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Research Article

Study on the Effect of Flocculation and Sedimentation on the Mechanical Properties of Iron Tailing Sand

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Tailings sand is the dam-building material of the tailings dam accumulation sub-dam, and its mechanical properties directly affect the safety and stability of the whole tailings dam. With the improvement of mineral sorting technology, the content of fine and ultrafine particles in the tailings gradually increases, which will affect the mechanical strength of tailings accumulation sub-dam. To improve the settling effect of tailings accumulation in the Chengchao iron ore mine (China), the effect of iron tailings flocculation and settling law on the mechanical properties of tailings sand was studied. Polymerized iron sulfate (PFS) as an inorganic polymer flocculant, compared with the traditional flocculant, has a stronger flocculation and adsorption capacity, is widely used in drinking water, industrial wastewater, and domestic sewage treatment, is an anionic polyacrylamide (APAM-800) for polymer compounds, mainly divided into nonionic, cationic, and anionic three, and is commonly used mine flocculant at home and abroad. Through different flocculants, PFS, and APAM-800 compound flocculation and settling experiments, the effect of the flocculant-dosing scheme on the settling rate and turbidity of clarified liquid was determined, and the change in tailings consolidation shear strength of the best dosing scheme was measured. The experimental results showed that the settling rate of iron tailings was the fastest when PFS was used in combination with APAM-800 at $1.2\,g\,L^{-1}$ and $0.20\,g{\cdot}L^{-1}$ dosages, respectively. The direct shear test results showed that the internal friction angle of tailings sand increased by 2.18°, the cohesion increased by 5.814 kPa, and the shear resistance of flocculated settled tailings increased, which can effectively improve the safety factor of tailings sand pile sub-dam.

1. Introduction

Fine grinding in the mineral sorting process can improve the beneficiation of minerals, but it also can cause several problems such as producing tailings at finer sizes as well as a slow settling rate of these tailings after beneficiation. Tailings is a solid waste discharged after grinding and finishing. As the dam material of tailings dam accumulation, the mechanical characteristics of tailings directly affect the stability of the whole tailings dam. The geotechnical properties of the tailings sand depend on the permeability and fines content of the sand, which in turn affects the undrained strength and drainage rate [1, 2] of the tailings sand. With the increase of fine grain content in sand, the shear strength of tailings sand will decrease, which will affect the accumulation strength [3, 4] of the tailings dam.

Fine-grained tailings have low permeability and are difficult to use directly for dam construction because they are not permeable enough to consolidate and obtain the necessary geotechnical stability in a short period. Pretreatment of fine-grained tailings with flocculants and pumping them into tubes or geotextile dewatering bags is a promising technique [5, 6] to solve this problem. Enterprises such as Dahongshan microfine grain iron tailings [7] and comprehensive tailings of an iron ore mine in Magang [8] have studied flocculation and sedimentation tests and have achieved better sedimentation results. Xiao et al. [9], Qian et al. [10], and Chen et al. [11] studied the settling effect of different flocculants on fine-grained copper oxide leaching slurry, ultrafine-grained manganese ore leaching slurry, and wet zinc refining slurry. Xiao et al. [9] used composite flocculant to settle a fine-grain copper oxide leaching slurry. The influence of flocculant type and dosage and slurry concentration on sedimentation properties are investigated. Qian et al. [10] used different flocculants to carry out the flocculation settlement test on the leaching pulp of electrolytic manganese ore and investigated the influence of the electrical properties, ionic degree, molecular weight, and additional amounts of flocculants on the flocculation settlement effect of the pulp. Chen et al. [11] conducted flocculation settlement tests on various kinds of pulp in the wet zinc smelting process of neutral leaching-weak acid leaching-reductive leaching-copper-hematite removal of iron. According to the properties of the pulp, different kinds of flocculants were selected to optimize the flocculation settlement effect of the pulp, so as to achieve a good liquid-solid separation effect and economic benefits. To improve the flocculation effect, Xiao et al.[12] studied the settling characteristics of iron tailings by compounding inorganic and organic flocculants. Inorganic and organic flocculant combinations are synergistic, which can significantly improve the settlement effect of tailings and provide a reference for the settlement of tailings, especially fine-grained tailings. Gao et al. [13] studied the flocculation and precipitation law of filled tailings in detail and improved the thickening technology and paste-filling process. The results show that when the concentration of tailings slurry is 15%, the dosage of XT9020 is 26.67 $g{\cdot}t^{-1}$, the concentration of XT9020 solution is 0.22%, and the maximum treatment capacity per unit area is 3.26 $t{\cdot}(h{\cdot}m^2)^{-1}$. The experimental value is in good agreement with the predicted value.

