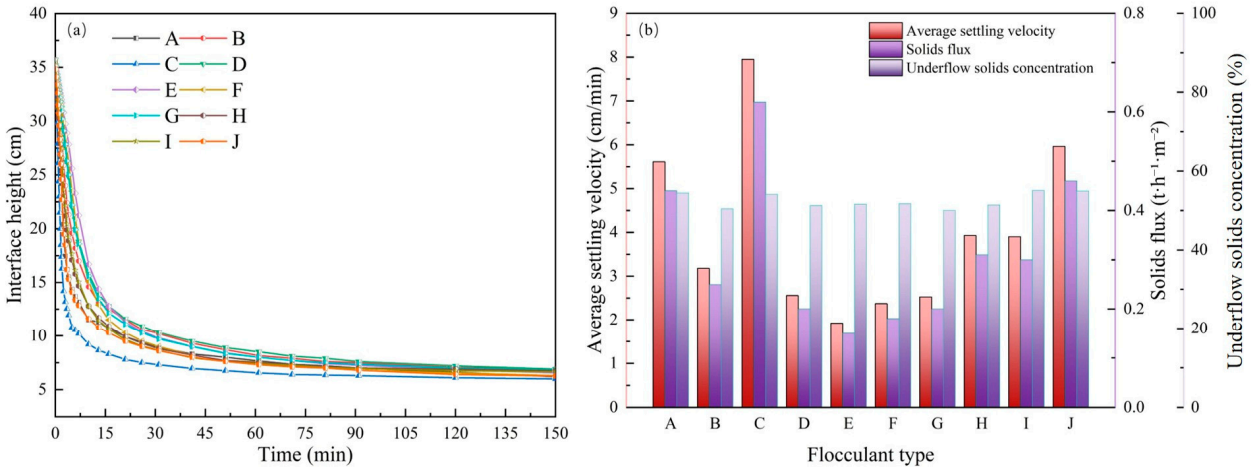



**Figure 5.** Flocculant selection sedimentation tests: (**a**) the relationship between interface height and the time; (**b**) Influence of flocculant type on the average setting velocity, solids flux and underflow solids concentration.

A comprehensive evaluation of the flocculants was performed based on the average settling velocity, solids flux, and underflow solids concentration. The results indicate that Flocculant C exhibited the best overall performance across all evaluation criteria and was therefore selected as the recommended flocculant for the subsequent process parameter optimization and dynamic sedimentation tests.

### *3.3. Optimization of Flocculant Dosage*

Based on the results of the flocculant selection test, Flocculant C was selected for further dosage optimization to investigate the effect of flocculant dosage on the sedimentation behavior of the classified fine tailings. The feed solids concentration was maintained at 12 wt%, while the flocculant dosage, based on the dry mass of the tailings, was set at 20, 25, 30, 35, and 40 g/t, respectively.

During the experiments, the prepared tailings slurry was thoroughly mixed before the corresponding amount of 0.5 g/L flocculant stock solution was added. After flocculant addition, the slurry and flocculant solution were mixed sufficiently to ensure uniform dispersion and facilitate floc formation. The resulting slurry was then transferred to a 2000 mL graduated cylinder and allowed to settle under static conditions. Flocculation performance at different dosages was evaluated by observing the characteristics of floc formation, the clarity of the supernatant, and the evolution of the solid–liquid interface.

The variation in solid–liquid interface height was continuously recorded throughout the settling process to obtain the settling curves. Combined with the average settling velocity, solids flux, and underflow solids concentration, these results were used to comprehensively evaluate the effect of flocculant dosage on sedimentation enhancement.

The experimental results indicate that the settling velocity, solids flux, and underflow solids concentration of the classified fine tailings initially increased and then decreased with increasing flocculant dosage (Figure 6). The optimum performance was achieved at a dosage of 30 g/t, where particle flocculation was most effective, producing stable flocs with excellent settling characteristics. Under this condition, the settling velocity, solids flux, and underflow solids concentration all reached their maximum values, while the supernatant exhibited the highest clarity. Considering both the sedimentation performance and reagent consumption, 30 g/t was identified as the optimal flocculant dosage for the classified fine tailings. This dosage was therefore adopted in the subsequent feed concentration optimization and dynamic sedimentation tests.

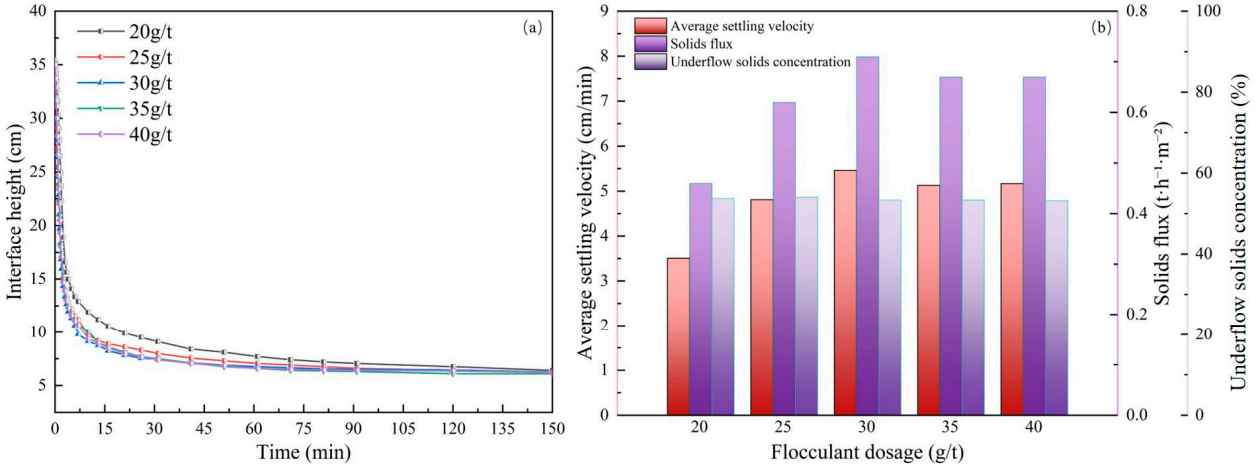



**Figure 6.** Flocculant dosage optimization tests: (**a**) the relationship between interface height and the time; (**b**) Influence of flocculant dosage on the average setting velocity, solids flux and underflow solids concentration.

### *3.4. Optimization of Feed Solids Concentration*

After determining the flocculant type and the optimal dosage, the feed solids concentration was further optimized, as it is another key process parameter affecting the settling efficiency and thickening performance of the classified fine tailings. A low feed solids concentration reduces thickening efficiency, whereas an excessively high concentration may adversely affect flocculation and settling performance. Therefore, an appropriate feed solids concentration was determined through experimental investigation.

