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Study on Natural Settlement Index Characteristics of Iron-Bearing Tailings Applied to Goaf Filling Treatment

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Abstract: In order to provide a technical basis for the subsequent concentration and utilization of the tailings treatment process in an iron ore mine, and to achieve the objectives of cost reduction and sustainable development, the settling concentration and settling capacity of a tailings slurry with an initial concentration of 40% in its natural state were tested in conjunction with the pumping supply concentration index of the beneficiation tailings slurry in a metal mine. The test results show that the iron ore tailings particles settle at an overall fast rate: basically, within 10 to 20 min they are able to reach or approach 85 to 99.5% of the final settling state-related index. During the settling process in the fixed container, at first, the clarified water at the top of the tailings slurry is very turbid. With the passage of time, the clarified water gradually becomes blurred and clear from turbidity, and the interface between the slurry and the water gradually becomes clearer. From the phenomena observed during the settling process and the test parameters such as the net increase in clear water and slurry variation, the maximum settling concentration and settling capacity indicators of 50% and 90% can be reached or approached in 5.5 to 7.25 and 10.5 to 15.5 min after settling, and the maximum settling concentration and settling capacity can be reached or approached in 10 to 20 min after the settling process. As the settling tests and observations continued, the relevant settling parameters basically reached the final settling state within the time period of 20 to 1440 min, during which the settling concentration of the tailing sand was 71.33 to 73.42% and the settling capacity was 1.85 to 1.91 g/cm^3. It can be judged from the test results that the natural settling of the low concentration tailings slurry can meet the technical specifications required for the filling process, and that the natural settling and concentration of dewatering can save the costs of the relevant facilities and flocculation chemicals, and therefore has good technical and economic feasibility.

Keywords: solid waste utilization; tailings settlement; sustainable development; goaf management; filling materials

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1. Introduction

The underground mining processes of many mineral resources are accompanied by the generation and emission of a large amount of solid waste to the surrounding environment, such as dirty smoke, poisonous gases, mineralized water, and different types of solid waste. These wastes have negative impacts on the surrounding environment. If reasonable measures are not taken to properly handle them in a timely manner, some harmful matter in the solid waste can migrate over a large distance under the influence of environmental driving forces such as wind, water, and air. After a period of natural transportation, the solid waste can seriously pollute the surrounding soil and water. Some ecological damage caused by industrial production is very expensive to remediate and sometimes the measures taken do not have a significant effect [1,2]. In the mining of ore containing heavy metals, the waste tailings usually contain heavy metals that cannot be completely screened out during production. These heavy metals can migrate into the surrounding environment and pose a contamination risk. Once the heavy metals enter part of the food chain of humans or animals, their health and lives can be seriously damaged [3]. The main types of solid waste produced in metal mines include waste rocks generated during tunneling and tailings generated during ore screening. Proper handling of these solid wastes is critical for safe mining production and can also reduce hidden risks and accident expenses due to the breakage of tailings dams, leakage from tailings deposits, and damage to the underground strata [4,5].

To prevent harmful substances such as heavy metals from damaging humans and creatures, engineering measures need to be taken to properly dispose of the solid waste, e.g., building large storage facilities for tailings at suitable locations near the mine. With good protective measures, the tailings storage can contain almost all of the tailings generated during the service life of the mine. Some of the tailings can be directly used as goaf backfill rather than being stored. These measures of handling tailings ensure the safe operation of the mine [6,7]. Goaf backfilling with tailings, waste rock, and/or their cemented forms is currently popular in the mining industry. These approaches involve creating a low-concentration tailings slurry in a large-volume container in a backfilling workshop to achieve natural or flocculating subsidence of the slurry. The tailings are transported via pipes to ensure the continuous operation of the backfilling with a high reliability, great stability, and low cost. These approaches can achieve the goal of permanent management of goaf stratum layer control [8–10]. To ensure that the backfilling material is suitable for mining construction, previous studies have conducted experiments to test the physical performance of cemented filling material that is combined with waste rocks and tailings. The transportation resistance characteristics and the consolidation hardening process of cemented filling materials with different formulas have been analyzed. These studies provide theoretical guidance for improving the mechanical properties of coarse aggregate backfill materials [11,12].