The tailings are the discharge of the tailing slurry discharged in the magnetic separation process after precipitation, and the composition of Chengchao iron ore tailings used in the experiment is shown in Table 1. The tailings of Chengchao iron ore belong to low calcium, magnesium, aluminum, and silicon type, and the SiO_2 content of tailings is 37.73%, which is very different from the SiO_2 content of yellow sand commonly used in building materials. However, the hardness of quartz is higher compared with other mineral components, which further shows that the fine grain content is not conducive to the strength improvement of tailings. In this study, to study the effect of iron tailings flocculation and sedimentation law on the mechanical properties of tailings sand, samples were taken at the site of Chengchao iron ore tailings pond. Flocculation and sedimentation experiments with different flocculants were carried out, and consolidation direct shear tests were conducted on the tailings sand after flocculation and sedimentation to study the mechanical properties of tailings sand, which in turn guided the construction of tailings dam accumulation sub-dams.

Table 1: Main components of tailings (%).

FE	SIO_2	MGO	CAO	AL_2O_3
7.18	37.73	11.48	13.52	9.00

2. Experimental Material and Methods

2.1. Experimental Materials. The experimental tailings were a mixed slurry of fine and coarse tailings from the Chengchao iron ore mine. Referring to the Geotechnical Test Method Standard (GB/T 50123–2019) [14], the particle analysis test was performed on the tailing sand, and because of the small particle size of the tailing sand, the particle size below 0.075 mm was tested by laser particle size analyzer, and the particle size above 0.075 mm was tested by sieving method. The coarse tailings amounted to 655 $t\ d^{-1}$ with a concentration of 11.52% and a particle size of 0~0.5 mm. Meanwhile, the fine tailings amounted to 2695.98 $t\ d^{-1}$ with a concentration of 27.69% and a particle size of less than 0.074 mm accounting for 60%. The concentration of the mixed slurry was 21.73% and the specific gravity of the tailings was 2.65 t/m^3. The composition is shown in Table 2. From the results in Table 2, it can be seen that the tailings are fine in size, with a yield of 66.18% for less than 0.076 mm particle size, poor permeability of fine tailings, and long drainage consolidation time, which is not conducive to the stability of the tailings dam.

2.2. Experimental Agents. Six kinds of flocculants were used to flocculate and settle the tailing slurry, and it was concluded through experimental screening that when PFS, PAM, PAC, PPFS, zinc polysilicate, and APAM-800 are used as flocculants alone, the flocculation effect on iron ore tailing pulp is general. When using polyacrylamide to flocculate and settle the tailing, the flocs produced were large and the settling speed was fast. However, the turbidity of the clarified layer was higher [15]. When using an iron polymer flocculant, the turbidity of the clarified liquid was low, but the settling speed was slightly lower than that of polyacrylamide [16]. Therefore, the flocculant APAM-800 and PFS were chosen for the tailings settling experiment to achieve a better settling effect. The molecular formula of PFS is $[Fe_2(OH)_n(SO_4)_{3-n/2}]_m$. PFS has good flocculation performance and wide applicability and has been widely used in urban sewage purification in recent years. APAM-800 molecular formula is $[CH_2CH(CONH_2)]_m[CH_2CH(COONa)]_n$. It is formed by the polymerization of anionic monomers with acrylamide. At present, the commonly used anionic monomers are sulfonic acid and carboxylic acid. These monomers have high activity, high yield after polymerization, and good thermal stability.

2.3. Experimental Methods. PFS were prepared into 0.6, 0.9, 1.2, and 1.5 $g{\cdot}L^{-1}$ solutions, and then 0.10, 0.15, 0.20, and 0.25 $g{\cdot}L^{-1}$ APAM-800 solutions were added, a total of 16 groups. Each time, the same amount of tailing slurry

Table 2: Results of tailings particle size analysis.