The experiments were conducted using the optimal flocculant dosage of 30 g/t, with feed solids concentrations of 8, 10, 12, 14, and 16 wt%. The same 0.5 g/L flocculant stock solution preparation procedure and 2000 mL graduated-cylinder settling method described above were adopted. Static flocculation settling tests were performed under each condition. During the tests, the characteristics of floc formation and the clarity of the supernatant were observed, while the variation in the solid–liquid interface height was continuously recorded to obtain the settling curves. The settling behavior under different feed solids concentrations was evaluated based on the settling velocity, solids flux, and underflow solids concentration, and the optimum feed solids concentration for the classified fine tailings was determined.

The experimental results indicate that the settling behavior of the classified fine tailings varied significantly with the feed solids concentration. As the feed solids concentration

increased, the average settling velocity gradually decreased from 9.24 cm/min at a feed solids concentration of 8 wt% to 2.74 cm/min at 16 wt% (Figure 7). This phenomenon can be attributed to the weaker particle interference at low feed solids concentrations, which facilitates the formation of stable flocs through the interaction between the flocculant and fine particles. The resulting flocs experience lower settling resistance and therefore settle more rapidly. During the experiments, a distinct clarification zone developed rapidly, accompanied by a clear downward movement of the solid–liquid interface.

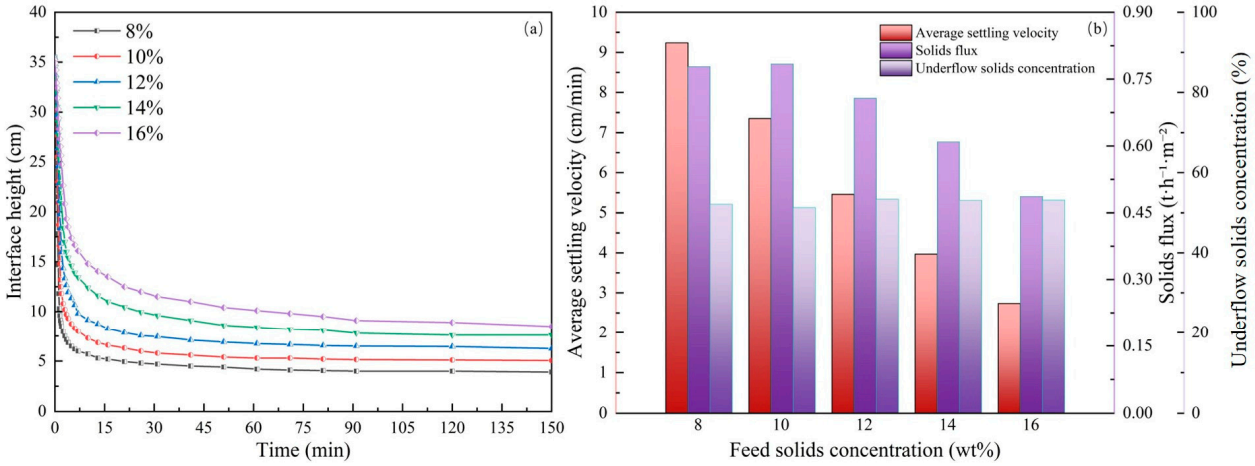



**Figure 7.** Feed solids concentration optimization tests: (**a**) the relationship between interface height and the time; (**b**) Influence of feed solids concentration on the average setting velocity, solids flux and underflow solids concentration.

However, settling velocity alone cannot comprehensively reflect the thickening efficiency. Although lower feed solids concentrations resulted in faster settling, the amount of solids processed per unit time was relatively low, limiting the overall throughput of the thickening system. Therefore, the solids flux was further adopted to comprehensively evaluate the settling performance under different feed solids concentrations.

The results show that the solids flux remained relatively high when the feed solids concentration ranged from 10 to 12 wt%. Among these conditions, a feed solids concentration of 12 wt% achieved an underflow solids concentration of 53 wt% while maintaining a relatively high solids flux and stable settling performance, resulting in the best overall thickening efficiency. Based on the comprehensive evaluation of the settling velocity, solids flux, and underflow solids concentration, 12 wt% was identified as the optimum feed solids concentration for this tailings system. This result provides a basis for the subsequent dynamic settling tests and the optimization of operating parameters for the deep-cone thickener.

### *3.5. Dynamic Flocculation Settling Tests*

Based on the optimum feed solids concentration of 12 wt% and the optimum flocculant dosage of 30 g/t determined from the static settling tests, dynamic flocculation settling tests were further conducted using a custom-built laboratory dynamic settling apparatus equipped with a motor-driven rake mechanism, as shown in Figure 3. The apparatus was designed to reproduce the continuous mechanical disturbance of the sediment bed by the rake mechanism during deep-cone thickening. During the dynamic settling tests, the rake rotational speed was fixed at 10 r/h, and the rake-drive torque was 2 N·m. The tests were conducted to compare the thickening behavior under static and rake-assisted dynamic conditions and to provide experimental support for the selection of tailings thickening equipment. The same flocculant preparation procedure and optimized flocculation conditions used in the static tests were adopted. During the tests, the underflow

solids concentration was measured at different settling times. The experimental results are summarized in Table 3.

**Table 3.** Results of the dynamic flocculation settling tests.

| No. | Test Type | Settling Time (h) | Underflow Solids Concentration (wt%) |
|---|---|---|---|
| 1 | Static | 24 | 53.38 |
| 2 | Dynamic | 2 | 58.45 |
| 3 | Dynamic | 4 | 60.31 |
| 4 | Dynamic | 8 | 62.35 |
| 5 | Dynamic | 24 | 62.73 |

The experimental results indicate that, under the same operating conditions, the underflow solids concentration obtained under dynamic settling conditions was significantly higher than that achieved under static settling conditions. After 24 h of static settling, the underflow solids concentration reached 53.38 wt%, whereas it increased to 62.73 wt% after 24 h of dynamic settling with a rake mechanism, representing an improvement of approximately 9.35%. This improvement can be attributed to the continuous agitation of the settled flocs by the rake mechanism during operation, which promotes floc restructuring and facilitates the release of entrapped water. As a result, the sediment bed becomes more effectively compressed, leading to a higher underflow solids concentration. This interpretation is consistent with previous studies showing that shear-induced floc restructuring can alter the compression and dewatering behavior of tailings beds.

A comprehensive comparison of the static and dynamic settling results demonstrates that, under the optimum feed solids concentration and flocculant dosage, dynamic settling significantly enhances the thickening performance of the classified fine tailings and is more effective in producing a high underflow solids concentration. Therefore, from the perspective of thickening performance, high-efficiency thickening equipment equipped with a rake mechanism is more suitable for engineering applications [30–32].