With the gradual implementation of stringent ecological and environmental protection policies in the mining industry, all mining enterprises are developing new techniques to save energy, reduce emissions, and achieve clean production according to their own operation characteristics. Moreover, since the forcing conditions of underground rocks are difficult to predict, the seepage and fracture characteristics of rocks may change greatly. To cope with the complex and changeable conditions of the rock strata, it is also necessary to develop good methods for the daily maintenance of the rock strata [13–15]. As a popular approach that conforms to the technology development trends of mining enterprises, the backfill mining method requires performance testing of inert aggregate backfill materials before they can be used in the goaf backfilling process. Such a test can ensure that the selected material satisfies the requirements of the backfilling process in order to achieve the best comprehensive effect from both technical and economic perspectives. Previous studies conducted simulated transportation experiments on certain materials and analyzed the factors that affect the rheological properties of paste cemented fillings slurry. Optimal formulas for backfill materials have been proposed [16,17]. The concentration subsidence of tailings has been analyzed [18,19] to reveal the different subsidence patterns of different types of tailings. In this study, experiments were conducted to assess the subsidence performance of tailings under different conditions such as various particle sizes for a mining enterprise. The factors influencing the tailings subsidence velocity were analyzed via comparison between natural subsidence and flocculating subsidence. The results of the tailings performance tests can be applied to mining production and provide guidance for the critical control of stabilized condensed tailings slurry.

Some large underground metal mines in the plain region use a cemented backfilling process involving tailings in an attempt to thoroughly solve the problems of goaf backfilling and solid waste emissions, with the goal of advocating green mining and sustainable development [20,21]. To meet the technical requirements of the backfilling process and its layout design, it is necessary to supply tailings continuously to the goaf backfilling area. Therefore, it is important to understand the subsidence characteristics of the tailings. Generally, for tailings flocculation and settlement, the amount of flocculant added to make the tailing sand settle to the required concentration for the filling process is 5~25 g/t. The commonly used flocculants are polyacrylamide flocculant and Eisen flocculant, of which the price of polyacrylamide is RMB 13,500/t and the price of Eisen flocculant is RMB 16,000/t. The cost of polyacrylamide as a flocculation and sedimentation agent can be calculated as 0.0675~0.3375 RMB/t, and the cost of Eisen flocculant as a flocculation and sedimentation agent is 0.0800~0.4000 RMB/t. For a mine that requires 1 million tons of tailings to be filled annually, the annual cost of chemicals used for flocculation and sedimentation will be as high as 6.75~33.75 million yuan/a or 8.00~40.00 million yuan/a. As flocculant dosing equipment and its ancillary facilities are also necessary facilities, for a single set of dosing equipment, the equipment input is usually 150~35 million yuan per set, which shows that the equipment aspect and investment in equipment is also considerable.

In previous tests, researchers have tended to focus too much on the rapid settling of the tailings slurry by adding flocculants to facilitate the settling of the tailings. While this has improved the settling rate of the tailings particles, it has also increased the cost of the tailings concentration and therefore needs to be considered to speed up the settling of the tailings in a cost-effective manner so that it can also meet the needs of the filling process at a low cost of operation. In the subsidence performance tests conducted on iron ore tailings in this study, the main focus was on the settling index of tailing slurries with a certain starting concentration, calculating and analyzing the change in the concentration and volume during the settling process, and finding the minimum time required to approach the final settling index of around 85~100% in order to achieve the purpose of preparing highly concentrated filled slurries. The basic physicochemical properties of the tailings were measured, including the performance parameters related to the storage, concentration, and natural subsidence. Several techniques were considered, including vertical tailings bin feeding, subsidence, storage, and air-pressurized slurry. The performance parameters related to the subsidence concentration and subsidence bulk density in their final states were analyzed. The performance of the natural subsidence in this study revealed that there was very little interference in the subsidence of the tailings due to the very small amount of flakey particles that did not easily settle. After 5.5–7.25 min of natural subsidence, the maximum subsidence concentration and the maximum subsidence bulk density reached 50% of the final stable values. After 10.5–15.5 min, they reached 90%. The upper part of the water layer after the subsidence of the tailings was basically clear and met the standard for backwater reuse. The results of this study provide guidance for the concentration and dehydration of tailings via natural subsidence.

