An Experimental Study on the Hindered Settling Properties of Backfill Tailings particles

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ABSTRACT

Mining using backfill methods has been utilized by many mines around the world. Tailings thickening, one of the ways to prepare backfill materials, has been studied worldwide and components of the process such as the thickening mechanism of the tailings tank and principles of selecting flocculants have already been worked out. The studies of hindered settling properties of tailings during this process have lagged which can restrict the precise control of tailings thickening and affect the backfill result. Using in-situ tailings from a mine, hindered and polydisperse settling experiments of tailing slurries with different concentrations and different particle size distributions have been launched to study and analyze the hindered settling features of tailing particles. The experimental results show that the R-square figure of the hindered settling rates of classified tailings between calculated values based on Richardson-Zaki model and experimental ones is over 0.87 proving the Richardson-Zaki model can be used to calculate and predict the hindered settling rates of classified tailings. Moreover, Selim's theory can capture the main properties of the polydisperse settling process of the mix of sieved and silica tailings. The self-flocculation of fine particles in silica tailings has increased the "hindering effect" among particles, the experimental settling rates of silica tailings are less than those theoretical values calculated by Selim theory.

INTRODUCTION

Mining, which is the main way to obtain mineral resources, is vital for industry. Meanwhile, it can also cause many hazards, such as the injuries of miners caused by underground rock bursts or failures of tailings dams and environment pollution. Mining with backfill is utilized by more and more mines now as it can manage tailings and place them in underground mined-out voids..

The preparation of backfill slurry is one of the critical procedures of backfill mining. In the preparation, tailings slurry coming from the mineral processing plant needs to be thickened first and then can be mixed with water and binders with a designed proportion in a backfill plant to become backfill slurries (Yang et al, 2018). Therefore, the quality of tailings slurry thickening is important for the efficiency of backfill.

Nowadays, studies about tailings thickening are commonly interested in the thickener selection and its parameters optimization such as the selection of structures of deep cone thickeners (Chalaturnyk, Don & Özüm, 2002). Besides this, thickening with flocculants is also a focus, including the selection of different flocculants (Alam et al., 2011) the mechanism of tailings flocculation (Botha & Soares 2015) and so on.

These previous studies have helped mines to improve their backfill qualities and enrich the understandings of tailings thickening. However, there has been less of a focus on tailing particles settling itself and the knowledge of the interactions between tailing particles. So, by using real (tailings from a mine) and silica tailings, a series of settling experiments have been launched in this study to gain some understandings of the hindered settling properties of tailings.

HINDERD SETTLING MODELS

The settling of particles can be divided into free settling and hindered settling. Stokes law is well accepted to calculate the free settling rate. As for hindered settling, based on the differences of specific gravity and size of particles, it can still be subdivided as polydisperse settling. Kynch developed the fundamental theory of hindered settling (Kynch, 1952). Based on Kynch, combined with Stokes law, Richardson and Zaki launched the equation of hindered settling rate (Richardson & Zaki, 1954):

$$v_{\mathrm{c}} = v_{\infty} \Phi_{\mathrm{f}}^{n} \, (n > 1) \tag{1}$$

Where v_{c} is hindered settling rate, v_{∞} is free settling rate calculated by Stokes model, Φ_{f} is volume fraction of particles, n is Reynolds number of particles.

Based on conservative law of mass, Selim assumed that the interaction of different tailings is like the settling of one kind particles in the mixed solution of other particles and then modified Richardson-Zaki model (Selim, Kothari & Turian, 1983) which can be written as:

$$v_{\infty,\mathrm{L},2} = \frac{d_{\mathrm{L}}^2(\rho_{\mathrm{L}} - \rho_{\mathrm{susp}})\mathrm{g}}{18\mu_{\mathrm{f}}} \tag{2}$$

Where $v_{\infty,\mathrm{L},2}$ is the polydisperse settling rate, ρ_{susp} is density of the mixed solution.

Davis emphasized the influence of differences of particle size and developed a coefficient to modify the Reynolds number used in Richardson-Zaki model (Davis & Gecol, 1994). This coefficient can be expressed as:

$$\alpha_{i,k} = -3.50 - 1.10\lambda - 1.02\lambda^2 - 0.002\lambda^3 \tag{3}$$

$$\lambda = \frac{d_k}{d_i} \tag{4}$$

Where $\alpha_{i,k}$ is modified *n* coefficient, λ is diameter ratio, *d* stands for diameter.

