

Research Article

Research on Precise Classification Technology of Tailings Sand

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Abstract

It is difficult to achieve dry and precise classification for fine sand characterized by small particle size, high content of micro-powder, and unstable gradation. In this study, a rectangle swing screen assisted by airflow & ultrasonic was employed to achieve precise classification of fine tailings. Through detailed process calculations and sample analysis, the following conclusions can be drawn: The movement trajectory of the fine sand within the rectangle swing screen follows a 360 ° parabolic path. The current theoretical formula for calculating the resistance coefficient of the transitional flow field within the airflow-assisted rectangle swing screen should be revised. After pre-dried, the magnetic tailings, vanadium-titanium magnetic tailings and molybdenum tailings were precise classified by the new multi-field coupled classifiers. The new classifiers enables the production of products with a mixed-grade rate of less than 5%. The classification efficiency is influenced by the inclination angle of the screen, the length of the sieve, the air velocity, the ultrasonic amplitude & etc., and parameters can be reasonably set according to engineering requirements. Furthermore, the prepared products have been successfully applied in the production of dry-mixed mortar and can be manufactured on a batch scale. The dry-mixed mortar containing tailings has been applied in urban renewal projects and has achieved good results.

Keywords

Tailings Sand, Classification, Rectangle Swing Screen, Airflow & Ultrasonic-assisted Classification

1. Introduction

1 to 2 billion tons of industrial tailings were produced annually in China. The accumulation of a large volume of tailings not only occupies vast tracts of land, pollutes the environment, but also poses safety risks such as dam failures [1-3]. However, the small particle size (mostly less than 1 mm), high micro-powder content (25% to 45%) and unstable gradation of tailings make it difficult for them to be directly used as aggregates in the general concrete and mortar indus-

tries, hinders them to be comprehensive utilized in large-scale. Nevertheless, with the depletion of natural sand resources, commercially available natural fine sand is becoming increasingly expensive and of poorer quality, with higher mud content and lower concentration, seriously affects the survival and development of the mortar and concrete industries. Utilizing tailings sand to produce building material products [4-6] can conserve natural resources and

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promotes the resourceful utilization of tailings, offers multiple benefits.

Current research has primarily focused on the utilization of tailings sand [7-13]; however, there is a lack of studies on the quality control of tailings sand. Mechanical screening methods can screen sand to obtain products. There are various types of mechanical screeners [14], such as trommel screens, linear vibrating screens, and circular vibrating screens. However, when these conventional screeners are used for large-scale screening of fine sand with small particle size (<1 mm), high micro-powder content (25% ~ 45% passing through a 0.125 mm sieve), and unstable gradation, their multi-stage screening accuracy is often low [15] (concentration mostly < 65%), failing to meet the requirements for preparing functional materials.

Swing screens are suitable for applications requiring very fine feed particle sizes, multi-stage screening, and high screening accuracy. Compared to circular swing screens [16, 17], rectangle swing screens can offer higher throughput [18]. However, the current rectangle swing screens can achieve a screening accuracy of only approximately 80% when screening the aforementioned fine sand, still falls short of the requirements (concentration $\geq$ 95%) for preparing high-value-added functional materials. Additionally, the lack of fundamental theoretical research on rectangle swing screens hinders the dry and fine classification of fine materials.

Therefore, this study systematically investigated the classification efficiency of a multi-field coupling classifiers, analyzing the entire process from theoretical calculations to parameter optimization. The technology is successfully applied in engineering cases to produce qualified dry-mixed

mortar products, providing an effective guarantee for the classification and comprehensive utilization of tailings sand, which is of great significance.

2. Materials and Equipment

2.1. Materials

The raw materials used in the experiments are tailings sand, including magnetite tailings (MT), vanadium-titanium magnetite tailings (VTMT), and molybdenum tailings (MOT). MT and VTMT were derived from magnetic separation, while the MOT was obtained from flotation.