## 4. Flowability Tests

Based on the optimum feed solids concentration and flocculant dosage determined from the tailings settling and thickening tests, the flowability of the backfill slurry was further investigated to evaluate the engineering applicability of the tailings for paste backfill. The flowability of backfill slurry is a key factor affecting the stability of pipeline transportation and the continuity of backfilling operations. It is governed not only by the slurry solids concentration but also by the particle size distribution of the tailings and the binder content.

Following the particle size regulation strategy proposed in this study, classified fine tailings obtained from the deep-cone thickener and classified coarse tailings dewatered using a high-frequency vibrating screen were used as the raw materials for backfill preparation. The two fractions were remixed at different mass ratios to optimize the particle size distribution, followed by the addition of a prescribed amount of binder and mixing water to prepare the backfill slurry. Slump flow tests and rheological tests were subsequently conducted to investigate the variation in the flow characteristics of the backfill slurry under different particle gradations, providing a basis for subsequent mix proportion optimization and strength evaluation.

### *4.1. Slump Flow Tests*

To evaluate the macroscopic flowability of the backfill slurry under different tailings particle size distributions and mix proportions, slump flow tests were conducted. Different slurry solids concentrations and binder-to-tailings ratios were adopted to investigate their effects on slurry flowability. The mass ratio of classified coarse tailings to classified fine tailings was set at 3:7, 4:6, 5:5, 6:4, and 7:3, while the binder-to-tailings ratio was set at 1:4, 1:7, and 1:10. Considering that increasing the proportion of classified coarse tailings generally improves slurry flowability, preliminary exploratory tests were first conducted to determine an appropriate solids-concentration range for each gradation. Accordingly, the investigated concentration range was progressively shifted upward with increasing coarse-tailings proportion so that the variation in flowability could be effectively characterized for each gradation. Therefore, identical solids-concentration levels were not imposed across all coarse-to-fine tailings ratios.

The slump flow tests were performed in accordance with the standard testing procedure. The freshly prepared backfill slurry was poured into a mold of specified dimensions. After the mold was lifted vertically, the slurry spread freely under its own weight. Once the spreading process stabilized, the maximum spread diameter on the horizontal surface was measured and used to characterize the flowability of the slurry. Two slump flow measurements were performed for each mix proportion, and the arithmetic mean of the two measurements was reported as the representative slump flow value. The experimental results indicate that the slump flow exhibited distinct variations under different tailings particle size distributions and mix proportions. Figures 8 and 9 present the effects of slurry solids concentration and binder-to-tailings ratio, respectively, on the slump flow.

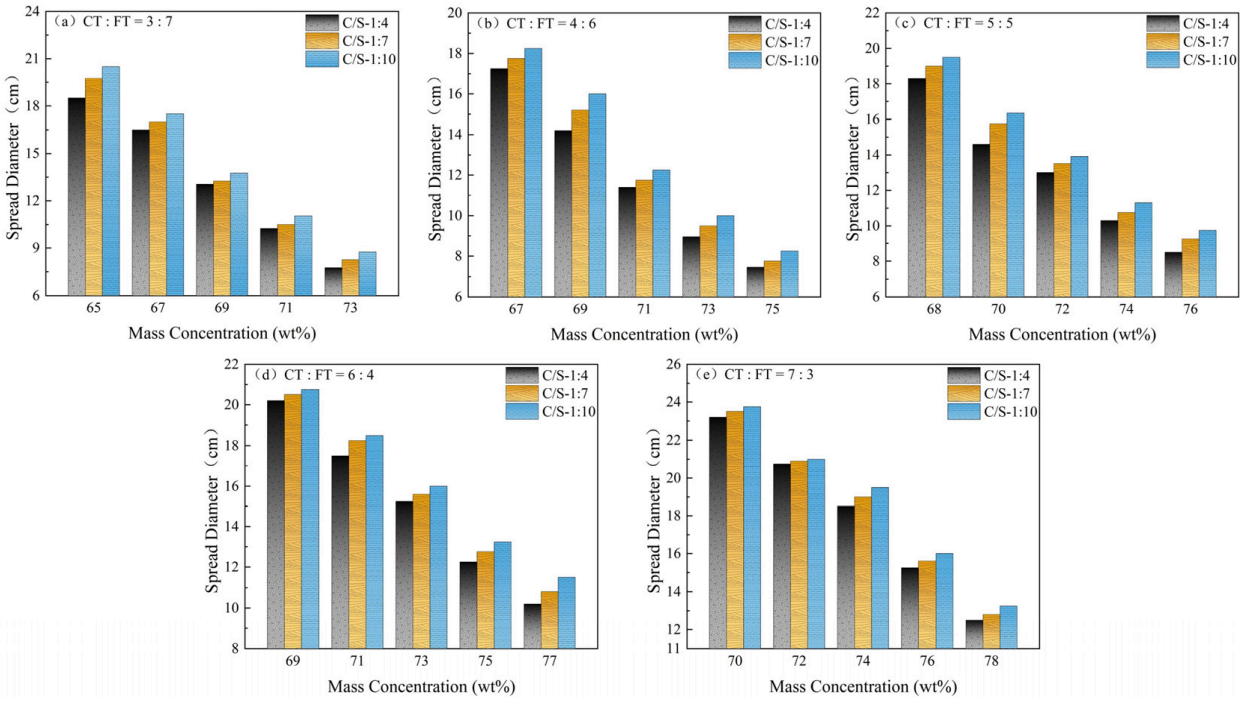



**Figure 8.** Effect of slurry solids concentration on slump flow (CT: classified coarse tailings; FT: classified fine tailings): (**a**) CT:FT = 3:7; (**b**) CT:FT = 4:6; (**c**) CT:FT = 5:5; (**d**) CT:FT = 6:4; (**e**) CT:FT = 7:3.

Under the same tailings particle size distribution and binder-to-tailings ratio, the slump flow decreased markedly with increasing slurry solids concentration (Figure 8). For example, at a classified coarse-to-fine tailings ratio of 3:7 and a binder-to-tailings ratio of 1:4, the slump flow decreased from 18.50 cm at a solids concentration of 65 wt% to 7.75 cm at

73 wt%, representing a substantial reduction. This trend was consistently observed under all particle size distribution conditions [33–35].