Grain size (mm)	Yield (%)	Positive cumulative yield (%)
Less than 0.010	13.39	13.39
0.010~0.019	13.72	27.11
0.019~0.0385	13.19	40.30
0.0385~0.076	25.88	66.18
Larger than 0.076	33.82	100

(200 mL) was put into a 500 mL beaker and the same amount (10 mL) of flocculant was added successively with a pipette. Each time an equal amount of tailing slurry in a beaker, using the coagulation experiment mixer (Shanghai Shimadzu ZR4-6) while adding flocculant, first fast stirring and then slow stirring was employed. After the stirring, the tailing slurry was poured immediately into the measuring cylinder to settle. The volume of the clarified layer was recorded at different settling times. The volume can reflect the settling rate of tailing after adding the flocculant. After settling, take the supernatant to determine the turbidity. The analytical instrument is HACH 2100Q turbidity meter produced by HACH Company. The instrument uses a tungsten filament lamp as the light source, the range is 0~1000 NTU, and the resolution is 0.01 NTU, in line with the required instrument parameters in the standard. According to a series of automatic readings, there is no extra measurement and estimation [17].

In order to study the shear strength of tailing sand under different stress conditions, the ZJ strain-controlled direct shear instrument and TSZ-3 strain-controlled triaxial instrument were used for shear tests. According to the requirements of the Geotechnical Test Code, axial loads of 100, 200, 300, and 400 kPa were applied in the direct shear test, and shear was carried out at a shear rate of 0.8 $mm{\cdot}min^{-1}$ until failure. The strength indexes such as cohesion C and internal friction angle φ were calculated.

The flocculants were screened and the best dosing scheme was determined. The flocculants were dosed according to the best dosing scheme, the settled tailings drainage was solidified, and direct shear experiments were conducted to analyze the effect of flocculation and settlement on the stability of fine-grained tailings ponds.

3. Tailings Flocculation and Sedimentation Experiment

When the flocculant is not added, the tailings slurry will settle naturally. The flocs observed under the microscope are shown in Figure 1. The overall color is light, and the flocs are mixed with mud and water, the flocs are blurred, and almost no flocs particles are formed. When PFS flocculant is added alone, as shown in Figure 2, alum flowers are generally dense. Compared with APAM-800 alone, as shown in Figure 3, alum flowers of APAM-800 flocculant are like small snowflakes, and the flocs are larger and cluster with each other.

In order to achieve a better flocculation settling effect, two kinds of flocculants, PFS and APAM-800, were used in the experiment. The dosage of PFS was quantified (0.6, 0.9,

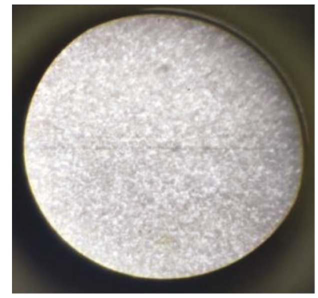


Figure 1: Raw water of tailings slurry.

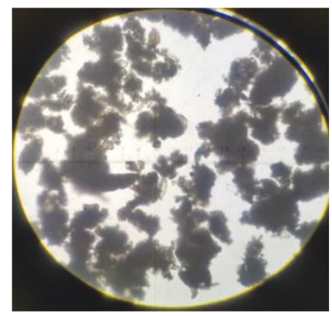


Figure 2: Plus the PFS alone.

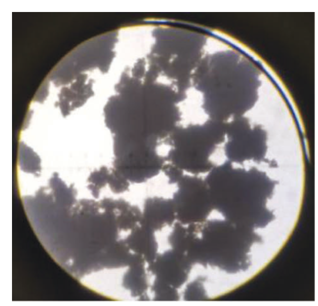


Figure 3: Plus APAM-800 alone.

1.2, and 1.5 $g\,L^{-1}$), and 0.10, 0.15, 0.20, and 0.25 $g{\cdot}L^{-1}$ APAM-800 were added, respectively. The volume of the clarified layer and turbidity of the clarified liquid was measured. The settling curves of the tailings when the two flocculants were used in combination at various combination rates are shown in Figures 4–7, and the turbidity of the clarified layer is shown in Table 3.