Table 1 presents the chemical composition of the tailings sand. Based on the experimental results, it can be observed that each type of tailings sand primarily consists of siliceous materials, followed by Fe_2O_3 . Additionally, magnetite tailings (MT) exhibit relatively high contents of CaO, MgO and Al_2O_3 . Table 2 shows the particle size distribution of the tailings sand raw materials. The results indicate that a significant proportion of particles in the tailings sand are smaller than 125 μm , suggesting that they should be finely classified and subsequently used to produce special dry-mixed mortars in specified proportions.

The tailings came from the tailings pond. The tailings should be dried and their moisture content should not exceed 0.5% before classification. The bulk density of MT, VTMT, and MOT are 1394-1766 kg/m^3 , 1500-1900 kg/m^3 , 1290-1630 kg/m^3 , respectively.

Table 1. Raw Materials Chemical Composition (wt.%).

Sample	SiO_2	Fe_2O_3	CaO	MgO	Al_2O_3	P_2O_5	TiO ₂	Na_2O	K_2O	SO_3	MnO	Other
MT	32.36	20.03	18.06	10.18	9.36	3.23	2.20	1.80	1.14	0.46	0.39	0.76
VTMT	44.42	29.45	7.29	5.04	6.92	0.87	1.13	1.43	1.27	0.90	0.51	0.78
MOT	59.75	14.37	2.39	1.23	0.52	6.88	0.27	0.09	0.04	0.03	59.75	14.37

Table 2. Particle Size Distribution of Tailings Sand.

Size (μm)	<75	75~125	125~250	250~500	500~1000	>1000	Sum
MT	13.4	15.5	30.4	36.3	4.6	0.0	100.2
VTMT	24.2	19.9	25.0	16.6	12.7	1.6	100.0
MOT	18.8	22.5	39.3	15.1	1.2	3.0	99.9

2.2. Equipment

The multi-field coupling classification technology mainly comprises the following components:

- 1) Utilizing a multi-field coupling of gravity, mechanical rotational inertial force, and airflow force to regulate the fine sand motion trajectory and classification efficiency within a rectangle swing screen.
- 2) Utilizing ultrasonic waves to forcibly break up the micro-powder agglomerates and dissociate the micro-powders adsorbed onto larger particles; employing a gravity field (via a distributor) to strongly disperse tailings sand, thereby reducing the thickness of the mechanical screening material layer and the screening

displacement.

- 3) Leveraging an airflow field to forcibly extract the micro-powders that have been disaggregated by ultrasonic waves, as well as dust generated from the materials curtain and within the rectangle swing screen, thereby reducing the micro-powder content in the product and minimizing the likelihood of screen aperture blockage by micro-powders.
- 4) Employing a variable-speed feeder to control the gradation and quantity of the feed material.

Based on the aforementioned improvement scheme, the structure of the multi-field coupling classifiers is illustrated in Figure 1, with a length (L) of 3.6 m and a width (W) of 1.5 m.