2. Materials and Methods

2.1. Tailings

Multiple samples were collected within 10 to 20 working days during the normal operation of the underground mining and ore screening processes. A temporary tailings pond with a volume of 4 to 6 m^3 was constructed in the tailing storage area. A tailings slurry discharge pipe was connected to the temporary tailings pond to drain the tailings slurry. Tailings slurry with an initial concentration of approximately 15.5–35% was allowed to settle and accumulate in the temporary tailings pond. Then, the clear water was discharged and the wet tailings with sculptured clay shapes and moisture contents of 10–15% were shipped to a lab using bags. The tailings blocks were broken into small pieces after they were dried, and then, they were evenly mixed. The small pieces were ground into raw material particle sizes for use in the subsequent subsidence tests. During the entire sampling process, special effort was carried out to avoid the loss of tailings and the consequent loss of certain particle size groups in order to ensure that the final sample was sufficiently representative.

Similarly, sampling was conducted in multiple time intervals in the laboratory tests to obtain the physical and chemical performance parameters through a series of tests. The main chemical compositions of the tailings were obtained (Figure 1). It can be seen from Figure 1 that the total iron TFe content of the tailings was approximately 14.0%, and the total content of Al_2O_3, CaO, and MgO was 9.17%. The tailings also contained small amounts of S and P. From a professional point of view, in mineral screening, the fineness of the particles is usually represented by the mesh size. For the tailings particles in this study, the 600 to 800 mesh (23–18 μm) particles accounted for 19.89–24.56%. The 500 mesh (25 μm) particles accounted for 26.62%. The 325 mesh (45 μm) particles accounted for 48.06%. The 200 mesh (75 μm) particles accounted for 70.33%. The correlation curve of the particle size distribution of the tailings and the mesh size is shown in Figure 2. Through a series of indoor laboratory tests, the specific gravity, loose bulk density, compacted density, porosity, porosity ratio, and natural repose angle of the tailings were obtained (Table 1).

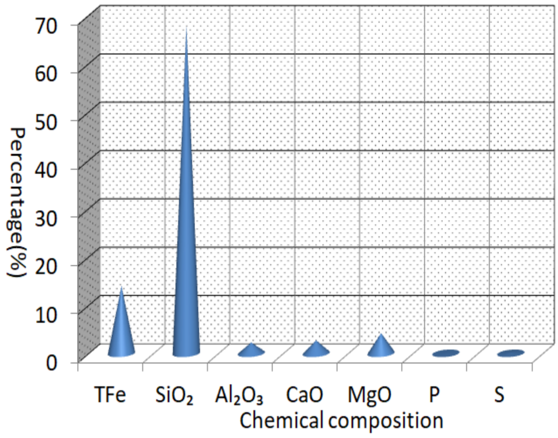


Figure 1. Chemical composition of the tailings.

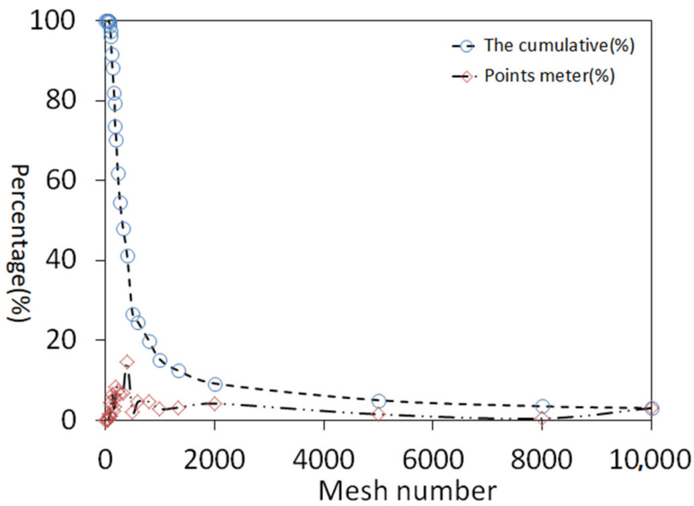


Figure 2. Mesh number of the particle content.

Table 1. Measured values of the basic physical properties of the tailings.

Material	Density	Loose Bulk Density (t/m^3)	Compacted Density (t/m^3)	Porosity (%)	Void Ratio	Natural Repose Angle (°)
Full tailings	2.897	1.269	1.701	41.28	0.703	37.97

The laser particle size test method was used to obtain the particle size data of the tailings. The cumulative and sub-count particle size distribution curves of the tailings are shown in Figure 3.