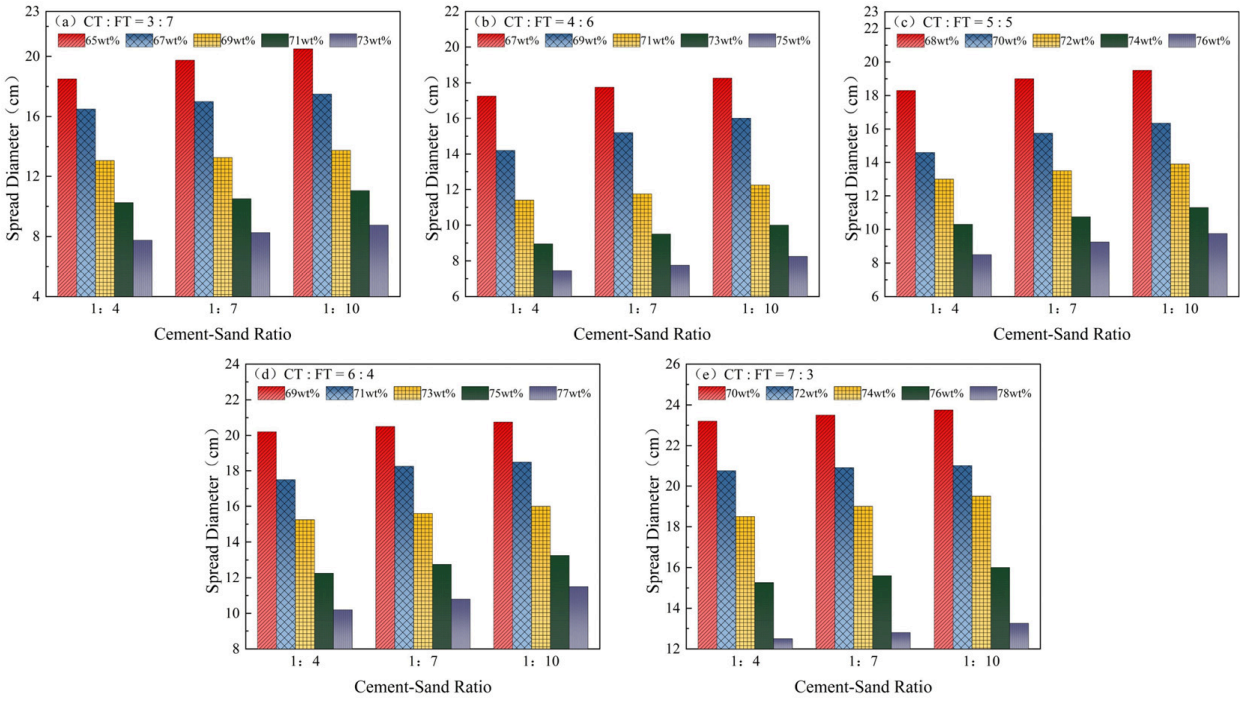



**Figure 9.** Effect of binder-to-tailings ratio on slump flow (CT: classified coarse tailings; FT: classified fine tailings): (**a**) CT:FT = 3:7; (**b**) CT:FT = 4:6; (**c**) CT:FT = 5:5; (**d**) CT:FT = 6:4; (**e**) CT:FT = 7:3.

This behavior can be attributed to the increase in the solid volume fraction with increasing slurry solids concentration, which intensifies interparticle contact and friction while reducing the amount of free water. Consequently, the internal flow resistance of the slurry increases, resulting in reduced flowability.

Under the same tailings particle size distribution and slurry solids concentration, the slump flow generally increased as the binder-to-tailings ratio decreased from 1:4 to 1:10 (Figure 9). For example, at a classified coarse-to-fine tailings ratio of 5:5 and a slurry solids concentration of 70 wt%, the slump flow increased from 14.60 cm at a binder-to-tailings ratio of 1:4 to 16.35 cm at 1:10.

This behavior can be attributed to the high content of fine particles in the binder, which enhances water adsorption and contributes to the formation of a stronger particle network. As the binder content decreases, the cohesiveness of the slurry is reduced, and the encapsulation effect between particles becomes weaker, allowing the slurry to flow more readily [36,37].

A comparison among different particle size distributions further shows that the slump flow increased markedly with increasing proportions of classified coarse tailings. For example, at a binder-to-tailings ratio of 1:4, the slump flow was only 7.75 cm at a classified coarse-to-fine tailings ratio of 3:7 and a slurry solids concentration of 73 wt%. In contrast, when the classified coarse-to-fine tailings ratio increased to 7:3, the slump flow still reached 18.50 cm even at a higher slurry solids concentration of 74 wt%, which was substantially greater than that obtained under fine-particle-dominated conditions. These results indicate that, within the investigated range, the tailings particle size distribution exerted a more pronounced influence on slurry flowability than the other variables.

The significant effect of particle size distribution on slurry flowability can be explained by two main mechanisms. First, increasing the proportion of coarse particles reduces the

specific surface area of the particle system, thereby increasing the amount of free water available for flow. Second, the incorporation of coarse particles weakens the flocculated network predominantly formed by fine particles, reducing interparticle cohesion and resulting in a looser internal structure with lower flow resistance [38,39].

### *4.2. Rheological Tests*

Based on the slump flow tests, rheological tests were further conducted to quantitatively characterize the flow behavior of the backfill slurry. A Brookfield RST-SST soft solids rheometer was used to determine the relationship between shear stress and shear rate, from which the yield stress and plastic viscosity of the slurry were obtained. The mix proportions used in the rheological tests were identical to those adopted in the slump flow tests. The experimental results are presented in Figures 10 and 11.