The experimental results show that the PFS and APAM-800 together have a greater settling rate and lower turbidity in the clarified layer than when they are used alone, bringing into play their respective advantages. As can be seen from Table 3, the main reason is that PFS forms various complexions through ionization and hydrolysis, and these ions can enter the solid-liquid interface through the periphery of colloidal particles and fine particles and neutralize the potential determining ions so that the total potential φ decreases. Therefore, ζ potential decreases, and thus the electrostatic repulsion between the colloidal particles decreases resulting in the colloidal particles destabilizing and

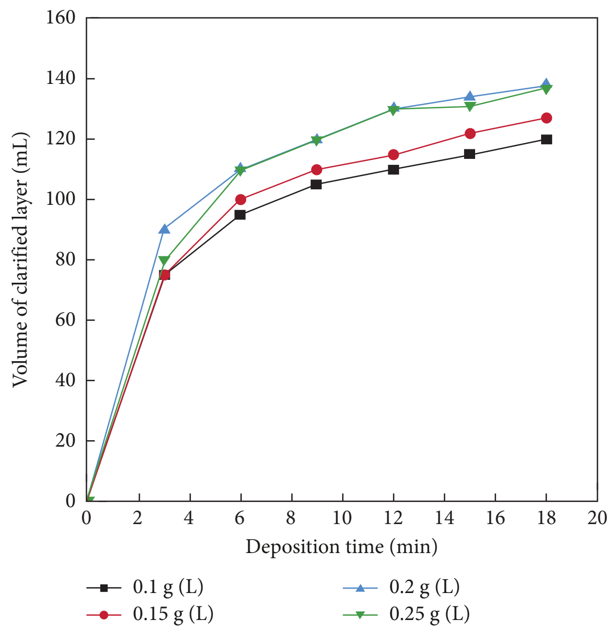


Figure 4: Settling curve of tailing slurry at different APAM-800 dosages with PFS addition of 0.6 g·L^{-1}.

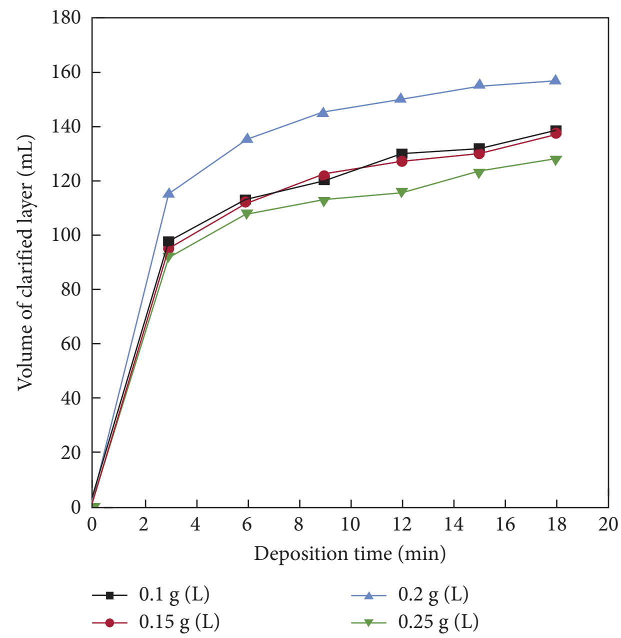


Figure 6: Settling curve of tailing slurry with different APAM-800 dosages at PFS addition of 1.2 g·L^{-1}.

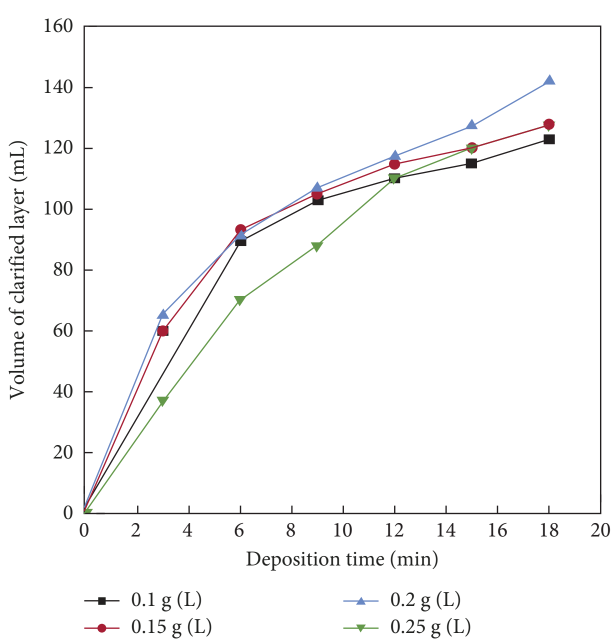


Figure 5: Settling curve of tailing slurry with different APAM-800 dosages at PFS addition of 0.9 g·L^{-1}.