There are some other empirical or semi-empirical models studying hindered settling. But some of them are complicated to be utilized in practice. So, the Richardson-Zaki model, Selim model and Davis model have been implemented in following analysis.

EXPERIMENTAL PROGRAM

3.1 Materials used

The particle size distribution (PSD) of tailings varies hugely from one mine to another. Therefore, the tailings (real tailings) which were obtained from a copper mine were firstly classified by a hydrocyclone to screen out extra fine particles and then were utilized as the sample materials for the hindered settling experiments. To highlight the differences of the materials used in polydisperse settling experiments, the classified tailings (C-tailings) were sieved by an electrical vibration sieve with the mesh sizes between 0.1~0.15 mm and the obtained sieved tailings (S-tailings) were treated as coarse materials for the polydisperse settling testing. The standard silicas were ground by a ball mill to decrease the coarse contents and the obtained ground silicas (G-tailings) were used as fine particles for the polydisperse settling experiments. The mineralogical properties of the real and silica tailings are as follows:

Table 1 Mineralogical composition of tailings

Tailings	**Mineralogy**						
	SiO_2	Ca	Al	Fe	Mg	K	Others
Real tailing (w_t%)	33.53	0.5	2.52	27.71	1.01	0.63	34.1
Silica tailing (w_t%)	99.8	-	-	-	-	-	0.2

The MasterSize-2000 laser particle size analyzer was utilized to measure the particle size distributions of the three tailings. The results are as follows:

Table 2 Physical properties of tailings

Tailings	Physical Properties					
	D_{10} (μm)	D_{30} (μm)	D_{50} (μm)	D_{60} (μm)	D_{90} (μm)	Gs (kg· m^{-3})
C-tailing	6.1	21.4	41.4	52.2	138.3	2920
S-tailing	5.6	20.1	95.7	116.48	223.8	
G-tailing	3.3	15.6	33.1	44.27	106.1	2710

After measures, the average volume diameters of classified tailings (C-tailings), sieved tailings (S-tailings) and ground silica tailings (G-tailings) are 41 μm, 96 μm and 33 μm respectively, which will be used as the parameters in further theoretical analyses.

3.2 Experimental process

(a) The hindered settling

Use C-tailings as materials to test the hindered settling rates of C-tailings slurries. Prepare tailing slurries with the mass contents of 60%, 63%, 65% and 70% respectively and with the volume of 800 ml. Each mass content of slurry prepares one sample. 1 L graduated cylinders were selected as the settling containers. After 1 min's stirring，the height of the settling surface of the 4 samples at each 30 seconds during a period of one hour was measured.

(b) The polydisperse settling

A designed glass settling cylinder with a diameter of 8cm and a volume of 2200ml was selected as the container for the polydisperse settling experiments. On one side of the cylinder scale labels were carved on it to measure the height of settling surface of the slurries. The S-tailings and G-tailings were mixed for 2 mins with the mass ratio of 7:3 （S-tailings : G-tailings）with the mass contents of 40%, 42.5%, 45%, 47.5%, 50% respectively in a volume of 1800 ml. Each mass content of tailings slurry prepares one sample. As the settling rate of coarse tailings is usually high, a digital camera was used to capture and record 1 hour of settling. By analyzing the recorded video data, the height of sediment surface of the 5 samples for the S-tailings was collected every 5 seconds during the 6 minutes of settling and for the G-tailings, the height of settling surface of the 5 samples was collected every 30 seconds during the whole 1 hour settling time.

RESULTS AND DISCUSSION

4.1 Hindered settling properties of C-tailings

To illustrate its hindered settling properties, the settling rate of C-tailings needs to be calculated. Fig. 1 shows the hindered settling curves of C-tailings. It can be seen from the figure that all four samples of tailing slurries have settled in 10 mins. Thus, by using the data within 10 mins, these four curves have been fitted by polynomial equations (with a fit over 0.95). An example of a fitted curve is shown in Fig. 2. According to the assumptions of Kynch theory, the derivative functions of these fitted equations can be regarded as the equations of settling rates. Therefore, after differentiating the fitted equations, the equations of settling rates have been derived.