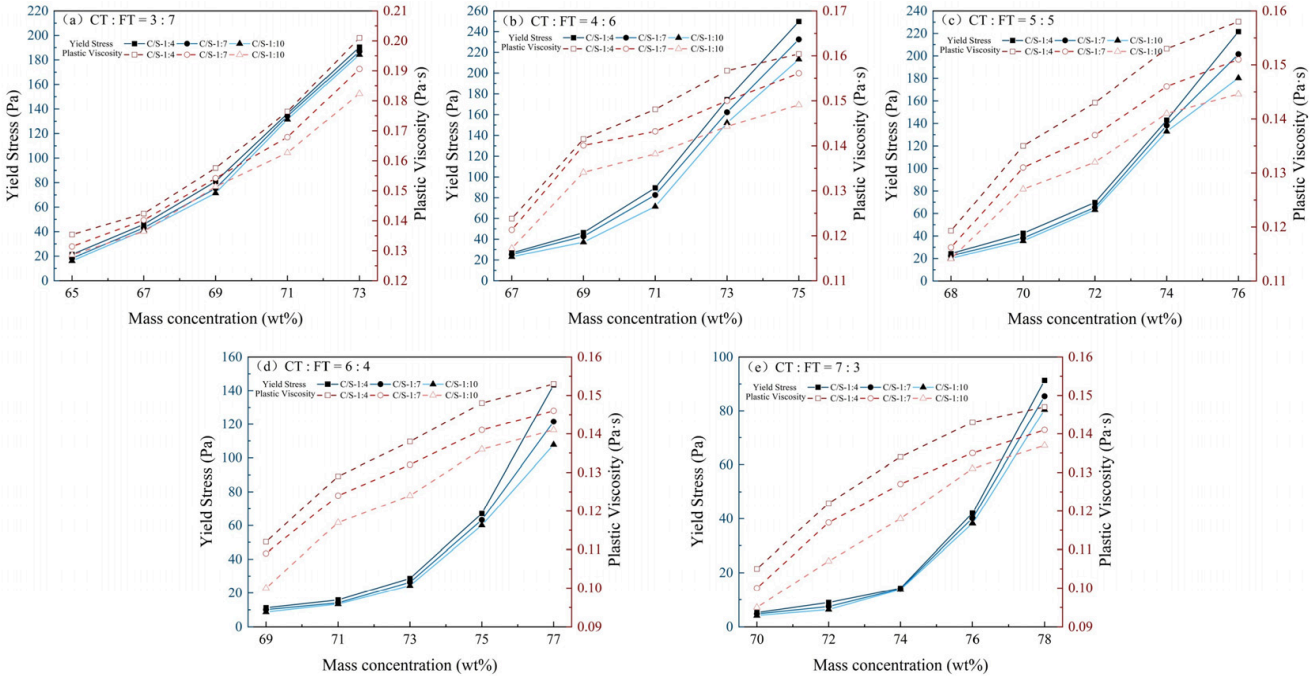



**Figure 10.** Effect of slurry solids concentration on rheological parameters (CT: classified coarse tailings; FT: classified fine tailings): (**a**) CT:FT = 3:7; (**b**) CT:FT = 4:6; (**c**) CT:FT = 5:5; (**d**) CT:FT = 6:4; (**e**) CT:FT = 7:3.

Under the same tailings particle size distribution and binder-to-tailings ratio, both the yield stress and plastic viscosity of the backfill slurry increased significantly with increasing slurry solids concentration (Figure 10). This behavior is mainly attributed to the increase in the solid volume fraction, which enhances interparticle interactions and consequently increases both the structural strength and the flow resistance of the slurry.

Under the same tailings particle size distribution and slurry solids concentration, both the yield stress and plastic viscosity generally decreased with a decreasing binder-to-tailings ratio (i.e., a lower binder content) (Figure 11). This behavior is attributed to the high proportion of fine particles in the binder, which contributes to the development of the slurry structure. As the binder content decreases, the flocculated particle network is weakened, leading to reduced cohesion within the slurry.

Overall, the rheological properties of the backfill slurry were governed primarily by the slurry solids concentration, and the observed rheological trends were consistent with the corresponding changes in slump flow. These findings indicate that the flowability of the slurry is jointly controlled by the slurry solids concentration and the tailings particle

size distribution. Specifically, the slurry solids concentration determines the overall flowability level, whereas the particle size distribution significantly influences the flowability limit by regulating the internal particle structure. This concentration-dependent rheological behavior is consistent with previous studies on high-concentration tailings slurries. The agreement between the slump-flow and rheological results further indicates that the observed macroscopic flowability changes originate from the evolution of interparticle interactions and the internal particle network.

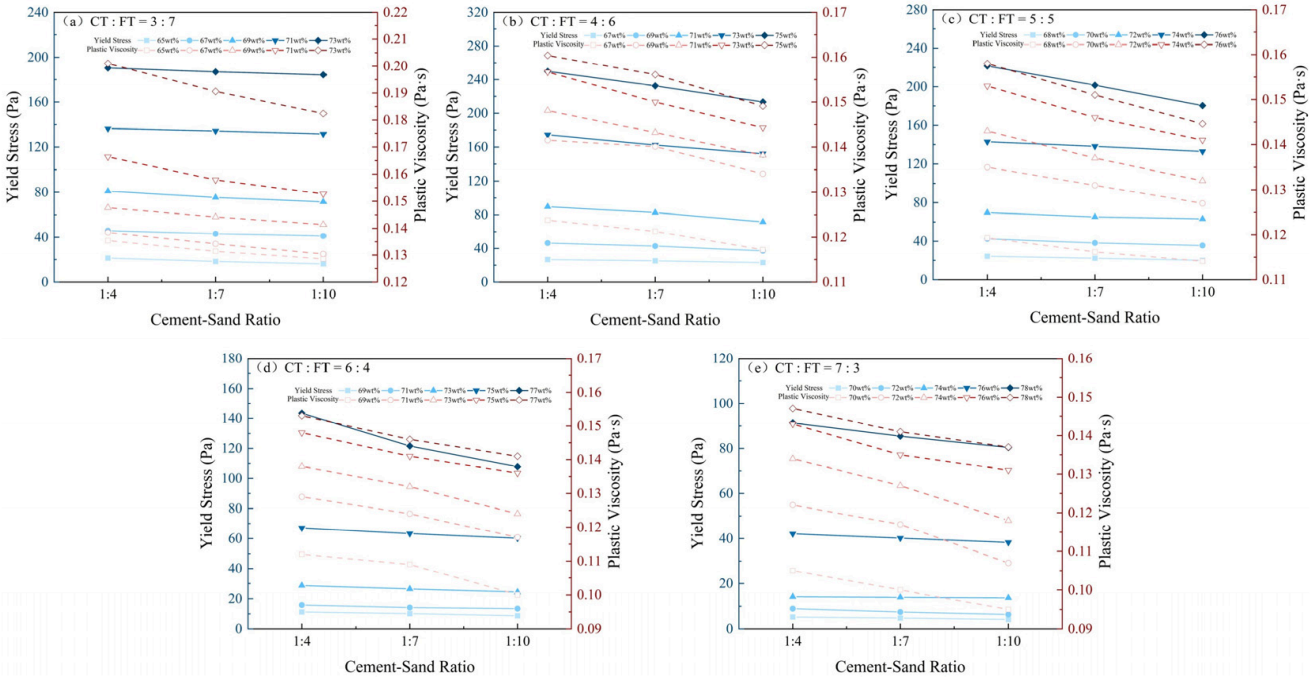



**Figure 11.** Effect of binder-to-tailings ratio on rheological parameters (CT: classified coarse tailings; FT: classified fine tailings): (**a**) CT:FT = 3:7; (**b**) CT:FT = 4:6; (**c**) CT:FT = 5:5; (**d**) CT:FT = 6:4; (**e**) CT:FT = 7:3.

Within the investigated concentration ranges, increasing the proportion of classified coarse tailings enabled the slurry to maintain comparatively better flowability at higher solids concentrations. These results were subsequently used as the basis for selecting the solids-concentration ranges for the strength tests. It should be emphasized that the concentration ranges investigated in this study were selected for comparative mix-proportion optimization rather than being defined as universal pumpability limits. These results indicate that the allowable slurry solids concentration can be progressively increased with increasing proportions of classified coarse tailings while maintaining satisfactory flowability.

