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Experimental Study on Surface Segregation Law of Three-Dimensional Accumulation Body of Sand and Stone Particles by Binary Mechanism

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Abstract

Sand and stone materials are one of the important raw materials for infrastructure construction. In recent years, natural sand resources have decreased rapidly. In order to protect rivers and DAMS and ecological balance, local governments have increased the control power of natural sand mining, and replacing natural sand with mechanically broken parent rock formation mechanism sand has become an inevitable trend of the industry development. During the crushing process of parent rock, sand particles of different particle size range are produced, and particle segregation occurs in the process of stacking in the yard, which brings great trouble to the calculation of particle grading and material sample detection, and hinders the large-scale application of machine-made sand. In this paper, three-dimensional stacking tests of irregular particles were carried out to identify the particle distribution on the surface of the stack by digital image technology, analyze the relationship between particle size composition of particle mixture and the particle distribution of the accumulation body, and study the distribution law and segregation characteristics of the accumulation body. The experimental results show that the mixture with different coarse particle content will produce the corresponding distribution on the surface of the accumulation body after the accumulation. On the surface of the accretion body, the content of coarse particles is vertically distributed along the height of the accretion body. The content of coarse particles in the lower part of the accretion body is greater than that in the upper part of the accretion body. The overall segregation coefficient on the surface of the pile decreases with the increase of coarse particle content, and the variation is the largest in the lower part of the pile surface with the initial coarse particle content. Based on the test results in this paper, it provides a basis for formulating the sampling and inspection method of machine-made sand, ensuring the quality of machine-made sand and improving the utilization rate of machine-made sand.

Keywords: manufactured sand, machine vision, particle shape, quality evaluation, deep learning

1. Introduction

Sand and gravel aggregates belong to the category of granular materials, and granular materials composed of particles with different sizes, densities, shapes, or surface characteristics will undergo particle separation (segregation) under external stirring such as vibration (Xie Z, Wu P, Wang S, et al., 2013; Rosato A, Strandburg K J, Prinz F, et al., 1987; Knight J B, Jaeger H M & Nagel S R., 1993; Kudrolli A., 2004; Dong H, Liu C, Zhao Y, et al., 2013; Zhu L, Lu H, Guo X, et al., 2022; An X & Li C., 2013; Sun J, Liu C, Wu P, et al., 2016; Tripathi A & Khakhar D V., 2013; Shishodia N & Wassgren C R., 2001) and shear (Antony S J & Kruyt N P., 2009; Tsai J C J C, Huang G H & Tsai C E., 2021; Ottino J M & Khakhar D V., 2000; Meier S W, Lueptow R M & Ottino J M., 2007; Mangwandi C, JiangTao L, Albadarin A B, et al., 2015; Shinbrot T, Alexander A & Muzzio F J., 1999; Xiu W Z, Li R, Chen Q, et al., 2021). The segregation process is complex and involves multiple mechanisms, and many scholars have explored the segregation mechanism. Silva et al. (2000) summarized 13 separation mechanisms, including trajectory, rolling, displacement, infiltration, screening, airflow, fluidization, agglomeration, concentration driven displacement, push away, impact/bounce, embedding, and angle of rest. Tang et al. (2004) classified the mechanisms of segregation into four categories based on the size of particle size, namely trajectory, screening (or screening), fluidization, and agglomeration segregation. According to Mosby et al. (1996), the main mechanism of separation depends on two types of parameters. One is particle characteristics, such as particle size distribution, density, shape, elasticity, friction coefficient, surface texture, cohesion and adhesion; The second is process variables, such as drop height, feed rate, stack size, moisture, and mixing ratio. Among all these parameters, particle size distribution, density and density distribution, and shape and shape distribution are the most important factors. On the other hand, it can be explained by the rapid increase in particle inertia with its size. Shinohara et al. (2011) studied the mechanism of particle segregation during the filling and unloading processes, and analyzed the process based on a screening hopper model, where small particles pass through the space between large particles. Then, based on the model, the critical size ratio at which separation may occur was estimated.