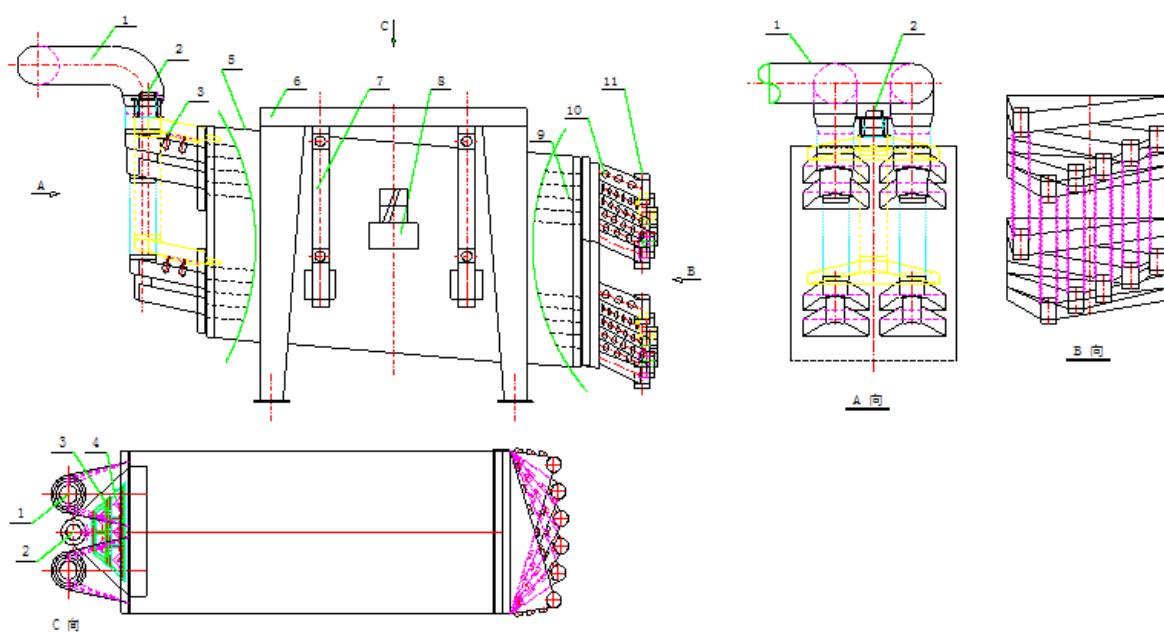


Figure 1. Construction Diagram of Multi-Field Coupling Classifiers.

(1- Air exhaust port, 2- Tailings feed port, 3- Ultrasonic frame, 4- Fabric feeder component, 5- Screen box, 6- Rack, 7- Connecting shaft, 8- Vibration exciter, 9- Sieve, 10- Air inlet, 11- Outlet)

3. Results and Discussion

3.1. Material Movement Trajectory

An LED light strip is suspended between the cover and the top-most sieve inside the rectangle swing screen. Additionally, a small-sized camera mounting device is designed to secure the high-speed camera OSMO ACTION 4 (set at 100 frames per second). Figure 2 shows the frame-by-frame images extracted from a portion of the video captured by the high-speed camera, where the white strip-like object is the LED light strip.

As can be seen from Figure 2, the tailings sand undergoes

a 360° parabolic motion on the top-most sieve of the rectangle swing screen. Among them, the direction in which the material is thrown tends to align with the direction of the screen's swing (a uniform circular motion with a 360° range in the horizontal plane), while the throwing angle varies depending on the position of the material within the screen. Further analysis reveals that when the swing frequency of the screen, $f = 280$ rpm, the swing (rotation) diameter, $A = 50$ mm, and the screen inclination angle, $\theta = 5^\circ$, the maximum horizontal throwing distance of characteristic sand particles in the lateral direction (Z-direction, perpendicular to the viewer) within the swing screen is approximately $L_1 = 150$ mm.

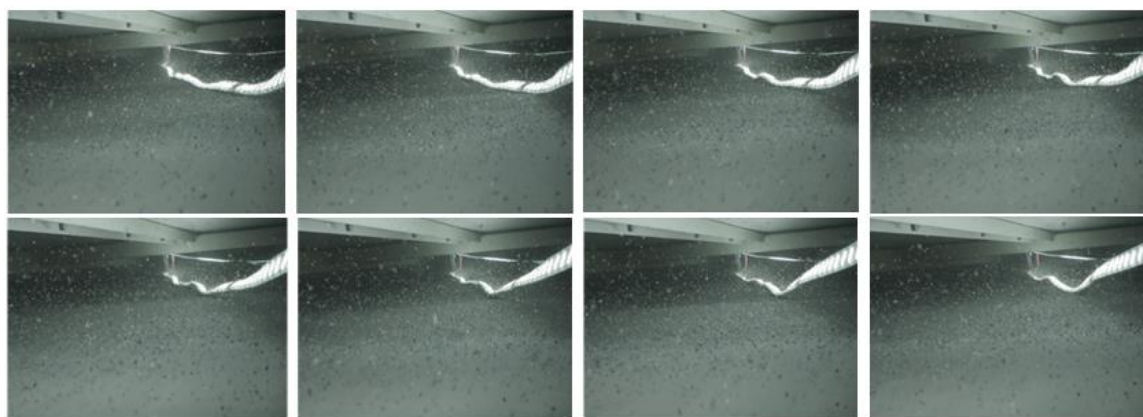


Figure 2. The Movement Trajectory of Fine Sand in the Rectangle Swing Screen.