On this basis, to achieve a balance between slurry flowability and the mechanical performance of the backfill, mix proportion tests were further conducted under the recommended slurry solids concentration ranges to determine the optimum mix proportion that satisfies both pipeline transportability and backfill performance.

## 5. Mix Proportion Strength Tests

The flowability tests provided a basis for selecting the slurry solids concentration ranges for subsequent strength evaluation under different tailings particle size distributions. To further improve the mechanical performance of the backfill while maintaining adequate transportability, mix proportion strength tests were conducted to systematically investigate the strength development of the backfill under different mix proportions and to determine an optimum mix proportion that balances flowability and mechanical performance. All mix proportions were selected within the recommended slurry solids con-

centration ranges established from the flowability tests to ensure the engineering relevance of the experimental results.

### *5.1. Experimental Method*

The main testing equipment included 70.7 mm × 70.7 mm × 70.7 mm standard cube molds, a laboratory mixer, and a Humboldt HM-5030 loading machine. During specimen preparation, the freshly mixed backfill slurry was cast into the cube molds. Three replicate specimens were prepared for each mix proportion and cured under specified conditions until the designated curing ages, after which uniaxial compressive strength (UCS) tests were performed. The UCS reported for each mix proportion and curing age represents the arithmetic mean of the three replicate specimens. The tests focused on evaluating the effects of the tailings particle size distribution, slurry solids concentration, and binder content on the strength development of the backfill. Combined with the flowability test results, the engineering applicability of different mix proportions was comprehensively evaluated.

### *5.2. Results and Discussion*

The experimental results (Figure 12) demonstrate that the tailings particle size distribution, slurry solids concentration, and binder-to-tailings ratio all exert significant influences on the uniaxial compressive strength (UCS) of the backfill. However, the mechanisms by which these factors affect strength differ, resulting in distinct controlling effects.

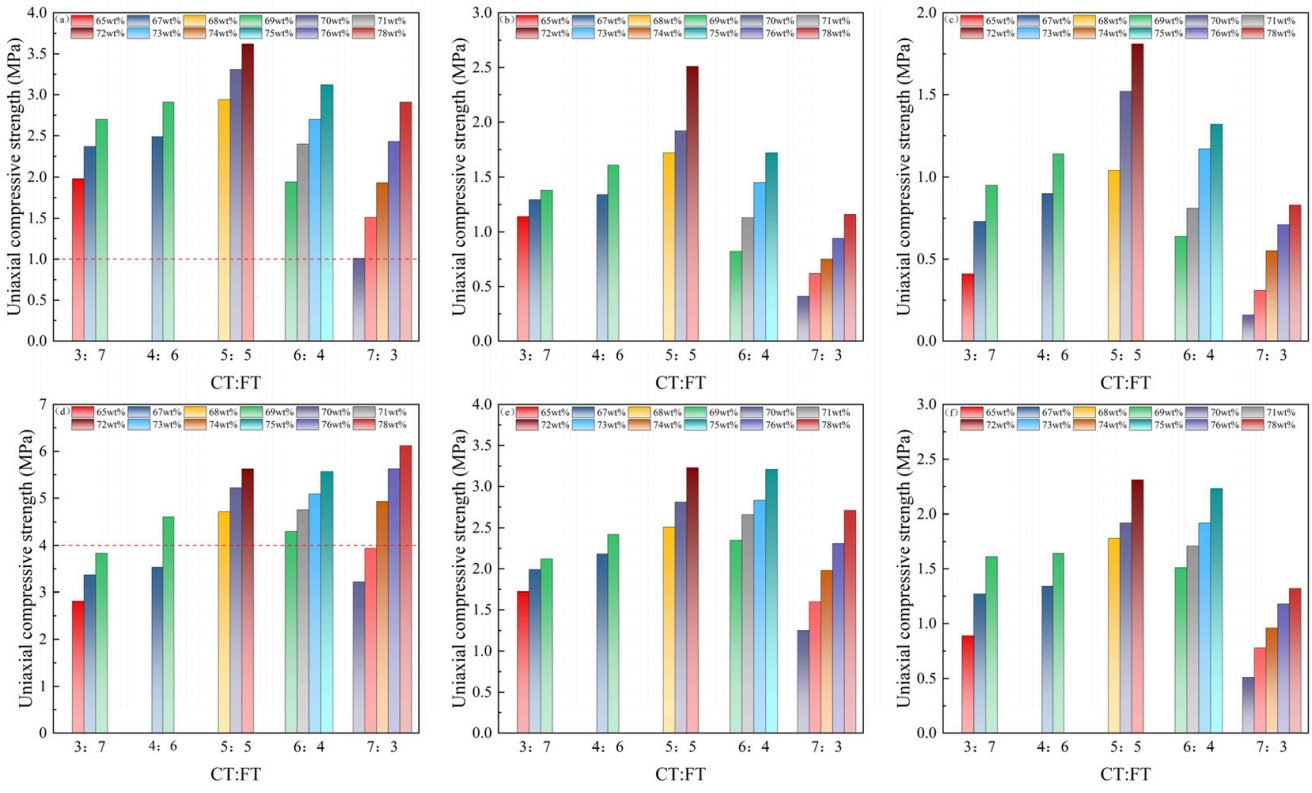



**Figure 12.** Effect of mix proportions on the UCS of the backfill: (**a**–**c**) 3 d UCS at binder-to-tailings ratios of 1:4, 1:7, and 1:10, respectively; (**d**–**f**) 28 d UCS at binder-to-tailings ratios of 1:4, 1:7, and 1:10, respectively.

Under the same tailings particle size distribution and binder-to-tailings ratio, the UCS of the backfill generally increased with increasing slurry solids concentration. For example, at a classified coarse-to-fine tailings ratio of 5:5 and a binder-to-tailings ratio of 1:4, the 28-day UCS increased from 4.71 MPa at a slurry solids concentration of 68 wt% to

5.63 MPa at 72 wt%. This improvement can be attributed to the increase in the solid volume fraction, which enhances particle contact and packing density, thereby promoting strength development [40,41].

Compared with the slurry solids concentration, the binder-to-tailings ratio exerted a more pronounced influence on the UCS. Under the same particle size distribution and slurry solids concentration, the UCS increased substantially as the binder-to-tailings ratio increased from 1:10 to 1:4. For instance, at a classified coarse-to-fine tailings ratio of 5:5 and a slurry solids concentration of 70 wt%, the 28-day UCS increased from 1.92 MPa at a binder-to-tailings ratio of 1:10 to 5.22 MPa at 1:4. These results indicate that the binder content is the primary factor governing the strength of the backfill. This finding contrasts with the flowability tests, in which the slurry solids concentration was identified as the dominant controlling factor. In other words, slurry flowability is governed primarily by the slurry solids concentration, whereas backfill strength is controlled mainly by the binder-to-tailings ratio [42,43].