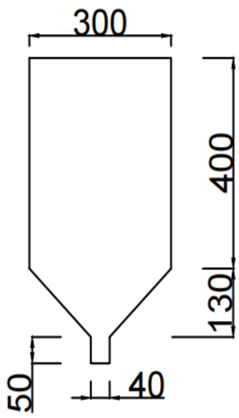
Shinohara et al. (1972) studied the segregation of multi particle mixtures during the filling process and found that segregation decreases with an increase in the minimum particle size ratio. Goyal et al. (2006) found through two-dimensional silo experiments that during the dumping process of bulk solids, the transition from complete segregation to partial segregation resulted in a critical particle size ratio of approximately 1.4. Ketterhagen et al. (2007) used discrete element simulation to study the effect of segregation of doubly dispersed particle materials during hopper discharge, and found that the degree of separation significantly increased when the size ratio was greater than 1.9. Deng et al. conducted an experimental study on rolling segregation of a granular material (calcium carbonate) with different particle size ranges. The experimental results showed that the degree of surface segregation increased with the increase of particle sphericity, and the degree of segregation increased with the increase of rest angle. However, when the rest angle was higher than 32 degrees, segregation was rare. Han et al. studied the influence of particle shape on the angle of repose and bottom porosity distribution of natural particle stacks through experiments. The results show that the main factor affecting the angle of repose and porosity is static friction, followed by particle shape. The angle of repose of the spherical pile is smaller than the angle of repose of the non spherical particles, but the angle of repose of the non spherical particles is not different. Engblom et al. (2012) studied the effects of free fall distance, intermittent discharge and filling, and filling rate on material distribution during silo filling. The results showed that as the free fall distance increased, segregation at the filling site of the silo significantly increased; Intermittent discharge and filling can affect the shape of the material surface inside the silo, and have a significant impact on segregation during filling; As the filling rate of the maximum free fall distance (1.25 m) increases, segregation decreases, but for smaller free fall distances (<1.05 m), segregation is not affected.

However, most of these studies focus on the bi dispersed mixture of inviscid spherical particles in quasi two-dimensional reactors. However, in practical situations, particle size is continuously distributed in both industrial and natural environments; Therefore, this article takes irregular crushed stone particles as the experimental material and studies the surface distribution and segregation characteristics of the three-dimensional accumulation of aggregate particles through the free falling three-dimensional accumulation experiment of binary particle mixing; By changing the content of coarse particles in binary mixtures, the influence of changes in coarse particle content on the degree of segregation of three-dimensional particle piles is studied, providing a basis for improving the concrete preparation process. The flow of particle mixtures is common in geophysical processes and industrial environments. Due to differences in material properties, including size, density, surface roughness, and shape, separation or stratification phenomena often occur. However, particles in geophysical flows and many industrial production processes are non spherical and polydisperse. For example, the granular materials used in civil engineering are often irregularly shaped and use graded particles. Almost all previous studies on particle segregation have focused on spherical or quasi spherical particles, while most have focused on quasi two-dimensional experiments, with little research on the separation behavior of irregular particles. This chapter investigates the distribution law of irregular particle conical piles by studying the free falling accumulation of binary non spherical particle mixtures. By changing the coarse particle content of the mixture, the influence of coarse particle content on the surface and internal segregation of the pile is studied.

2. Test principle

2.1 Test Overview

The indoor testing device is shown in Figure 1, which consists of two parts: a silo and a bracket. The height of the bracket is 150cm, made of stainless steel material, mainly used for lifting the silo. The silo is fixed to the bracket through iron chains and pulleys, and the falling height can be freely adjusted through the pulleys. The silo is made of machine glass to observe the falling process of the mixture in the silo. The silo is composed of a cylinder and a conical funnel as shown in. The cylinder size is: 100mm radius, 400mm height, and 5mm wall thickness. The radius of the outlet at the lower end of the conical funnel is 16mm, the radius at the upper end is 100mm, the inclination angle of the funnel is 45°, and the length of the leakage nozzle is 50mm.



(a) Indoor test device diagram

(b) Gray crushed stone 3mm-5mm

(c) White crushed stone 6mm-9mm

Figure 1. Photographs and morphologies of granular materials

2.2 Test Plan

In order to study the stacking morphology, particle size distribution and segregation patterns on the surface of binary particles under different particle size ratios, the experimental conditions were divided into 7 groups, with the mass percentage of coarse particles as the control variable and a gradient of 10%. The designed experimental conditions are shown in Table 1. The experimental conditions are designed according to Table 1. The initial coarse particle content w in the mixed particles is the percentage of the coarse particle mass in the total mass of the binary particle mixture. In this chapter, the coarse particle content used for the initial mixed particles is w = 20%, 30%, 40%, 50%, 60%, 70%, and 80%. The required particles are weighed according to the total mass required for the test, and then thoroughly mixed. The experiment is divided into two parts: the free fall three-dimensional stacking test and the binary crushed stone particle mixing test. The total mass of the mixture in the three-dimensional stacking test is 50Kg.