3.2. Air Resistance Coefficient in Airflow Assisted Rectangle Swing Screen

Particle Reynolds number Re_p can be expressed as the following equation [19].

$$Re_p = \frac{d_p u \rho}{\mu} \quad (1)$$

In the formula, d_p is the mean particle diameter, m; u is the relative velocity of the particle in the airflow field, m/s; ρ is the air density, 1.29 kg/m^3 ; μ is the air viscosity coefficient, $1.8 \times 10^{-5} \text{ N/m.s}$.

Calculations shows that $1 < Re_p < 1000$ when the particle is

in the rectangle swing sieve assisted by airflow.

When $1 < Re_p < 1000$, there are three commonly used formulas [19] for calculating the air resistance coefficient ζ , which belong to the transitional flow zone.

$$\zeta = \frac{24}{Re_p} (1 + 0.15 Re_p^{0.687}) \quad (2)$$

$$\text{or } \zeta = \frac{24}{Re_p} + \frac{3}{16} \quad (3)$$

$$\text{or } \zeta = \frac{30}{Re_p^{0.625}} \quad (4)$$

According to the formula (3), the calculated results are detailed in Table 3.

Table 3. The Maximum Displacement L_2 (mm) of the Material When the Screen Swings for One Cycle at Different Air Speeds.

d_p (μm)	750	428	303	200	125	50
air speed (m/s)	0.1	24.7	22.4	19.5	15.7	2.0
	0.2	23.7	20.0	15.2	8.1	-11.0
	0.3	22.7	17.6	10.9	0.4	
	0.4	21.7	15.1	6.7	-7.1	
	0.5	20.7	12.8	2.5		
	0.6	19.8	10.4	-1.5		

As shown in Table 3, according to existing theoretical formulas, the air velocity must not exceed 0.2 m/s; otherwise, particles with a diameter of 125 μm will be carried away (with a horizontal displacement < 0) by the airflow, which is

inconsistent with actual conditions (see Table 4). If calculations are performed based on Equations (2) or (4), the results are even worse.

Table 4. Actual Detection Results of the Rectangle Swing Screen Dust Collection.

Mesh size (μm)	>150	>125	>100	>75	<75	Sum
Residue (%)	0.1	0.0	0.1	3.3	96.5	100.0

Therefore, the calculation formula (3) for the resistance coefficient ζ of the transition flow field is modified to equation (5).

$$\zeta = \frac{24}{Re_p^3} + \frac{3}{16} \quad (5)$$

According to equation (5), the relevant results calculated by using programming are shown in Table 5.

Table 5. The Maximum Displacement L_3 (mm) of the Material When the Screen Swings for One Cycle at Different Air Speeds.

$d_p/\mu\text{m}$		750	428	303	200	125
Air speed m/s	0.0	26.0	25.9	25.8	25.6	25.1
	0.1	25.6	25.2	24.8	24.1	22.9
	0.2	25.2	24.5	23.8	22.7	20.7
	0.3	24.8	23.8	22.8	21.2	18.5
	0.4	24.4	23.1	21.8	19.7	16.3
	0.5	24.0	22.3	20.8	18.2	14.0
	0.6	23.5	21.6	19.8	16.7	11.7

3.3. Minimum Number of Tailings Sand Jumps in Airflow Assisted Swing Screen

Table 6. The Minimum Number i of Materials Jumps in the Screen Under Different Air Speeds.

d_p (μm)		750	428	303	200	125
Air speed (m/s)	0.0	138	139	139	141	143
	0.1	140	143	145	149	157
	0.2	143	147	151	159	174
	0.3	145	151	158	170	195
	0.4	148	156	165	183	221
	0.5	150	161	173	198	257
	0.6	153	167	182	216	307

Table 6 shows the minimum number i of materials jumps in the airflow-assisted rectangle swing screen under different air speeds by calculating according to Table 5 and relative documents [14].