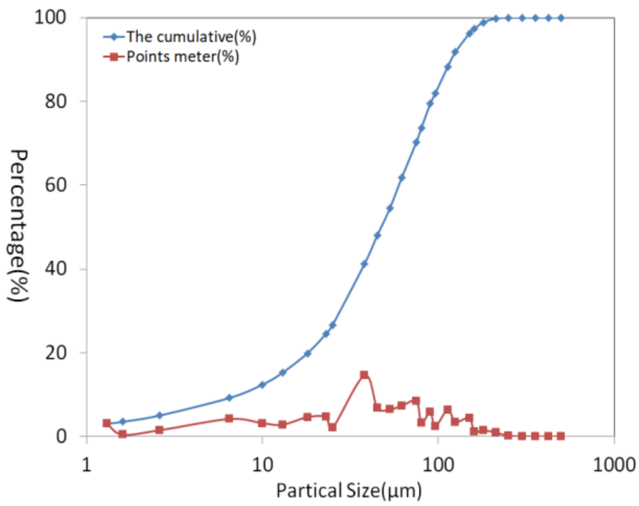


Figure 3. Particle size distribution curve of the tailings.

2.2. Water

The water used to prepare the tailings slurry was tap water from the laboratory, which was clear and transparent. The tap water came from the Xiangjiang Pumping Station of a water company. Several tests at different time intervals revealed that the density of the tap water was 1.0 g/cm^3, the pH was 7.1–7.3, the residual chlorine content was 0.033–0.076 mg/L, and the temperature was 17.5–21.3 °C. According to a series of basic performance parameters of the tap water, the water used in this study was conventional common water and was appropriate for the tailings subsidence performance tests.

2.3. Tailings Slurry Preparation and Subsidence Parameter Test

The backfilling system used in industrial production is usually operated in the open air or indoors. To simulate the actual production conditions, an indoor system was used in the natural subsidence test on the tailings under a natural indoor temperature of 22–26 °C. In order to avoid the phenomenon of data dispersion, the experimental test was repeated 3 times, which was used as the basis to study the rules followed by the experiment. The humidity level was the same as the natural conditions of the indoor air. During the tests, appropriate amounts of dry tailings and tap water were used to prepare the slurry. After a short period of full wetting and soaking, the evenly mixed slurry was quickly poured into a 1000 mL graduated cylinder and natural subsidence was allowed to occur. Vibration and shaking were avoided. The subsidence parameters, including the net increment of clear water (the "clear water" mentioned here refers to the water in the upper part of the turbid tailings slurry, which has a relatively clear boundary with the turbid slurry. Same below), the total amount of clear water, the amount of slurry, and the total amount of the tailings slurry (i.e., the slurry amount plus the total amount of clear water) were recorded once during every time period. Based on these measured parameters, the subsidence concentration and the subsidence bulk density were calculated. The variation trends of the total amount of clear water and the net increment of clear water were statistically analyzed (Figure 4). The variation trends of the amount of the slurry and the total amount of the tailings slurry are shown in Figure 5. The subsidence concentration and the subsidence bulk density of the tailings slurry at different times were calculated (Table 2).

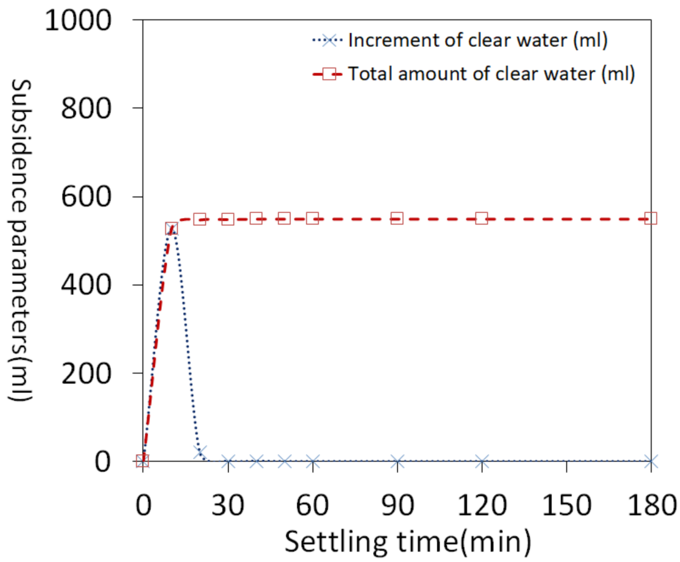


Figure 4. Variations in the total amount and the increment of clear water.