Table 1. Design of test conditions

Granular material	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6	Condition 7
Grey crushed stone (3-5mm)	20%	30%	40%	50%	60%	70%	80%
White crushed stone (6-9mm)	80%	70%	60%	50%	40%	30%	20%

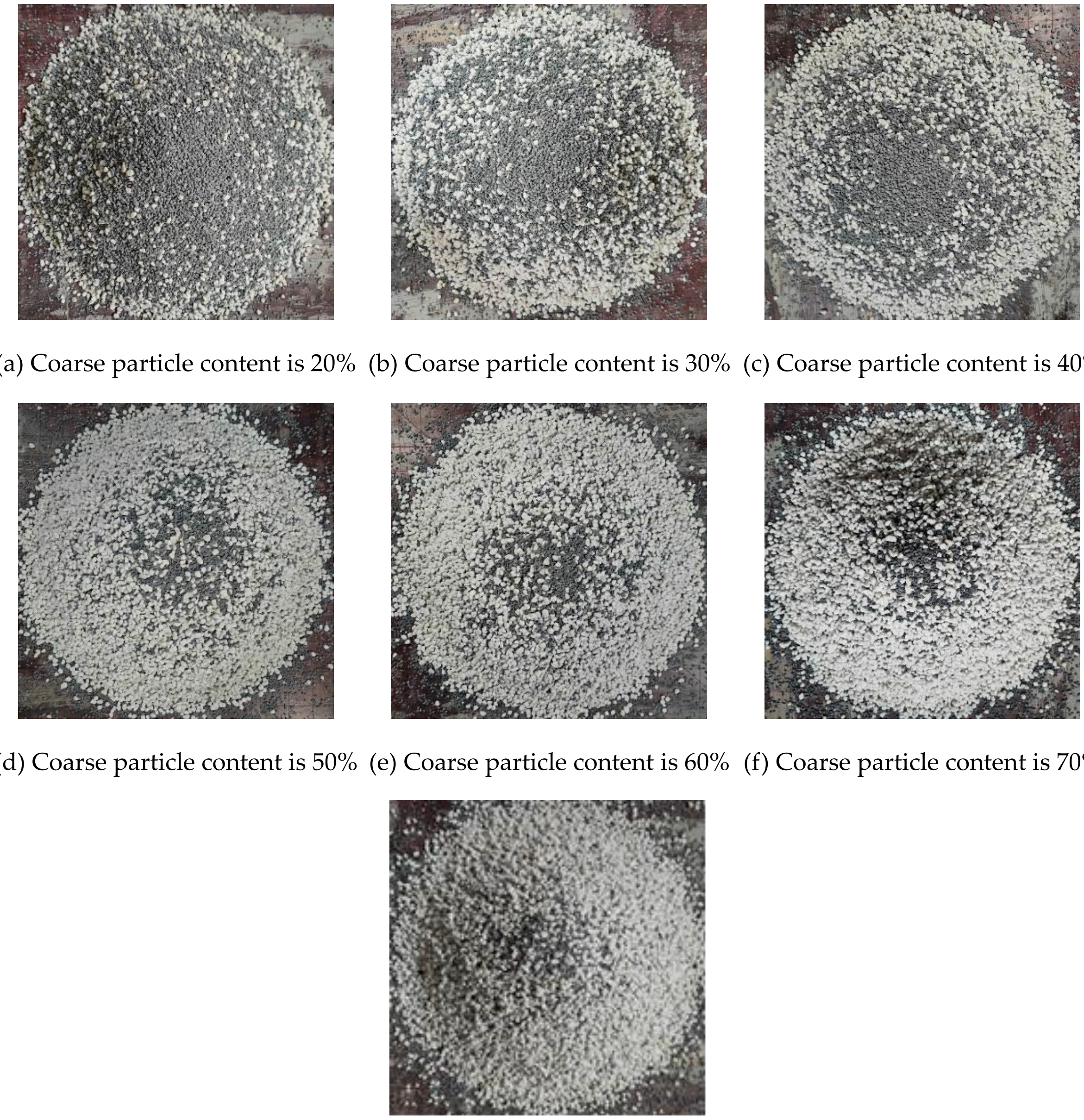
This article studies the degree of segregation of particles after stacking through image processing technology. It is necessary to collect and analyze images of the distribution of particle mixtures before stacking to obtain the distribution of particles before stacking, in order to compare and study with the results after stacking, and analyze the degree of segregation of particles after stacking. In the experiment, the control parameters of the mixture are controlled through quality control, while in processing image data, the area occupied by particles in the image is identified. Therefore, in order to determine the relationship between the proportion of particles in the image and the particle mass fraction, particle mixing experiments are conducted.

3. Test Results

3.1 Analysis of the Overall Characteristics of the Accumulation Body

3.1.1 Surface Distribution Pattern of Accumulation Body

Figure 2 shows the 360 degree accumulation results of free fall accumulation under different particle size and mass ratios from a top view angle. The spatial distribution characteristics of the accumulation body are observed from a top view angle. The particle stacking body has a circular shape on the plane, and obvious particle separation can be observed on the surface of the particle stacking body. The area of particle separation is divided into two parts. Firstly, large white particles are distributed in a circular shape at the front edge of the particle pile; The second is that gray fine gravel particles gather in the central area of the top of the particle pile. In the middle of the particle pile, white coarse particles and gray fine particles are evenly distributed. As the content of white coarse particles increases, the annular area of large white particles at the front edge of the particle pile increases; The area of gray fine particles on the top of the pile decreases as the initial content of coarse particles increases.