The effect of the tailings particle size distribution on UCS exhibited a non-monotonic trend. As the proportion of classified coarse tailings increased, the UCS first increased and then decreased, with the highest overall strength achieved at a classified coarse-to-fine tailings ratio of 5:5, indicating that an optimum coarse-to-fine tailings ratio existed under the investigated conditions. When the proportion of coarse tailings increased from a low to a moderate level, the increase in UCS may be associated with a more favorable particle size composition, in which fine particles can fill part of the void space between relatively coarse particles and contribute to the formation of the cemented structure. However, a further increase in the coarse tailings content reduced the amount of fine particles available for void filling and decreased the effective specific surface area participating in cement hydration, thereby limiting further strength development or even causing a reduction in strength [44,45]. Therefore, the observed strength variation can be interpreted as the combined effect of particle size composition and cementation. This result further indicates that increasing the proportion of coarse tailings does not necessarily lead to a continuous increase in backfill strength. An appropriate coarse-to-fine tailings ratio is therefore required, and the ratio of 5:5 provided the highest overall strength under the conditions investigated in this study.

In terms of strength development with curing age, once the proportion of classified coarse tailings exceeded the optimum particle size distribution, further increases in coarse tailings had a more pronounced adverse effect on the 3-day UCS than on the 28-day UCS. This suggests that excessive coarse particles hinder the formation of the early cemented structure, whereas their adverse influence becomes less significant as hydration continues during later curing. In addition, under higher binder contents, the UCS became less sensitive to variations in the particle size distribution, indicating that increasing the binder content can partially compensate for the unfavorable effects associated with changes in particle gradation.

By integrating the results of the flowability and strength tests with the strength requirements of the planned mining method (3-day UCS $\geq$ 1 MPa and 28-day UCS $\geq$ 4 MPa), a classified coarse-to-fine tailings ratio of 5:5 was found to satisfy the engineering requirements over a relatively wide range of operating conditions. Based on the laboratory-scale results, a slurry solids concentration of 68–72 wt% was identified as a suitable range, with 70–72 wt% showing the most favorable overall performance among the tested conditions.

## 6. Proposed Process Scheme

Based on the results of the tailings settling and thickening tests, flowability tests, and mix proportion strength tests, the key controlling factors governing tailings classifi-

cation, dewatering, particle size distribution reconstruction, and paste preparation were systematically identified. The results demonstrate that classified fine tailings can produce a high-concentration underflow after treatment in a deep-cone thickener, whereas the wide particle size distribution and relatively high coarse-particle content of the full tailings indicate a potential for increased rake resistance and blockage when directly treated in the thickener. Furthermore, secondary mixing of classified coarse and fine tailings provides an effective approach for simultaneously optimizing the flowability and mechanical performance of the backfill slurry. Based on these findings, a paste backfill process suitable for the tailings characteristics of the studied gold mine is proposed.

The proposed process is illustrated in Figure 13. Full tailings are first separated into classified coarse tailings and classified fine tailings through hydrocyclone classification. The classified fine tailings are then fed into a deep-cone thickener for flocculation, settling, and dewatering. A Type C flocculant with a dosage of 30 g/t and a feed solids concentration of 12 wt% is adopted to obtain a high-concentration underflow slurry. Meanwhile, the classified coarse tailings are dewatered using a high-frequency vibrating screen to produce a filter cake with an appropriate moisture content. The thickened fine-tailings slurry and the dewatered coarse-tailings filter cake are subsequently delivered to a mixer at a classified coarse-to-fine tailings ratio of 5:5, where binder and supplementary water are added for secondary mixing. Based on the laboratory-scale optimization results, a slurry solids concentration of 70–72 wt% is proposed as the initial target range for subsequent engineering verification. After thorough mixing, the prepared paste slurry is transported through pipelines to the underground stopes for backfilling.

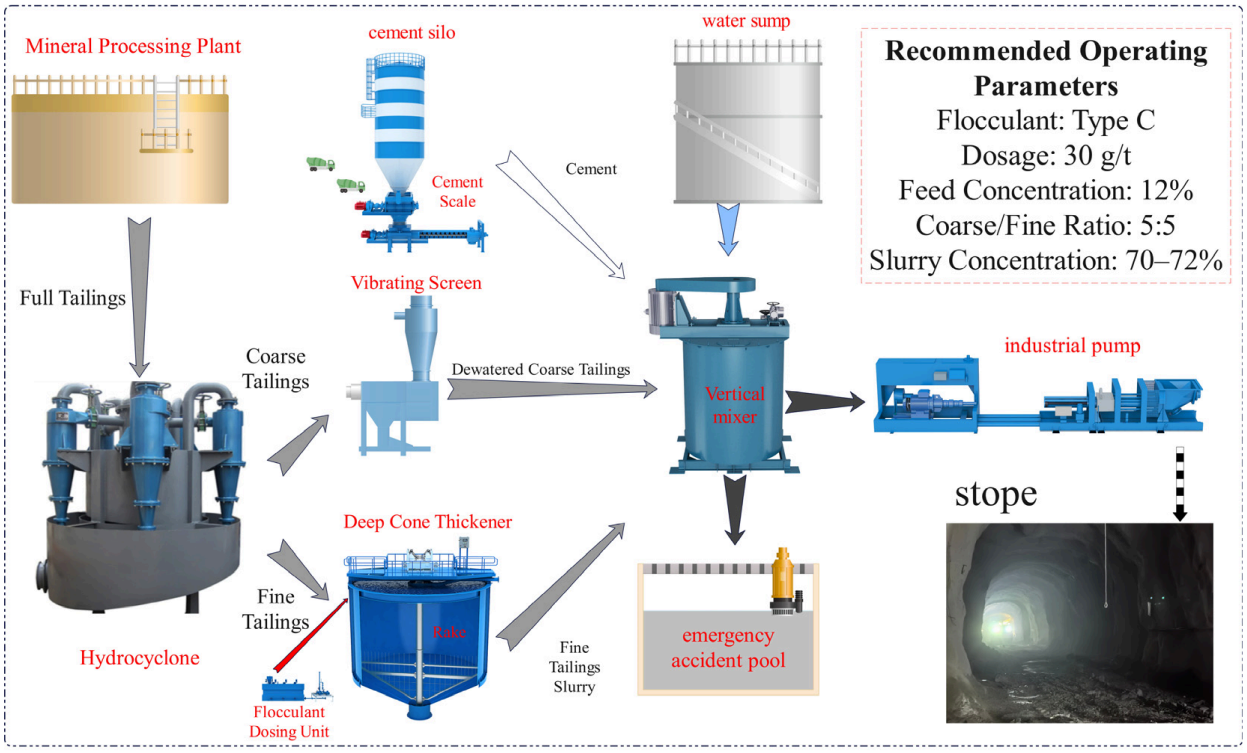



**Figure 13.** Paste backfill process.

The proposed process offers several advantages. First, by separating coarse and fine tailings and treating them independently, coarse particles are prevented from directly entering the rake zone of the deep-cone thickener. This particle-regulation strategy reduces the exposure of the rake mechanism to coarse particles and therefore provides a process-level basis for potentially lowering the risk of rake resistance and blockage. It should