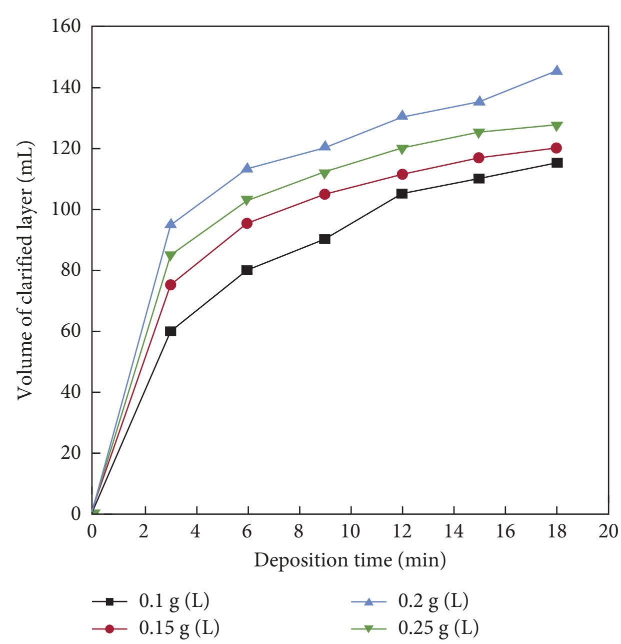


Figure 7: Settling curve of tailing slurry with different APAM-800 dosages at PFS addition of 1.5 g·L^{-1}.

coagulating. However, if the dosage continues to increase, the surface electrical properties of the colloidal particles will be reversed and the opposite charge will be applied to make the colloidal particles have electrostatic repulsion and restabilize the dispersion [18].

The settling rate of tailings increases significantly when the amount of APAM-800 is increased from 0.10 g·L^{-1} to 0.20 g L^{-1}. The settling rate is maximum when the amount of APAM-800 is 0.2 g L^{-1}. The maximum speed is 8.87 mL·min^{-1}. The settling rate decreases when the amount of APAM-800 is more than 0.2 g L^{-1}. The minimum speed is 6.89 mL·min^{-1}. APAM-800 is a chain polymer with large linearity and long molecular chains. The molecular formula is $[CH_2CH(CONH_2)]_m[CH_2CH(COONa)]_n$ [19]. The molecular structure of APAM-800 is shown in Figure 8, and through the action of electrostatic gravitational force, van der Waals force, and hydrogen bonding force in the active part, it has a bridging effect with colloidal particles and fine

Table 3: Settling rate and turbidity of tailing slurry under PFS and APAM-800 compounding.

APAM-800 dosages (g·L^{-1})	PFS dosage (g.L^{-1}) 0.6			0.9			1.2			1.5		
	Clarified layer volume (mL)	Turbidity (NTU)	Settlement rate (mL.min^{-1})	Clarified layer volume (mL)	Turbidity (NTU)	Settlement rate (mL.min^{-1})	Clarified layer volume (mL)	Turbidity (NTU)	Settlement rate (mL.min^{-1})	Clarified layer volume (mL)	Turbidity (NTU)	Settlement rate (mL.min^{-1})
0.10	120	23.3	6.67	123	26.3	6.82	139	28.7	7.72	115	29.7	7.67
0.15	127	26.1	7.05	128	23.8	7.11	137	24.2	7.61	120	21.7	7.33
0.20	138	20.6	7.67	142	15.05	7.90	157	17.8	8.87	145	23.1	6.94
0.25	137	19.3	7.61	127	22.2	7.06	128	28.3	7.11	128	26.2	6.89