(a) Coarse particle content is 20% (b) Coarse particle content is 30% (c) Coarse particle content is 40%

(d) Coarse particle content is 50% (e) Coarse particle content is 60% (f) Coarse particle content is 70%

(g) Coarse particle content is 80%

Figure 2. Three-dimensional stacking top view of binary irregular particle mixtures

From Figure 3, it can be observed that there is a clear phenomenon of particle separation on the surface of the particle pile. Coarse particles gather on the surface of the particle pile and the bottom area of the pile, while fine particles gather on the top area of the pile. In the middle position of the pile surface, coarse and fine particles are in a mixed state. As the initial coarse particles increase, the area of white coarse particles at the bottom of the particle pile increases along the top of the pile.

(a) Coarse particle content is 20%

(b) 30% coarse particle content

(c) 40% coarse particle content

(d) 50% coarse particle content

(e) 60% coarse particle content

(f) Coarse particle content is 70%

(g) 80% coarse particle content

Figure 3. Oblique view of 3d stacking of binary irregular particle mixtures

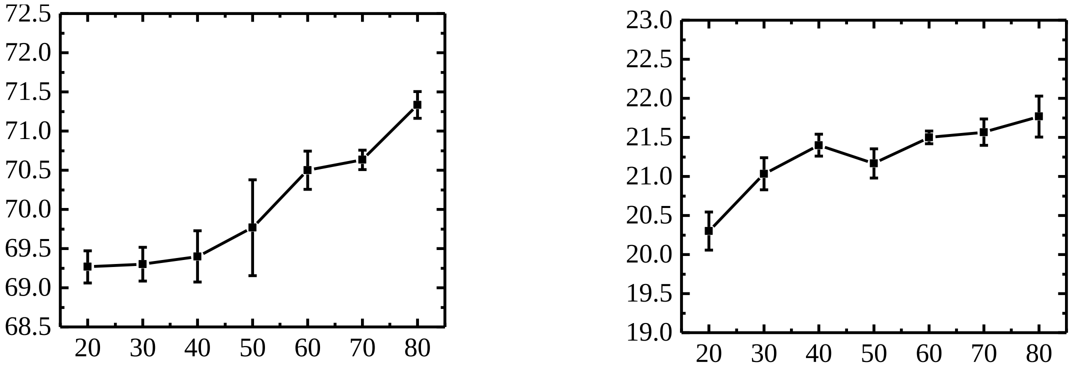
3.1.2 Stacking Diameter and Height

After the stacking is completed, use a ruler to measure the stacking radius and height of the 360 degree particle pile, respectively, to describe the stacking shape of the particle pile. The measurement results are shown in Table 2:

Table 2. Binary irregularly shaped particle mixture 360°heap height and accumulation diameter

Coarse content fraction	Stacking diameter R				Stacking height H			
	1	2	3	average	1	2	3	average

20%	69.0	69.5	69.3	69.3	20.5	20.3	20.1	20.3
30%	69.0	69.5	69.4	69.3	21	21.4	20.6	21.0
40%	69.0	69.8	69.4	69.4	20.9	21.6	21.7	21.4
50%	69.8	69.0	70.5	69.8	20.8	21.4	21.4	21.2
60%	70.8	70.2	70.5	70.5	21.1	21.7	21.7	21.5
70%	70.5	70.6	70.8	70.6	21.4	21.7	21.7	21.6
80%	71.5	71.1	71.4	71.3	21.7	21.8	21.9	21.8



(a) Stacking diameter (b) Stacking height

Figure 4. Tacking height and stacking diameter of binary irregular particle mixtures

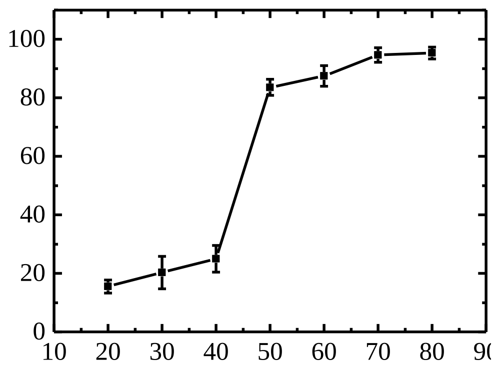
From Figure 4, it can be seen that due to the irregular shape of the particles, the standard deviation of the test results is relatively large, but it can still be seen that the stacking diameter and height vary with the content of coarse particles. The diameter and height of particle accumulation exhibit a monotonic trend. The stacking diameter of particles increases with the increase of large particle content, while the stacking height of particles decreases with the increase of large particle content.