be noted, however, that this inference is based on the particle-size characteristics of the tailings and laboratory material tests rather than direct measurements of rake load, blockage frequency, or long-term thickener operation. Second, the classified fine tailings can be thickened to produce a high-concentration underflow, which is subsequently remixed with the dewatered coarse tailings to reconstruct the particle size distribution. This approach reconstructs the particle size distribution, enabling the prepared backfill slurry to achieve both satisfactory flowability and high mechanical strength. The experimental results demonstrate that, under the recommended operating parameters, the UCS of the backfill satisfies the strength requirements of the planned mining method. Finally, the proposed process makes full use of the intrinsic particle size characteristics of the tailings, thereby promoting efficient tailings utilization and providing a laboratory-scale parameter basis for subsequent process design, equipment selection, and engineering implementation of paste backfill systems at the studied mine.

It should be noted that the proposed scheme represents a process-level strategy rather than a fixed equipment configuration. In industrial applications, the feed flow rate, fluctuations in tailings particle size distribution, and required system throughput should be considered when determining the specifications and capacities of the hydrocyclone, deep-cone thickener, and high-frequency vibrating screen. Variations in feed conditions may also affect classification performance, underflow concentration, and the moisture content of the dewatered coarse tailings. In addition, during continuous industrial preparation and pipeline transport, variations in slurry solids concentration and prolonged mixing and shear history may alter the rheological response and flowability of the paste slurry compared with laboratory-scale conditions.

Overall, the proposed process based on particle classification–tailings dewatering–secondary remixing provides a practical strategy for paste preparation using full tailings with a wide particle size distribution. The findings of this study may serve as a useful reference for optimizing paste backfill processes in mines with similar tailings characteristics. Future work should focus on pilot-scale and industrial-scale validation, including direct monitoring of rake load and blockage occurrence, to further evaluate the long-term operational stability, economic feasibility, and backfill performance of the proposed process under field conditions.

## 7. Conclusions

To address the potential risk of rake blockage in deep-cone thickeners, the difficulty in controlling slurry flowability, and the limited optimization of backfill strength during paste preparation from full tailings with a wide particle size distribution, this study proposed a particle classification–tailings dewatering–secondary remixing strategy. Systematic investigations were conducted on tailings settling and thickening behavior, slurry flowability, and the mechanical performance of the backfill. The main conclusions are as follows:

(1) The tailings are composed primarily of Si, Al, and Ca, indicating that they satisfy the basic requirements for use as backfill aggregate. Considering the wide particle size distribution and high coarse-particle content of the full tailings, classified fine tailings were selected for the settling and thickening investigations. Under natural settling conditions, the settling rate was low, and the underflow concentration was insufficient to satisfy the requirements of high-concentration paste backfill, demonstrating the necessity of flocculation-assisted settling.

(2) The flocculation settling tests showed that flocculation significantly enhanced the settling efficiency of the classified fine tailings. Among the tested flocculants, Type C flocculant achieved the best overall performance in terms of settling rate, solids flux, and underflow concentration. The optimum flocculant dosage and feed solids concentration

were determined to be 30 g/t and 12 wt%, respectively. Dynamic settling tests further demonstrated that the underflow concentration obtained under rake-assisted conditions was substantially higher than that under static settling, indicating that deep-cone thickeners are more suitable for the efficient dewatering and thickening of this type of tailings.

(3) The flowability tests indicated that increasing the slurry solids concentration significantly reduced the spread diameter while increasing both the yield stress and plastic viscosity of the slurry. A lower binder-to-tailings ratio (i.e., lower binder content) improved slurry flowability. Increasing the proportion of classified coarse tailings markedly enhanced the spread diameter and reduced flow resistance. Based on the combined results of the slump flow and rheological tests, within the investigated concentration ranges, increasing the proportion of classified coarse tailings allowed the slurry to maintain comparatively better flowability at higher solids concentrations.

(4) The strength tests showed that increasing the slurry solids concentration promoted the development of UCS, whereas the binder-to-tailings ratio was the dominant factor controlling the strength level. Under different particle size distributions, the UCS first increased and then decreased with increasing proportions of classified coarse tailings, with the highest overall strength achieved at a classified coarse-to-fine tailings ratio of 5:5. This finding indicates that an appropriate coarse-to-fine tailings ratio is beneficial for coordinating particle size composition and cementation, thereby improving the overall strength performance.

(5) Based on the experimental results, a paste backfill process consisting of full-tailings classification–deep-cone thickening of classified fine tailings–dewatering of classified coarse tailings by high-frequency vibrating screening–secondary remixing was proposed. By preventing the classified coarse fraction from directly entering the deep-cone thickener, the proposed process provides a potential pathway for reducing rake-blockage risk while achieving a balance between slurry transportability and backfill strength, thereby providing a process-level reference for the design of paste backfill systems using full tailings with a wide particle size distribution.

Overall, the scientific contribution of this study lies in clarifying the effects of reconstructed coarse-to-fine tailings ratios on slurry flowability and backfill strength and in establishing an integrated paste preparation strategy combining particle classification, differentiated dewatering, and secondary remixing. From an engineering perspective, the proposed strategy provides a process-level basis for the subsequent design and optimization of paste backfill systems using tailings with a wide particle size distribution. However, the present study is limited to laboratory-scale experiments and process scheme development, and no pilot-scale or long-term industrial validation has yet been conducted.

**Author Contributions:** M.L.: Methodology, Software, Formal analysis, Investigation, Data curation, Writing—original draft, Writing—review and editing, Project administration, Funding acquisition; K.Y.: Conceptualization, Investigation, Resources, Writing—review and editing, Supervision, Project administration, Funding acquisition; C.S.: Methodology, Validation, Supervision, Project administration, Funding acquisition; S.R.: Methodology, Formal analysis, Data curation, Visualization; Z.Y.: Methodology, Formal analysis, Data curation, Visualization; T.R.: Methodology, Software, Formal analysis, Data curation, Visualization; L.C.: Conceptualization, Methodology, Investigation, Supervision, Project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. Data are not available for data protection reasons.

**Conflicts of Interest:** Authors Mengyuan Li, Kai Yang, Caixing Shi, Shishan Ruan, Zepeng Yan, and Lu Chen were employed by the BGRIMM Technology Group. The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from BGRIMM Technology Group. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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