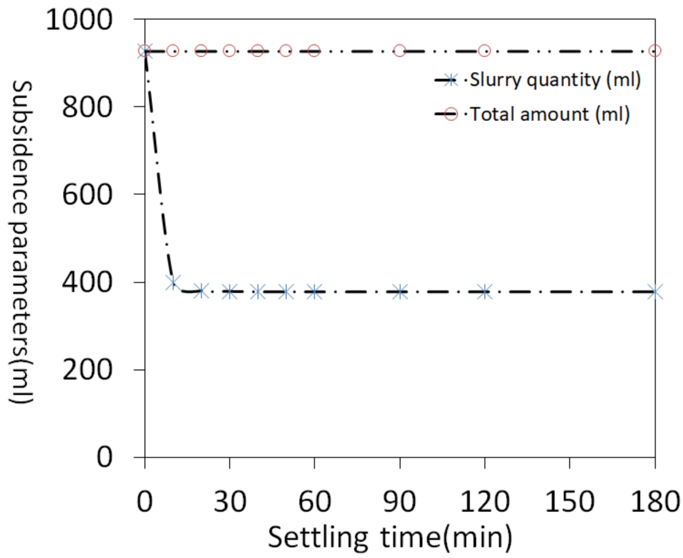


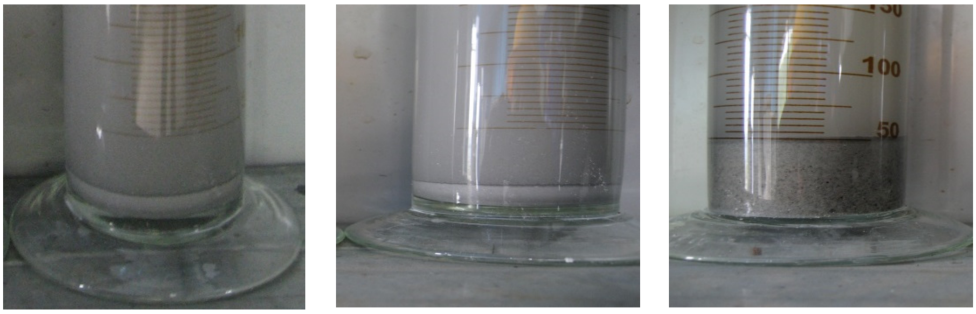
Figure 5. Variations in the slurry quantity and the total amount.

Table 2. Calculated values of the subsidence concentration and subsidence bulk density of tailings slurry.

Test Time (min)	0	10	20	30	40	50	60	90	120	180
Subsidence concentration (%)	40	69.85	71.92	71.99	72.03	72.03	72.03	72.03	72.03	72.03
Subsidence bulk density (g/cm^3)	1.35	1.823	1.867	1.867	1.867	1.867	1.867	1.867	1.867	1.867

To better understand the entire tailings subsidence process, some pictures of key points in the process were taken at different moments during the test to provide intuitive observations for the subsequent analysis of the subsidence process. The pictures are shown in Figure 6a–c. Figure 6a shows that the tailings slurry was generally cloudy in the initial stage, with only a small amount of tailings settled at the bottom of the container, and there was no clear interface between the tailings and water. Figure 6b shows that in the intermediate stage, there was still no clear separation interface between the tailings and the water, but the amount of tailings that had settled to the bottom of the container was larger.

Figure 6c shows that in the final stage, there was an interface between the tailings and water, and a large amount of tailings had settled to the bottom of the container. Moreover, the supernatant water in the container was clear and transparent, and there were clear patterns of the accumulation state of both the coarse and fine particles of the tailings at the bottom of the container.



(**a**) (**b**) (**c**)

Figure 6. Tailings subsidence states during different testing periods. (**a**) Initial state; (**b**) intermediate state; and (**c**) final state.