3.2 Distribution Pattern of Particle Accumulation

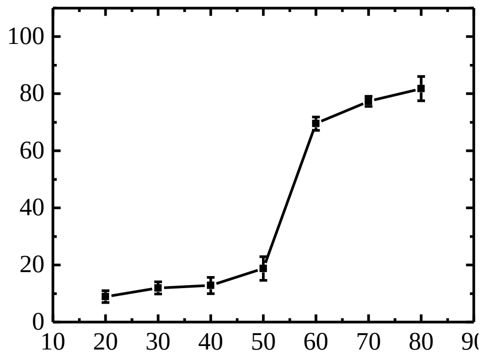
3.2.1 Distribution Pattern of Particle Accumulation Surface Under Top View Angle

To study the distribution of particles in the accumulation body from the perspective of top view, take the whole of the particle pile and the center of the particle pile center (the radius of the circle is half of the radius of the pile) in the top view as shown in Figure 5, where the overall area of the particle pile is represented by S1, and the center circle area is represented by S2. Perform digital image processing on the overall image and the center of the center circle, and then calculate the proportion of coarse particles (white particles) in the particle pile at a top view angle. The calculation results are shown in Figure 6.

Figure 5. Schematic diagram of sampling position of heap



(a) Concentration of coarse particles in region S1



(b) Concentration of coarse particles in region S2

Figure 6. The coarse particle concentration curve of l accumulation from top view

As shown in Figure 6(a), as the percentage of coarse particles increases, the proportion of coarse particles under the viewing angle after vertical stacking also increases, and the entire concentration curve of coarse particles shows an S-shape. When the initial coarse particle content is between 20% and 40%, the concentration of coarse particles in region S1 increases with the initial coarse particle content. As the content of coarse particles increases, there is a sudden change in the concentration of coarse particles after stacking. When the content of coarse particles increases from 40% to 50%, the concentration of coarse particles in region S1 sharply increases from about 35% to about 80%. As shown in 5(b), in the circular region S2, this range ranges from 50% to 60%, and segregation phenomenon can also be seen from the figure. Under the same coarse particle content, the concentration of coarse particles in the center circle S2 of the pile is generally lower than the proportion of overall S1. When the coarse particle content is 50%, the degree of particle segregation is the highest.

3.2.2 Distribution Pattern of Particles on the Surface of Particle Stacking

In order to obtain the distribution pattern of the particle pile surface, when collecting the image results of the particle pile surface, the camera shooting angle should be perpendicular to the inclined plane of the particle pile as much as possible. As shown in Figure 7, samples are taken from the collected images, with a sampling area width of 1200 pixels and a length equal to the length of the particle stack. Divide the sampling area X into four parts, from the top of the pile to the bottom of the pile, X1, X2, X3, and X4, and perform the same steps for the four positions of the pile, front, back, left, and right. By using digital image processing technology, the image results were analyzed and statistically analyzed. The average value of the data was taken for each experiment, and three experiments were repeated for each experimental condition. The test results are shown in Table 3.

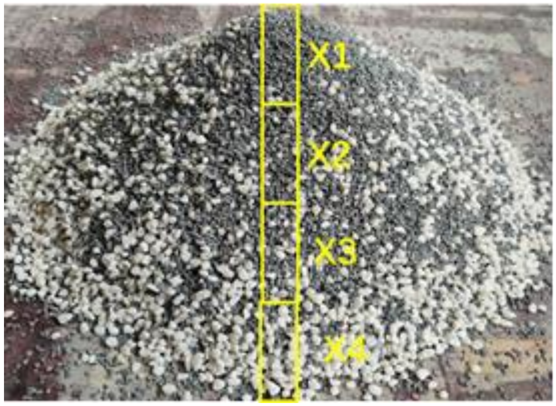


Figure 7. Schematic diagram of sampling position on the surface of the accumulation

Table 3. Calculation results of coarse particle concentration on accumulation surface

Test conditions	Coarse particle	Number of tests	Zone X	X1	X2	X3	X4
		1	17.80%	3.32%	11.68%	18.32%	35.19%
Condition 1	20%	2	14.69%	6.15%	7.25%	18.14%	30.88%
		3	17.44%	6.57%	9.32%	19.06%	31.06%