3.4. The Grading Efficiency of Tailings Sand in the Multi-field Coupling Classifiers

3.4.1. Calculation Formula for Grading Efficiency

Based on the previous research results, the formula for

calculating grading efficiency η was modified.

$$\eta = 1 - \frac{1}{1-q_{x0}} \sum (1 - q_x (1 - c_x)^i) \quad (6)$$

In the formula, q_x represents the proportion of particles with a relative size of x on a certain screen sieve relative to the total material mass; q_{x0} denotes the proportion of particles with $x \geq 1.0$ on a certain sieve relative to the total material mass; i represents the minimum number of collisions between particles and the screen mesh, as shown in Table 6; c_x is the probability of a particle with diameter d passing through a single collision with a sieve surface having an aperture size of a and a wire diameter of δ .

When the inclination angle of the sieve surface is θ , the probability of passing through the sieve can be expressed as the following equation [14].

$$C_x = \frac{(a-d+\psi\delta)((a+\delta)\cos\theta-\delta-d+\psi\delta)}{(a+\delta)^2\cos\theta} \quad (7)$$

Here, when $x = d/a$ takes the values of 0.3, 0.4, 0.6, and 0.8 respectively, ψ takes the values of 0.2, 0.15, 0.10, and 0.05 respectively [14].

3.4.2. Grading Probability and Efficiency

Assume that the total feed rate (G) of the multi-field coupling classifiers is 5t/h, and the measured bulk density (γ_m) of the iron tailings is 1.66t/m³. The required particle size fractions after grading are 0~100, 100~150, 150~250, 250~355, 355~500, ≥ 500 μm .

Based on Equations (6) and (7) and Table 2 and 6, the calculation results for the grading probability and classification efficiency of tailings with different mesh in the classifiers are shown in Table 7.

Table 7. Grading Efficiency of Tailings Sand by Calculating.

	a (μm)	δ (μm)	G (5t/h)	q_{x0}	η
1st sieve	500	224	5.00	0.2459	99.31%
2nd sieve	355	140	3.75	0.1357	96.92%
3rd sieve	250	125	3.20	0.2830	99.31%
4th sieve	150	100	2.25	0.3865	96.96%
5th sieve	100	71	1.35	0.5103	99.47%

3.5. Factors Affecting the Classification Efficiency of Multi-field Coupling Classifiers

Based on Equations (6) and (7) and Table 6, the impacts of factors such as screen length and air velocity on classification efficiency are presented in Tables 8, 9, and 10.

As seen from Table 8, the inclination angle of the screen has a highly significant effect on screening efficiency, with a smaller inclination angle resulting in higher screening efficiency (correspondingly, lower throughput capacity). According to Table 9, a longer rectangle swing screen leads to

higher classification efficiency; however, once it reaches a certain value, the increase in classification efficiency becomes relatively insignificant.

From Table 10, it can be observed that as the air velocity increases, the classification efficiency improves; moreover, the smaller the particle size, the greater the influence of air velocity.

From above, it can be concluded that it makes sense to use ultrasound to disperse the aggregated micro-powders.

By integrating the study of these influencing factors and considering the requirements in practical applications, appropriate process parameters can be reasonably selected.

Table 8. The Influence of the Inclination Angle θ on the Classification Efficiency η ($a = 0.1$ mm).

θ ($^\circ$)	3	5	7	9	11	13	15	17	19
η	100%	99.5%	94.0%	85.5%	77.0%	69.2%	62.2%	56.7%	52.0%

Table 9. The Influence of Sieve Length L on Grading Efficiency η ($a = 0.5\text{mm}$).

L (mm)	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
η	85.6%	91%	93.3%	94.8%	95.9%	96.8%	97.5%	98.1%	98.5%	98.8%

Table 10. The Influence of Air Speed on the Classification Efficiency η of Particles With Different Sizes.

D_p (μm)		750	428	303	200	125
Air speed (m/s)	0.0	97.2%	95.5%	98.2%	91.8%	91.3%
	0.3	97.4%	96.2%	98.8%	94.4%	96.4%
	0.6	97.6%	96.9%	99.3%	97.0%	99.5%

3.6. Case Study of the Multi-field Coupling Classifiers

The engineering application of the multi-field coupling classifiers involves the following steps. First, the multi-field coupling classifiers is employed to precise processing tailings sand. Subsequently, dry-mixed mortars is prepared using dry-mixing equipment with precise processed tailings sand. Then, composite EPS panels with tailings mortar are

fabricated by utilizing the dry-mixed mortar. Finally, these panels and dry-mixed mortars are applied in the renovation of civil buildings.