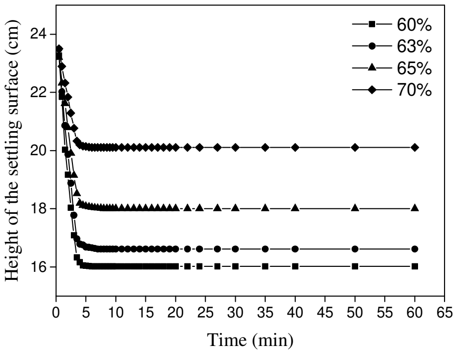


Figure 1 Settlement curves of the settling processes of C-tailings

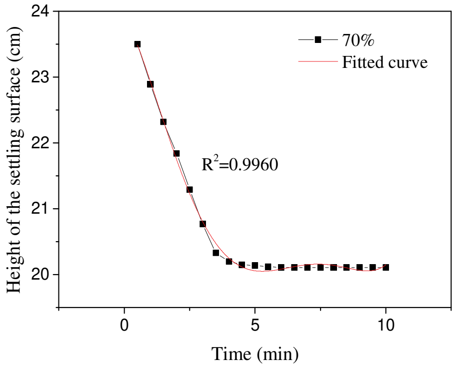


Figure 2 Curve fitting of the 70%(wt) C-tailings slurry

Based on Richardson-Zaki theory, Eq. (1) was used to calculate the hindered settling rate of C-tailings. To avoid the disturbance of initial turbulence caused by the initial stirring, the settling rate at the time point of 3 min has been chosen to represent the average settling rate during the experiment. The comparison diagram of fitted and calculated values is showed as Fig. 3.

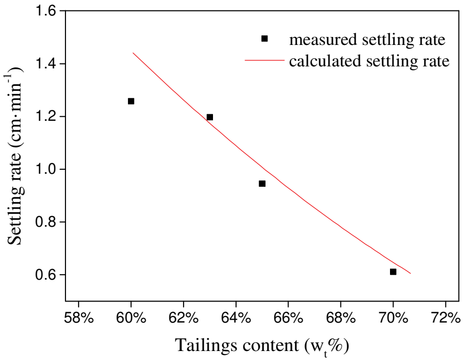


Figure 3 Comparison diagram of experimental and theoretical hindered settling rate of C-tailings

As it can be observed in Fig. 3, except for the settling rate of slurry with the tailings content of 63%, the other three slurries have smaller experimental values than theoretical ones, which means the residual errors of these four values are fluctuating. Moreover, the coefficient of determination (R-square figure) between these two kinds of values is around 0.87, which proves there is a strong correlation between experimental and theoretical values. Therefore, it can be concluded that Richardson-Zaki model has the applicability to calculate and predict the hindered settling rates of C-tailings. Meanwhile, the R-square figure is still less than 0.9. This is likely explained by the fact that the shapes of tailings are not perfectly round and although the tailings have been classified, there is still a difference of particle size distribution amongst the tailings which can affect the settling process.

4.2 Polydisperse settling properties of the mix of S-tailings and G-talings

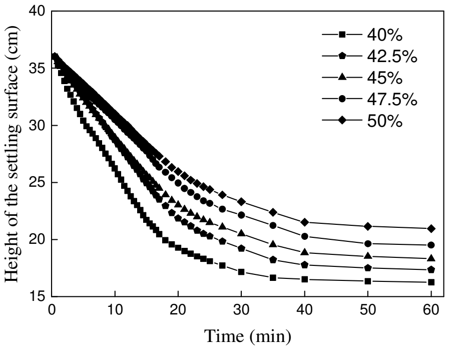


Figure 4 Settling curves of the G-tailings

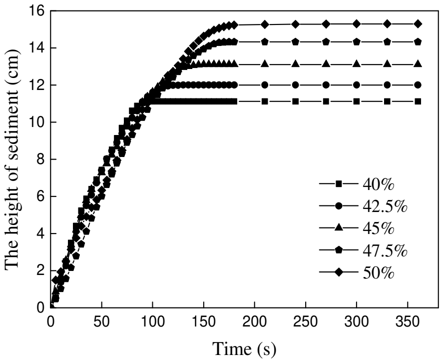


Fig. 5 Increasing curves of the sediments of S-tailings

Fig. 4 shows the settling curve of G-tailings. By using the polynomial fitting method mentioned above, the polydisperse settling rate equation of G-tailings can be derived. Whilst, for S-tailings, because of the high speed of settling, its settling process is not observable. Thus, the sedimentation process of S-tailings was recorded. The sketch diagram of the relation between settling and sedimentation process can be described as Fig. 6.