		1	23.27%	6.05%	17.52%	26.26%	43.43%
Condition 2	30%	2	23.71%	6.46%	14.94%	26.93%	41.74%
		3	24.37%	10.47%	15.47%	23.90%	41.49%
		1	26.17%	8.52%	16.10%	29.27%	42.99%
Condition 3	40%	2	31.46%	12.96%	23.66%	32.09%	48.09%
		1	29.14%	14.97%	15.31%	34.21%	44.74%
		1	39.25%	22.15%	30.34%	42.92%	52.00%
Condition 4	50%	2	37.29%	16.78%	25.27%	35.68%	49.05%
		3	39.45%	24.98%	29.31%	44.19%	53.20%
		1	61.63%	21.31%	40.74%	89.90%	97.55%
Condition 5	60%	2	72.06%	27.15%	48.07%	93.71%	97.74%
		3	64.75%	28.05%	42.83%	91.70%	94.59%
		1	77.37%	36.29%	62.51%	96.87%	97.79%
Condition 6	70%	2	77.42%	36.18%	63.28%	97.00%	94.83%
		3	80.70%	37.82%	59.15%	98.70%	98.36%
		1	89.99%	74.74%	84.37%	97.54%	97.52%
Condition 7	80%	2	91.90%	68.88%	89.10%	99.53%	97.01%
		3	93.36%	82.04%	83.71%	97.16%	97.53%

Figure 8 shows the overall concentration curve of coarse particles on the surface of a pile of binary nearly spherical particles with different percentages of coarse particle content. From the experimental results, it can be seen that the deviation of the three test results is not significant, and the repeatability of the experiment is good, which can reflect the distribution pattern of particles on the surface of the pile. The concentration of coarse particles on the surface of the stacked body increases with the initial content of coarse particles, and the proportion of coarse particles on the surface after stacking also increases. When the content of coarse particles increases from 50% to 60%, the particle concentration on the surface of the pile increases sharply from about 35% to about 70%.

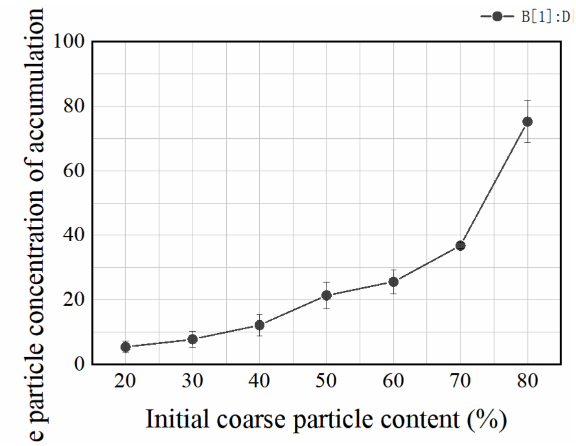
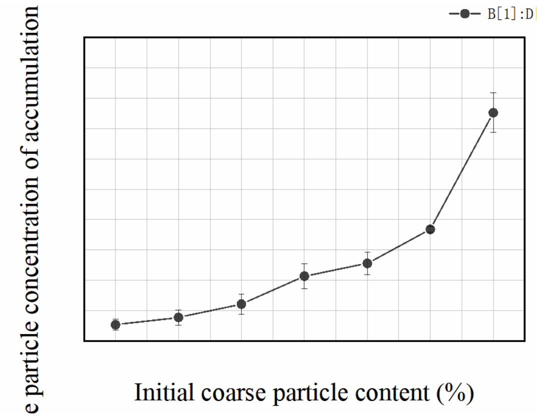
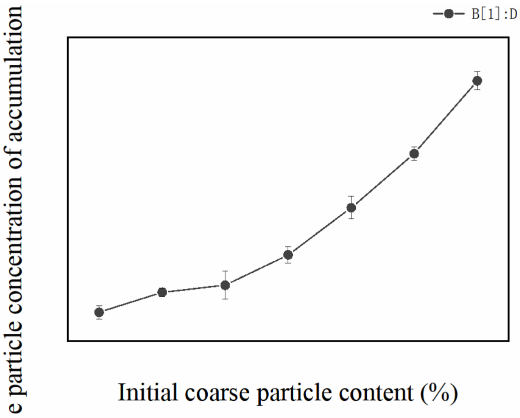


Figure 8. Concentration curve of coarse particles after accumulation in sampling area