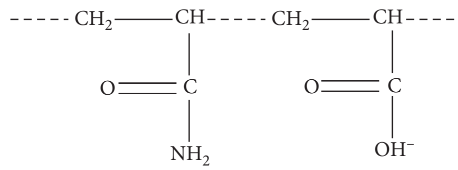
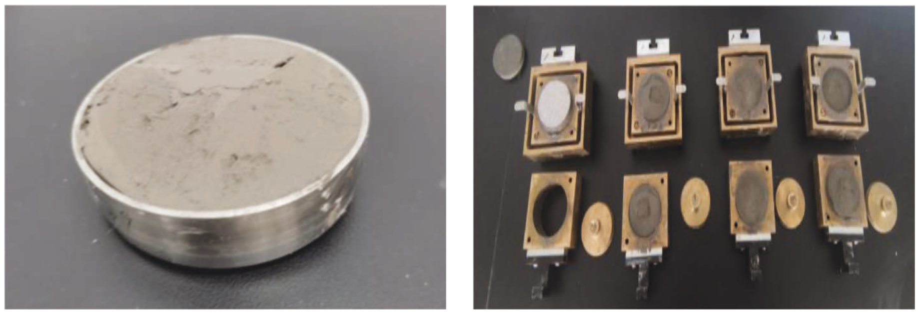


Figure 8: The molecular structure of the APAM.



(a) (b)

Figure 9: (a) Specimens before and (b) after shear strength experiments.

particles. When one end of it adsorbs a certain colloid, the other end adsorbs another colloid so that the colloid coalesces gradually and becomes larger, forming a coarse floc, thus settling fast. When the dosage is too large, molecular chains may appear around colloidal particles and fine particles to make them stable again, resulting in fine flocs, slow settling speed, and high turbidity.

According to the experimental tailings flocculation sedimentation experiment and turbidity measurement, the clarification layer volume of 157 mL with the PFS dosage of 1.2 g L^{-1} and APAM-800 dosage of 0.20 g L^{-1}, the maximum settling rate, and turbidity 17.8 NTU; the clarification layer volume of 142 mL with the PFS dosage 0.9 g L^{-1} and APAM-800 dosages 0.20 g L^{-1}, the lowest clarification layer turbidity 15.05 NTU. The complexions generated by the PFS will agglomerate the fine particles into larger particles through electro-neutralization, and then the APAM-800 polymer chain bridging effect will cause the particles to form large flocs quickly, which will accelerate the settling speed of the fine particles and reduce the turbidity of the clarified layer, thus improving the settling effect of the tailings. In addition, the results show that the volume of the clarified water layer after tailings flocculation settlement is much higher compared with the tailings natural settlement. The upper clear liquid accumulation is about 33 mL after natural settlement. After PFS and APAM-800 mixings, about 140–150 mL can be obtained, that is, 30% clarification liquid can be obtained for 18 min. In practice, extending the settlement time will obtain more clarification liquid, so the reuse rate of the clarification liquid can be greatly improved.

4. Tailings Flocculation Settling Shear Strength Experiment

The slow settling and difficult dewatering of fine particles in the tailings have a great impact on the stability of the tailings pond. By adding flocculants, the fine particles can be coalesced into large flocs to accelerate the settling of the tailings and the discharge of the supernatant, which is an effective way to alleviate the stability problems of the tailings. The shear strength experiments were carried out with the best flocculant-dosing ratio, as PFS 1.2 g L^{-1} and APAM-800 0.20 g L^{-1}. The tailings were solidified by discharging the clarified liquid under low stress after settling, the specimens were prepared and the mass and density were measured, as shown in Table 3. Four specimens were subjected to straight shear experiments at different normal stresses (100 kPa, 200 kPa, 300 kPa, and 400 kPa) at a shear rate of 0.8 mm·min^{-1} until the specimens failed. The specimens before and after shear strength experiments are shown in Figure 9. The same method was used for straight shear experiments on the original tailings to measure the shear stress τ_f at different normal stresses σ. Based on the Moore-Coulomb damage theory

$$\tau_f = c + \sigma \tan \varphi. \quad (1)$$

The graphs are plotted with σ and τ_f as horizontal and vertical coordinates, from which the friction angle φ and cohesion c can be determined, two parameters that are important for the design and simulation of tailings dams. The results of shear strength compared with and without flocculant are shown in Figure 10, and the friction angles φ and cohesion c are shown in Table 4.

