Experiment Study on Pumpability of Full Tailings Consolidation and Discharging Slurry of An Iron Mine

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Abstract. In order to treat tailings more economically and effectively and improve the pumping efficiency of the slurry, the pumpability of full tailings consolidation and discharging slurry (FTCDS) was tested. The three evaluation indicators, i.e., slump, slump flow, and bleeding rate, were measured under the conditions of HA-7 and PO42.5 as the cementing material, with the slurry concentration of 75% to 80% and the cementing material dosage of 2% and 3%. Based on these three evaluation indicators, the pumpability of the FTCDS was analyzed and evaluated, and the slurry ratio suitable for pumping was obtained. The results show that the slurry can be pumped well when HA-7 selected as the new cementing material, the concentration is 75% to 79%, and the amount of cementing material is 2%. The research results have implications for similar processes.

1. Introduction
Tailings are the solid waste left after the raw ore is beneficiated, which is usually filled in the underground goaf or discharged to the tailings pond for storage in the form of the slurry. At present, most of the tailings are mainly stored in tailings ponds. The massive dumping of tailings on the surface not only wastes resources and occupies a large amount of land, but also destroys the natural ecological environment, leading to the secondary pollution of the environment. What's more serious is that tailings pond has safety hazards such as dam break [1, 2]. In view of this, the full tailings consolidation and discharging process has been proposed to solve the problems existing in tailings disposal [3]. The key to this process is to add a certain amount of cementing material in the low-concentration full tailings slurry in the concentrator, and the slurry is stirred well and then dehydrated to be concentrated into full tailings consolidation and discharging slurry (FTCDS), which is finally discharged to be stored in a suitable position on the ground, thus forming a tailings consolidation body with certain strength. This technology has changed the traditional tailings discharge mode to a safe and environmentally friendly one, which has significant advantages in improving the comprehensive utilization rate of mine waste.
and tailings disposal efficiency, reducing production costs and resolving surface collapse pit backfill and land reclamation. Thus, the process has become a new method for tailings disposal in China.

The pipeline is mostly used to pump slurry in the tailings consolidation and discharging process. For slurry pumped by pipeline, it is necessary to meet the requirements of pipeline transportation, among which whether the slurry itself has good pumpability is the key to determine whether it can be pumped successfully. Pumpability refers to the workability of slurry in the pipeline pumping process. Pumpability evaluation indicators vary widely in different fields [4-6]. Therefore, the indicators used to evaluate pumpability of slurry should be determined based on the specific properties of the slurry. FTCDS is a kind of viscoplastic fluid and the particle size distribution of cementing material mixed with full tailings is improved, and the bonding property and deformation resistance (plasticity) of the mixture are strong. Therefore, the workability of FTCDS studied in this paper mainly considers its fluidity, water retention, and stability. The pumpability of FTCDS requires that its workability should meet the pumping requirements for smooth transportation along the pipeline. In other words, the frictional resistance between the slurry and the pipe wall should be small. The slurry should have a small bleeding rate, and there should be no segregation, precipitation and pipe blockage occur in the pipeline. According to the properties of FTCDS, the pumpability of FTCDS can be evaluated by three indicators, i.e., the slump, slump flow, and bleeding rate. Specifically, the slump and slump flow can reflect the yield shear stress of slurry [7], and thus, they are used to characterize the fluidity of FTCDS; the bleeding rate can characterize the water retention of FTCDS and further reflect its stability in flowing state. These three indicators are interrelated and contradictory, and the pumpability can be well evaluated by comprehensively considering the influence of the three indicators.

In the present study, the slump, slump flow, and bleeding rate of FTCDS under different conditions were measured and then used to evaluate its pumpability. Finally, the suitable slurry concentration, cement-sand ratio, and types of cementing material for pumping were determined based on the evaluation results. The research results are of significance for the successful implementation and promotion of the full tailings consolidation and discharging process.

2. Experiment and methods

2.1. Sample preparation

2.1.1. cementing materials. The cementing materials are the ordinary Portland cement (P.O42.5) and the new cementing material (HA-7). HA-7, a kind of full tailings consolidation cementing material which is suitable for full tailings consolidation and emission and has low environmental load, is designed and developed based on the requirements and consolidation characteristics of full tailings consolidation and discharging process and by making full use of industrial solid wastes (such as slag, fly ash) with certain hydration activity or potential hydration activity. HA-7 has strong consolidation capacity and can also greatly reduce the production cost.