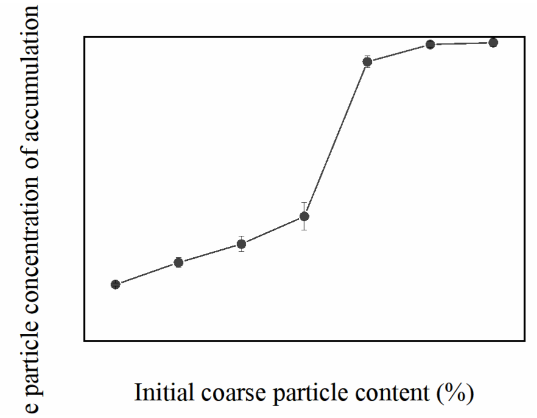
Figure 9 shows the proportion of coarse particles at different positions on the surface of the pile. As the content of coarse particles increases, the proportion of coarse particles on the surface of the pile also increases. When the concentration of coarse particles on the surface of the pile increases, there is a sudden change in the lower edge parts X3 and X4 of the particle accumulation body. In the graph, it can be seen that the proportion of coarse particles in the top area X1 is smaller than that in the bottom area X4, indicating a phenomenon of particle segregation. Coarse particles gather at the bottom of the pile during the accumulation process, while fine particles gather at the top. When the content of coarse particles is 60%, the particle segregation phenomenon is most obvious. At the same initial coarse particle content, the concentration of coarse particles on the surface of the particle pile increases sequentially from the bottom to the top of the pile. In the figure, it is shown that under the same initial coarse particle content, the concentration of coarse particles X4>X3>X2>X1.



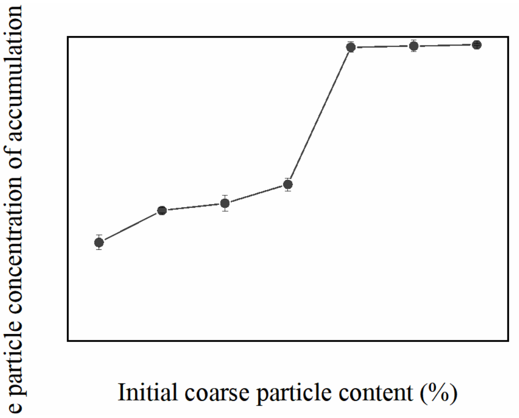
(a) Concentration of coarse particles in region X1



(b) Concentration of coarse particles in region X2



(c) Concentration of coarse particles in region X3



(d) Concentration of coarse particles in region X4

Figure 9. Distribution of coarse particles at different positions on the surface of accumulation

3.3 Analysis of Segregation Characteristics of Accumulations

3.3.1 Initial Concentration of Particle Mixture Before Stacking

Prepare the mixture according to the designed working conditions in Table 1. After weighing the particles, thoroughly mix them, collect images after mixing, and analyze the proportion of coarse particles in the images. Repeat the experiment 6 times for each working condition. The results show the concentration of coarse particles in the mixture before stacking, use the least squares method to perform linear fitting on the calculated results, and the fitted equation is:

$$y = 0.01436x - 0.23759 \tag{1}$$

Substitute the initial coarse particle content into formula (1) and sequentially calculate the initial concentration C0 of coarse particles in the mixture corresponding to different coarse particle contents in the image, as shown in Table 4.

Table 4. The concentration corresponding to the mass fraction of coarse particles before mixing

Initial coarse particle content	20%	30%	40%	50%	60%	70%	80%
Initial concentration of coarse particles in the mixture c_0	4.96%	19.32%	33.68%	48.04%	62.40%	76.76%	91.12%

3.3.2 Segregation of Particle Stacks at a Top View Angle

By using image processing technology to analyze the segregation of particle piles at a top view angle, the results are shown in Figure 10:

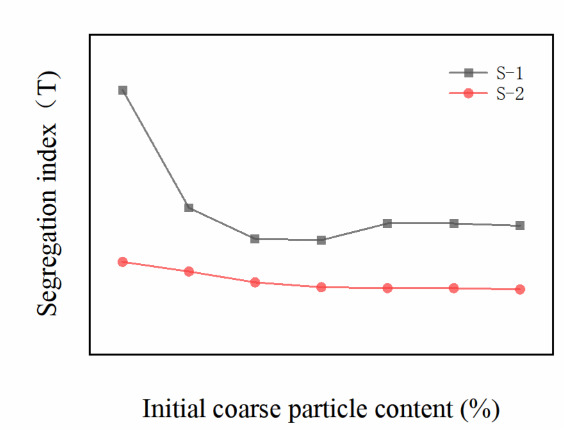


Figure 10. Segregation curves of particle heap from top view

From Figure 10, it can be seen that as the content of coarse particles increases, the segregation of accumulated particles decreases and then tends to stabilize. When the initial particle content is 20%~50%, the overall S1 decreases with the increase of the initial particle content. When the initial particle content is 20%, the surface segregation degree of the particle pile is the highest at a top view angle; The degree of segregation of S2 in the central region of the circle increases with the increase of coarse particle content, and it is in a negative segregation state, that is, the concentration of coarse particles after stacking is lower than the concentration of the mixed state before stacking. When the initial coarse particle content is 50%~80%, the segregation situation of the overall S1 and central S2 of the pile remains basically unchanged.