3. Analysis of Test Results

The sedimentation process of tailings is usually complex, and its settling rate is closely related to the particle size and chemical composition. For example, during the discharge of tailings from a tailings pond, differences in the physical and chemical properties of the tailings particles can cause differential settling, resulting in certain potential hazards [22]. The subsidence analysis of the tailings slurry with a certain initial concentration revealed that the particle dispersion of the tailings was satisfactory due to the high SiO_2 content. The slurry with water added did not exhibit a viscous state and could be stirred uniformly without bonding and clogging in a short period of time. During the addition of the water, the water quickly flowed into the interior of the tailings and then flowed out from the bottom of the tailings. The infiltration rate of the water in the tailings particles was fast, and the molecular force between the tailings and water was small, resulting in rapid subsidence of the tailings. Therefore, the tailings could sink down freely in a short period of time. The apparent structure of the tailings showed that most of the particles existed in a granular state and there were very few fine flakey particles. Therefore, the tailings particles had a low flow resistance during the subsidence process and could sink to the bottom of the container in a short period of time. The particles sank and stacked up in a layer-by-layer pattern from large to small and finally formed a layered deposit with an obvious stratified pore structure that could be observed through the transparent container wall.

As shown by the curve in Figure 4, the variation trend of the net increment of the clear water shows that the total amount of clear water produced reached 50% of the final total amount of clear water (245–265 mL) after 7.25 min of continuous subsidence of the tailings. During the first 10 min of the tailings subsidence, the net increment of the clear water increased sharply. During the 10–20 min period, the net increment of the clear water decreased gradually. After a period of slight increase, the net increment of the clear water finally approached zero and remained stable until the end of the entire test cycle. The variation trend of the amount of clear water presented in Figure 4 shows that the fine particles attached to the large particles gradually separated as the tailings settled, and the large particles settled significantly faster than the fine particles. During this process, the amount of clear water increased continuously. The total amount of clear water basically remained the same after 20 min, and there was no increase in the total amount of clear water. The pores in the tailings particles were filled with water. Based on these conditions, it can be concluded that the tailings approached or reached the final subsidence state. For similar tailings settling law tests, relevant researchers have used different ways to characterize the settling law of tailings, using the settling height indicator of tailings per unit time to analyze the settling performance of tailings to obtain indicators that can guide production applications. When testing the settling velocity indicator of tailings, the same change in supernatant is observed as the judgement criterion [23].

As shown by the curve in Figure 5, the variation trend of the total amount of tailings subsidence during the test (total amount = slurry + clear water) revealed that except for the small perturbation of the total amount at the beginning of the test when the slurry was poured into the measurement cylinder, the total amount remained constant without significant changes during the 0–180 min period. The reason for this is that when the tailings slurry with an initial concentration of 40% was prepared, the original dry tailings were soaked with water to form supersaturated slurry through mixing and stirring. For both the coarse and fine particles, the pores in the particles were filled with water, and finally, a uniform saturated tailings slurry with a stable total volume was formed. The change curve of the quantity of the slurry shows that during the continuous subsidence of the tailings particles, the tailings subsidence velocity was fast in the first 10 min and there was a significant reduction in the slurry volume during this process. Although the quantity of slurry decreased in the 10–20 min period, the amplitude of this reduction was not significant, and it basically became stable after 20 min.

Comprehensive analysis of the four curves in Figures 4 and 5 revealed that the sum of the total amount of clear water and the amount of slurry was the total amount. When the total amount was stable and no longer changed, the amount of clear water continuously increased as the tailings continuously settled. The amount of slurry continuously decreased, but the total amount of the mixed materials in the container remained unchanged. The total amount of clear water was the sum of the net increments of the clear water. There was a functional relationship between the variation in the total amount of clear water and time. When the subsidence time reached 10 min, the subsidence concentration and the subsidence bulk density reached 96.97% of the final stable values. When the subsidence time reached 20 min, they reached 99.85% of the final values. When the discharge of the clear water was zero or did not change, the total amount of clear water also remained stable, and the subsidence concentration and the subsidence bulk density of the tailings no longer changed. When the slurry reached the final subsidence state, the subsidence concentration of the tailings was 72.03% and the subsidence bulk density was 1.867 g/cm^3.

4. Discussion

In the daily beneficiation production of the mine, the grinding of the ore after the beneficiation process usually does not have economic utilization value under the existing technical conditions. The remaining tailings slurry is discharged into the tailings storage tank through a slurry pump [24,25]. When the goaf needs backfilling, a tailings slurry discharge pipe is connected to a standing tailings bin in the backfilling station to feed the tailings. The slurry is allowed to settle and concentrate to form a high-concentration tailings slurry that meets the technical requirements. The mechanical properties of the backfill materials can be tested according to the physical performance indexes of the backfill tailings. The different factors affecting the properties of the backfill materials can be analyzed. The properties can be improved to achieve a better forcing environment for the goaf [26,27]. With consideration of the costs of all of the materials, in this study, tailings subsidence experiments were conducted to verify the natural subsidence characteristics of the tailings. The results revealed that when a flocculating agent was not added, the tailings still settled and concentrated quickly. The subsidence concentration and the subsidence bulk gravity of the tailings slurry reached 85% of the final stabilized values in 6–8 min. Therefore, natural subsidence of the tailings slurry can meet the requirements of the backfill slurry preparation for the backfilling process using a standing tailings bin to feed, store, and prepare the slurry using pressurized gas.