2.1.2. Water. Untreated city tap water.

2.1.3. Full tailings. Full tailings come from an iron mine, and the test results of its basic physical parameters are shown in Table 1. The chemical composition of the full tailings is shown in Table 2. As shown in Table 2, the main chemical components of the tailings are SiO₂, Fe₂O₃, Al₂O₃, CaO, and MgO, accounting for 98.508% of the total. The full tailings can be classified to acidic tailings due to the highest SiO₂ content, reaching 82.052%. Moreover, the cumulative particle size distribution curve of the full tailings is shown in Figure 1. Overall, the median particle size is 178.28 μm, which is relatively coarse [8]. The non-uniformity coefficient is 3.64, which is less than 5, and the tailings gradation is poor. Curvature coefficient is 1.61, which is greater than 1 and less than 3, and the continuity of particle size distribution is fine.
Table 1. Physical parameters of the full tailings.

| Material      | Bulk density (g·cm⁻³) | Density (g·cm⁻³) | Porosity (%) | Repose angle (°) |
|---------------|-----------------------|------------------|--------------|-----------------|
| Full tailings | 1.75                  | 2.80             | 37.50        | 39              |

Table 2. Main chemical component of the full tailings.

| Chemical component | MgO  | Na₂O | Al₂O₃ | Fe₂O₃ | CaO | SiO₂ | K₂O | SO₃ | MnO | Total |
|--------------------|------|------|-------|-------|-----|------|-----|-----|-----|-------|
| Content/%          | 2.143| 0.179| 3.849 | 8.003 | 2.461| 82.052| 0.700| 0.076| 0.021| 99.48 |

Figure 1. Accumulative distribution curves of the full tailings particle size.

2.2. Experiment methods

According to relevant research and previous experience, discharging slurry with a high concentration (over 75%) under certain pumping conditions can increase the emission of tailings per unit time, and can reduce the water yield of the stacked body, which is beneficial to the formation of early strength of the consolidated body. Accordingly, the full tailings, cementing materials and water were prepared into FTCDS with mass concentration of 75%, 76%, 77%, 78%, 79%, and 80%. It should be noted that because the strength value required for the FTCDS consolidation body is very low (generally less than 0.5 MPa), and the amount of the cementing material is only about 2% to 3% (as a percentage of the total amount of the slurry). Therefore, the amount of cementing material was set to 2% and 3%.

According to the test method for slump and slump flow of concrete mixture, the prepared slurry is loaded into a slump cone and compacted. After the slump cone is lifted, the measured vertical height from the highest point of the top surface of the slurry to the top of the slump cone is the slump value of the FTCDS. Then, the final maximum diameter and minimum diameter of the slurry after expansion were measured with the straightedge, and their arithmetic average value is used as the slump flow value. The measurement results were all accurate to 1 mm. The bleeding rate is the ratio of bleeding amount to slurry water content. The prepared slurry was loaded into a graduated cylinder, and the water secreted from the slurry was transferred to another cylinder with stopper until no bleeding occurred. Finally, the total bleeding amount was weighed and the bleeding rate was calculated.

3. Experiment results analysis

3.1. Evaluation of pumpability by slump and slump flow

FTCDS with good pumpability must have a certain slump and slump flow. Figures 2 and 3 show the changes of the slump and slump flow of FTCDS with concentration, respectively. As can be seen from Figures 2 and 3, both the slump and slump flow decrease rapidly with the increase of concentration. This is because with the increase of concentration, the slurry becomes thicker and the free water
decreases, resulting in increased friction between the particles, better adhesion, and decreased fluidity. Thus, the slump and slump flow of the slurry decrease. From the microscopic point of view, the water in the slurry is the only liquid phase and is the main factor affecting the fluidity. Adsorption of water molecules on the surface of hydration products or evaporation will reduce the free water, resulting in the loss of slump and slump flow. In the process of material hydration, the material is dispersed and the particles in the water are increased due to the physical and chemical effects. Brownian motion and the action of various forces can cause more water molecules to be adsorbed on the surface of the dispersed particles and between the particles, while the water will participate in the hydration reaction of the tailings and the cementitious materials, forming hydration products such as C-S-H gel, Ca(OH)2, and AFt, which will greatly reduce the water content in the slurry [9] and thus reduce the pumpability.

Hydration products such as C-S-H and AFt can enhance the viscosity of the slurry and gradually reduce the slump of the slurry with time. As the hydration reaction continues, the amount of the hydration products produced and solid particles increase, leading to the decrease of the repulsive force between the particles. When the repulsive force is small enough, the particles will gather together to form a mass structure. With the increase of the mass structure, the voids are gradually filled, the slurry structure becomes dense [10], and the internal friction resistance of the slurry will increase at the same time, resulting in the decrease of the slump and slump flow. It can be seen that pumpability is affected by the hydration reaction of materials and depends on the degree of hydration reaction. The faster the hydration reaction rate and the higher the hydration reaction degree, the poorer the pumpability.