3.3.3 Surface Segregation of Particle Stacks

From Figure 11, it can be seen that as the initial coarse particle content increases, the degree of segregation at various positions on the surface of the particle pile tends to stabilize. When the initial coarse particle content is between 20% and 50%, the segregation coefficients of X4, X3, and X decrease with the initial coarse particle content. When the initial coarse particle content exceeds 50%, the coarse segregation coefficient on the surface of the pile tends to 0, indicating that the overall concentration of coarse particles on the surface of the pile is basically the same as before the pile, while the particles are in a mixed state in the local position of the pile, in a positive segregation state in the lower region (X3 and X4) of the pile, and in a weak segregation state in the upper region (X1 and X2) of the pile.

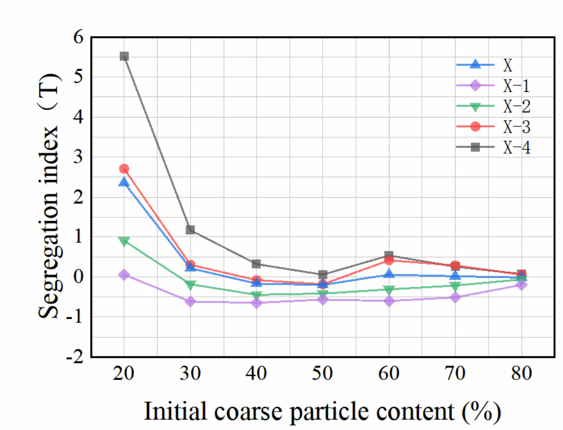


Figure 11. The particle segregation curve on the surface of granular heap

3.3.4 Surface Segregation of Particle Stacks

From Figure 12, it can be seen that when the initial coarse particle content is 20%, the closer it is to the surface of the pile, the greater the degree of segregation, such as N15 being greater than N16 and greater than other positions. The segregation coefficient (N15) at the edge area near the bottom of the accumulation decreases with the initial coarse particle content. The segregation coefficient in the internal region of the accumulation (N10, N11, and N16) is basically stable and does not change with the change of coarse particle content. At the same time, the internal segregation state is in a negative segregation state, and the concentration of coarse particles inside the pile is lower than the concentration before stacking, while it is in a positive segregation state on the surface of the pile.

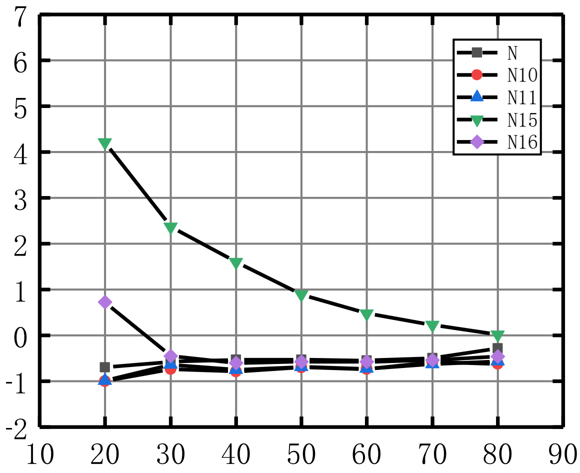


Figure 12. The internal particle segregation curve of granular heap

4. Conclusion

This article conducts free fall stacking experiments on aggregate particle mixtures with different coarse particle contents. Image processing technology is used to process and analyze the particle stack, studying the distribution patterns of the surface and interior of the particle stack, and studying the impact of changes in coarse particle content in the mixture on the particle distribution and segregation degree of the particle stack. The following conclusions are drawn:

(1) The three-dimensional cone formed by the free falling accumulation of binary irregular particle mixtures exhibits obvious particle separation phenomena. On the surface of the pile, coarse particles gather in the lower area of the pile, and fine particles gather in the central area of the top of the pile. Inside the pile, coarse particles gather at the bottom of the particle pile;

(2) A binary particle mixture composed of irregularly shaped particles with different particle sizes forms a conical pile after free falling and stacking, and the distribution of particles on the surface and inside the pile has a certain regularity. The distribution of particles along the slope direction on the surface of the pile is basically the same;

(3) As the initial coarse particle content increases, there is a sudden change in the content of particles on the surface of the particle pile, that is, the particle content on the surface of the pile increases sharply within a certain range, and the particle distribution curve shows an S-shape;

(4) The segregation pattern on the surface of the particle pile decreases with the increase of coarse particle content, while inside the particle pile, the segregation of particles is in a stable state and does not change with the change of coarse particle content in the mixture. The segregation of particles on the surface of the pile is in a positive segregation state, while it is in a negative segregation state inside the pile body.

Through the research in this article, it is of great significance to improve the sampling and inspection process of mechanical sand and gravel aggregates in the laboratory, ensure the quality of mechanical sand and gravel, improve the effective utilization rate of mechanical sand and gravel, save mining resources, and protect the ecological environment.

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