From the experimental results, it can be seen that the density of tailings is significantly reduced after adding flocculant, which indicates that the porosity increases; it can be concluded from the results of the direct shear experiment that the degree of tailings' shear resistance is greatly improved after adding flocculant. After adding the flocculant, the friction angle of the tailing increases by about 2.18°, which indicates that flocculation can improve the friction property of the tailing so

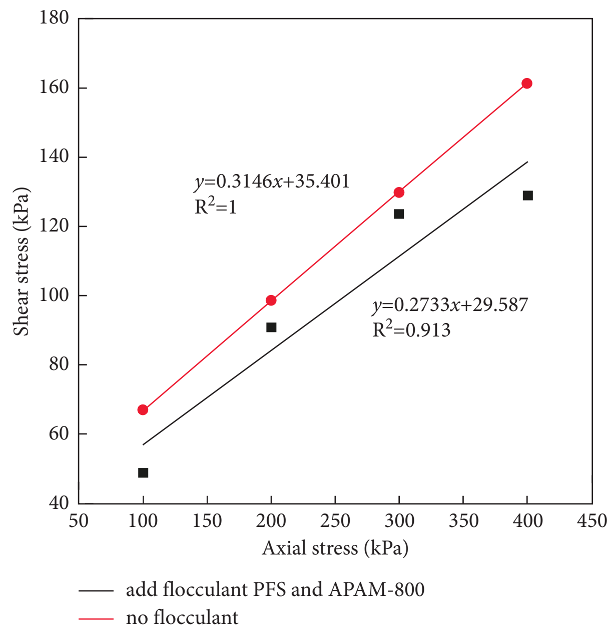


FIGURE 10: Shear strength results of with flocculant compared to without flocculant.

TABLE 4: Physical properties of tailing slurry before shearing and the angle of internal friction and cohesion after shearing.

Type	Average mass (g)	Density/(g·mL^{-1})	Internal friction angle/(°)	Cohesion (kPa)
Raw tailings	109.47	1.82	15.28	29.587
Add 1.2 g·L^{-1} PFS and 0.20 g·L^{-1} APAM-800	97.73	1.63	17.46	35.401

as to improve the stability of the tailing pond. The cohesive force increased by 5.814 kPa, indicating that the flocculant increased the attraction between mineral sand molecules, made the cementation of compounds in mineral sand more obvious, and enhanced its ultimate resistance to shear failure. These results show the effect of flocculant addition on tailings slurry parameters, which not only improves the dewatering of tailings slurry but also the degree of shear resistance, which is of great significance to the stability of tailings ponds.

5. Conclusion

Iron tailings with fine particle size, slow natural settling speed, and high turbidity in the clarified layer require the addition of flocculants to accelerate the settling rate and reduce the turbidity in the clarified layer. Through the experimental screening of PFS, PAM, PAC, PPFS, zinc polysilicate, and APAM-800 these six conventional flocculants; PFS and APAM-800 effect are significant. In the experiment, the best solution for flocculation and settlement of iron tailings was determined, the changes in the solidification shear strength of flocculation settling tailings were measured, and the effect of flocculation settling on the dewatering and solidification performance of fine-grained tailings and geotechnical strength was studied.

(1) Organic polymer flocculants can significantly improve the settling rate of iron tailings, and inorganic flocculants can significantly reduce the turbidity of the clarified layer. 1.2 g L^{-1} of PFS and 0.20 g·L^{-1} APAM-800 have a synergistic effect in improving the settling rate and reducing the turbidity of the clarified layer, which is better than using one flocculant alone.

(2) Compared with no flocculant added, the internal friction angle of tailings after flocculant treatment increases by 2.18° the cohesive force increases by 5.814 kPa, which improves the frictional resistance, and the stability of tailings sand and the tailings dam can obtain better geotechnical performance. In addition, after the tailing slurry is flocculated and settled, the clarified layer has low turbidity, and the settled tailing sand can also be used for mine filling after concentration, which can effectively solve the two major safety hazards of metal mine tailings dams and mining areas.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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