On the other hand, when the concentration and the amount of the cementing material are the same, the slump and slump flow of the FTCDS containing HA-7 are generally greater than those of the slurry containing PO42.5, respectively (Figures 2 and 3), indicating that the HA-7 is more conducive to improving the fluidity of the FTCDS. When the concentration is the same, the slump and slump flow of the slurry with 3% P.042.5 and the corresponding slump and slump flow of the slurry with 2% P.O42.5
have a big difference. The slump and slump flow of the slurry with 2% P.O42.5 are generally less than those of the slurry with 3% P.O42.5 when the concentration ranged from 75% to 77% and are larger than those of the slurry with 3% P.O42.5 when the concentration ranged from 78% to 80%. Moreover, the slump and slump flow of the slurry with 2% HA-7 are generally larger than those of the slurry with 3% HA-7. In summary, the slump and slump flow are relatively large when the account of cementing material is 2%. This may be because when the amount of cementing material increases, the bonding performance of the slurry increases and the slump and slump flow decreases, which is not conducive to the pumping of the FTCDS.

3.2. Evaluation of pumpability by bleeding rate

Figure 4 shows the variation of bleeding rate with slurry concentration. It can be seen that when the concentration and the account of the cementing material are the same, the bleeding rate of the FTCDS containing HA-7 is generally lower than that of the slurry containing PO42.5. When the concentration and types of cementing material are the same, the bleeding rate of the slurry with 3% cementing material is lower than that of the slurry with 2% cementing material. This is because the increase in the amount of cementing material increases the total specific surface area of the material particles in the slurry, and the water required by the particles increases, thus reducing the bleeding rate. In addition, the increase in the amount of cementing material will enhance the cohesiveness of the slurry and increase the water demand, which can enhance water retention of the slurry and prevent the bleeding of water. When the bleeding rate is small, the slurry is not easy to separate and precipitate in the pipeline, which can ensure the stability of its flow and thus achieve good pumpability. Therefore, in actual production, a small bleeding rate should be selected within the allowable range.

![Figure 4. Variation of bleeding rate with concentration.](image)

The bleeding amount of the FTCDS is closely related to bleeding performance of various materials added. The particle size distribution, thickness, setting time and hydration reaction of the materials will affect the bleeding rate of the slurry, thus affecting its pumpability. Materials with good particle gradation can reduce the void ratio inside the materials, cut off the movement path of free water inside the slurry [11], and effectively prevent bleeding of the slurry. The finer the material, the larger the specific surface area, the faster the material is hydrated, the higher the degree of hydration, and the greater the amount of water required for the slurry before hardening, the less likely it is to bleed. The longer the setting time of the material, the longer the time for the slurry to harden, and the longer the settling time of the material particles, the easier the slurry will bleed. In addition, the interior of the mixed slurry begins to undergo hydration reaction after the cementing material, the full tailings and the water are stirred, and the flocculent hydration product generated causes the mixed slurry to settle fast [12], which is easy to cause bleeding. As a result, the possibility of blocking the pipe is high, which is not conducive to pumping. Studies have shown that the slurry that is poor in pumpability and prone to blockage has the characteristics of excessive bleeding rate.
A reasonable slump, slump flow, and bleeding rate values range can be determined according to actual slurry characteristics and pumping conditions, and a large slump and slump flow values and a low bleeding rate value should be selected in the determined range in practical application. In general, FTCDS can be pumped as slump reaches 80 mm, while it has good pumpability when the slump in the range of 120 to 250 mm [13]. Based on the above analysis results, the recommended slurry ratio that is suitable for pumping is a concentration of 75% to 79%, the amount of cementing material is 2%, with the HA-7 selected as the cementing material. This not only can meet the requirements of the pumping process and achieve good pumpability, but also can reduce the cost of consolidation and discharging and improve the process efficiency, which is conducive to obtaining good technical and economic indicators.

4. Conclusions
(1) Slump, slump flow, and bleeding rate are inversely related to concentration, and the decline is relatively great. When the concentration and types of cementing material are the same, the slump and slump flow of the slurry with 2% cementing material is generally greater than that of the slurry with 3% cementing material, the bleeding rate of the slurry with 3% cementing material is lower than that of the slurry with 2% cementing material. When the concentration and the account of the cementing material are the same, the slump and slump flow of the FTCDS containing HA-7 are generally greater than those of the slurry containing PO42.5, respectively, the bleeding rate of the FTCDS containing HA-7 is generally lower than that of the slurry containing PO42.5.
(2) The recommended slurry ratio that is suitable for pumping is a concentration of 75% to 79%, the amount of cementing material is 2%, with the HA-7 selected as the cementing material. This not only can meet the requirements of the pumping process and achieve good pumpability, but also can reduce the cost of consolidation and discharging and improve the process efficiency.

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