The new multi-field coupling classifiers (Figure 3(a)) was installed in the demonstration project. Based on the optimized fine classification system (Figure 3(b)), a comprehensive retrofit was carried out on the original tailings processing line. Additionally, screening tests were conducted using different types of tailings sands, and the results are presented in Table 11.



(a) Fine grading machine



(b) Fine grading system

Figure 3. On Site Renovation of Tailings Sand Production Equipment.

Table 11 presents the test results after the actual classification of magnetite tailings, vanadium-titanium magnetite tailings, molybdenum tailings respectively. The new multi-field

coupling classifiers demonstrates good classification performance for these types of tailings, with the mixed-grade rates of the classified products all being less than 5% (and the

concentration ratios all exceeding 95%).

Table 11. Accumulated Screening Residue of Graded Tailings Sand (%).

Sample	Mesh size/ μm	500 μm	425 μm	300 μm	250 μm	212 μm	150 μm	125 μm	106 μm	75 μm	Mixing rate
Magnetite tailings sand	250-500	0	5.2	82.5	98.4					99.8	1.6%
	125-250				0	16.1	83.7	98.8		99.9	1.2%
	75-150						0.6	50.8	75.5	99.1	1.3%
	0-125						0	1.2	2.8	64.7	1.2%
Vanadium titanium magnetite tailings sand	250-500	0	10.4	86.8	99.0					99.7	1.0%
	125-250				0	16.2	82.2	98.0		99.8	2.0%
	75-150						1.4	42.5	72.4	98.6	2.8%
	0-125						0	0.2	0.6	51.8	0.2%
Molybdenum tailings sand	250-500	0	1.9	78.6	96.8					99.5	3.2%
	125-250				0	12.8	81.0	98.1		99.4	1.9%
	75-150						1.8	46.6	72.2	99.3	2.5%
	0-125						0	0	0.4	39.0	0

The retrofitting of the aforementioned production line has significantly enhanced product quality, making the products suitable for mortar preparation and enabling them to completely replace natural sand. In this study, the tailings sand products were utilized in the production of dry-mixed mortar and EPS composite panels, resulting in the development of a series of full-tailings dry-mixed mortar products and full-tailings special mortar composite EPS panels.

The performance of the prepared products with full-tailings aggregates fully meet the requirements of application requirements. These related products have been applied in bulk in a civil building renovation project, achieving favorable results.

4. Conclusion

Through the aforementioned research, the following conclusions can be drawn:

(1) It is difficult to achieve dry and precise classification of fine tailings sand. However, by employing measures such as coupling rotational inertial force field, airflow field, ultrasonic field and gravitational field, precise classification of fine tailings sand can be achieved, with the mixed-grade rate of the classified products being less than 5% (and the concentration ratio exceeding 95%).

(2) The trajectory of fine sand within the rectangle swing screen follows a 360° parabolic path. The theoretical formula for calculating the resistance coefficient ζ of the transitional

flow field within the multi-field coupling classifiers should be revised to $\zeta = \frac{24}{Re_p^3} + \frac{3}{16}$.

(3) The influencing factors on classification efficiency include the inclination angle of the screen, the length of the sieve, the air velocity & etc. The inclination angle of the screen has a significant impact on screening efficiency, with a smaller inclination angle resulting in higher screening efficiency. A longer sieve leads to higher classification efficiency, but there exists an optimal value. As the air velocity increases, the classification efficiency improves, and the smaller the particle size, the greater the impact of air velocity. Utilizing ultrasound to disperse the aggregated micro-powders could improve the classification efficiency. By considering these influencing factors, process parameters can be reasonably selected based on the requirements in practical applications.

(4) High-quality tailings sand products can be prepared using the improved technology in this study, enabling the production of qualified mortar products. The technology obtained in this research has been applied in engineering cases.

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Author Contributions

Zhang Yinxiang: Investigation, Methodology, Data curation, Writing - original draft

Wang Zhaojia: Supervision, Validation

Qiu Junfu: Data curation

Zhang Ruifeng: Data curation

Rui Yafeng: Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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