In the daily operation of the backfill system of the mine, it is necessary to be able to determine the subsidence concentration and the velocity of the tailings in a timely manner in order to develop a reasonable plan for backfilling. Tailings subsidence experiments are often conducted to reveal the subsidence performance of the tailings and their physicochemical properties. For example, in previous studies [28,29], the tailings of a copper mine were found to settle slowly, but the addition of flocculants greatly increased the subsidence velocity. This technique has been used in practical applications to effectively improve the tailings subsidence velocity in a backfilling machine with a deep cone for a high-concentration slurry. The subsidence velocity of tailings with a high content of fine particles can be increased through the use of admixtures. The supernatant indicates that the subsidence met the related requirements. The initial concentration of the tailings slurry in this study was 40%, which can ensure a better backfilling process in the mine. Usually, the concentration of the tailings slurry under ideal conditions can reach 25–45% in the discharge process and transportation of the slurry from the concentrator to the slurry pump. This parameter selection considers the characteristics of the discharge of the tailings slurry from the concentrator from a practical point of view.

In general, the tailings subsidence performance test needs to consider the current technical process. The production cost and the environmental protection factors should also be considered in order to provide a reliable basis for selecting a test plan with a low cost and satisfactory effect. In the comparison of natural subsidence and flocculating subsidence of tailings, previous researchers have conducted tests by adding flocculants to promote subsidence and to increase the subsidence velocity to greater than 1.5 cm/min. These tests directly helped improve the backfilling [30]. In research on the characteristics of natural subsidence, previous researchers observed and analyzed the subsidence processes of tailings slurries with different concentrations (low, medium, and high) to understand the slow subsidence process of fine particles. It was found that there is a negative correlation between the tailings subsidence velocity and the concentration [31,32]. Compared with tailings from other mines that did not easily settle, the iron ore tailings used in this study had a high silica content, regular particle shapes, and very few flakey particles. The subsidence process was basically dominated by vertical sedimentation of the particles, indicating that gravity had a significant impact.

5. Conclusions

(1) Usually, the technological process of the backfill system is determined by the properties of the backfill material. From the initial, mid-term, and final whole process of the natural sedimentation of tailings particles in this study, it can be seen that the natural settling speed of this iron ore tailing sand is fast, and the total amount of clear water produced can reach 50% of the total final clear water in 5 to 7.25 min. Within 10 to 20 min, it can approach 95 to 98% of the parameters of the final settlement state.

(2) From the natural settling effect of tailing sand in this study, the process of tailing sand settling concentration and tailing sand slurry preparation is well integrated, the tailing sand settling speed is faster in the natural state, and the use of the natural settling concentration of low-concentration tailing sand slurry can save a lot of flocculant costs, thus creating conditions for the continuous preparation of low-cost filling slurry. The rapid natural settling of tailing sand also greatly improves the preparation efficiency of filling system tailing sand storage and air-pressurized slurry.

(3) The natural settling test of the tailings slurry in this study shows that the tailings sand particles settle and compress in a relatively short period of time, where the settling trajectory of the tailings sand particles is largely linear and less influenced by water molecules during the downward movement, and the final formation of the tailings slurry has a more uniform particle arrangement with no obvious difference in the particle size in the horizontal direction. The maximum settling concentration of the tailing slurry is 72.03% after testing in this research system; therefore, the reference concentration for the preparation of the tailing slurry can be determined to not exceed this limit value, which corresponds to a settling capacity of the tailing slurry of approximately 1.867 g/cm^3.

Author Contributions: Z.L. and D.D. wrote the main text of the manuscript. J.F. (Junfa Feng) and R.W. collected and analyzed the data. J.F. (Jinkuan Fan) and Y.M. tested some of the experimental data. All authors reviewed and commented on the manuscript. All authors have read and agreed to the published version of the manuscript.

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