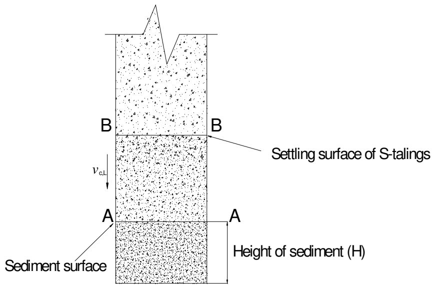


Fig. 6 The sketch diagram of settling and sedimentation process of S-tailings

Assuming the cross-sectional area of A-A is S and all solid and liquid phase are incompressible, according to conservative law of mass Eq. (5) can be derived:

$$v_{c,L} = \Delta h \frac{\Phi_{L,F}}{\Phi_{L}} \tag{5}$$

Where Δh is sedimentation rate, $\Phi_{\mathrm{L,F}}$ and Φ_{L} are average volume fraction of sediments under surface A-A and average volume fraction of particles in area B-A respectively.

Use the polynomial fitting method to gain the settling rate and sedimentation functions of the G-tailings and S-tailings respectively. For G-tailings, the values within 15 mins after settling have been collected and fitted to calculate the average settling rate. For S-tailings, by using the data within the initial 90 seconds and putting them into Eq. (5), the representative settling rate has been obtained. The comparisons of measured and calculated settling rates can be depicted as Fig. 7 and Fig. 8.

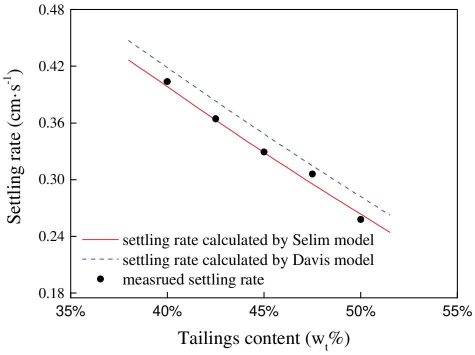
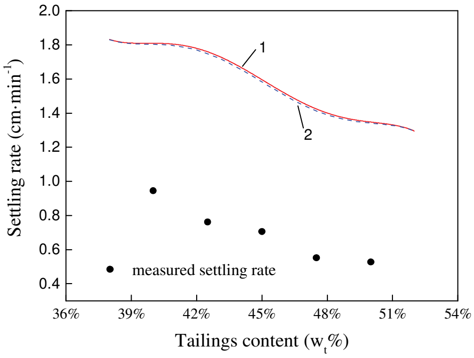


Fig. 7 The comparison between the calculated settling rates and experimental results of S-tailings



1—settling rate calculated by Selim model；2—settling rate calculated by Davis model

Fig. 8 The comparison between the calculated settling rates and experimental results of G-tailings

As showed in Fig. 7, the measured values are located between the two kinds of theoretical values. After calculations, the average relative errors of these 5 measurements are 2.05%（Selim model）and 8.98%（Davis model）respectively which are both within 10%. This proves that both the Selim and Davis models have the applicability to describe the polydisperse settling properties of S-tailings. Meanwhile, comparing to Davis model, values gained by Selim model match better to experimental ones, and the R-square figure, after calculating, is over 0.95 which also indicates the Selim theory can be implemented to explain some features of polydisperse settling process of S-tailings.

However, Fig 8 shows that the measured settling rates of G-tailings are all lower than the theoretical results. This means both theories have underestimated the polydisperse reactions among G-tailings. Whilst previous researches about settling and consolidation of soils or silts have already demonstrated that when the particle diameters are less than 0.03 mm the particles will attract and attach to each other to form a flocculated structure because of their surface chemical properties which is called the self-flocculation phenomena (Mehta, 1994). From Table 2, the D_{50} of G-tailings is 33.1 μm namely the diameters of nearly 50% of particles are smaller than 0.03 mm. Therefore, because of the self-flocculation trend of fine particles the hindered reactions can meddle with the settling process and impact the measured settling rates so that they are lower than calculated values.

CONCLUSION

(1) For the hindered settling of classified tailings, after a series of settling experiments, the results showed that the theoretical and experimental values match with each other. The R-square figure of calculated and measured results is around 0.87 (>0.85), proving the applicability of the Richardson-Zaki model in predicting the hindered settling rates of classified tailings.

(2) Through the experiments of polydisperse settling, it has been proved that compared to the Davis model, the values calculated by the Selim model better match the experimental values. The R-square figure of results predicted by the Selim model and measured values is over 0.95 which indicates the Selim model can well predict the polydisperse settling process of sieved coarse tailings.

(3) In terms of ground silica tailings, the experimental settling rates are all lower than the calculated values. This could be explained by the self-flocculation caused by the high content of fine particles in the tailings samples. So, to precisely predict the settling rate of this kind of tailings, the self-flocculation process needs to be considered.

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