Experimental Calibration of Parameters of Discrete Element Model for Ginkgo Nut

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In order to ensure the reliability of the simulation test on the shelling process of ginkgo nuts, the physical parameters (characteristic dimensions, thousand grain mass, moisture content, density, Poisson's ratio, elastic modulus, and shear modulus), contact parameters (restitution coefficient, static friction coefficient, and dynamic friction coefficient) and actual stacking angle of the ginkgo nuts were measured by physical test methods. A stacking angle test model was established, and simulation tests were performed. Parameter intervals for the simulation were selected according to the measured parameters. Three factors affecting the stacking angle significantly were determined using the Plackett–Burman test: static and dynamic friction coefficients of ginkgo nut–ginkgo nut and the restitution coefficient of the ginkgo nut–steel plate. Each factor's range was selected using the steepest climbing test. A quadratic polynomial regression model of the stacking angle considering these factors was obtained using the Box–Behnken test. Taking the actual stacking angle of 39.59° as the optimization objective, the optimal combination was formed: the static and dynamic friction coefficients were 0.5 and 0.36, respectively, and the restitution coefficient was 0.42. This combination was used for the verification test. The stacking angle was found to be 41.12°. The relative error was 3.86%, indicating that the model is reliable and can provide a useful reference for relevant research.

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Keywords: Ginkgo nut; Stacking angle; Discrete element; Parameter calibration; Experiment

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INTRODUCTION

Ginkgo biloba (gingko) is planted widely in China (Liu *et al*. 2022). The number of cultivated plants exceeds 2.5 billion and is still increasing rapidly every year (Zhang *et al*. 2022a). *Ginkgo biloba* is an important biomass resource. Many studies have been carried out on the extraction of biomass resources such as cellulose and lignin from gingko trees, leaves, and shells (Usuki *et al*. 2011; Andersson *et al*. 2015; Jiang *et al*. 2018). The ginkgo nutshell contains about 44.3% cellulose, 46.3% lignin, and 7.0% hemicelluloses (Ni *et al*. 2020), which has been successfully used as a raw material for the preparation of activated carbon and biosorbents (Crouvisier-Urio *et al*. 2017; Qin *et al*. 2019). Moreover, ginkgo nutshell is widely used in medicine (Nowak *et al*. 2021; Shen *et al*. 2021) and chemistry (Jiang *et al*. 2018; Hong *et al*. 2021).

Shelling is the routine method for obtaining ginkgo nutshell. The shell is subjected to mechanical effects such as extrusion and friction during the shelling process. Therefore, the study of the extrusion process is beneficial to obtain a reasonable combination of shelling parameters and thereby improve the shelling quality. Discrete element method (DEM) is an effective method to study particulate materials, which has been widely used in different fields. Discrete element simulation can simulate the extrusion process of ginkgo nut, which provides a useful reference for force analysis (Yu *et al*. 2005).

For discrete element simulation, the intrinsic parameters and contact parameters of the simulation model need to be defined. The intrinsic parameters include density, shear modulus, *etc*., and the values are consistent with the real values. Contact parameters include restitution coefficient, as well as the static friction coefficients between particles and between particles and contact materials. Due to the difference in geometry between the particle simulation model and the real particles, the simulation contact parameters are in error from the real values, and the contact parameters need to be calibrated. Parameter calibration can effectively ensure the reliability of simulation tests (Horabik *et al*. 2016; Coetzee. 2017; Hou *et al*. 2020). Li *et al*. (2019) increased the average particle size of the wheat particle simulation model and calibrated the relevant parameters of wheat particles. Wen *et al*. (2020) proposed a simulation parameter calibration method by comparing the measurement results of the repose angle using different particle characteristic test methods. Liu *et al*. (2018a) conducted uniaxial compression and impact tests by combining a nonlinear viscoelastic contact model with a hysteretic model to calibrate the normal damping parameters between wheat grains, and between wheat grains and steel plates. Liu *et al*. (2018b) optimized and calibrated the simulation parameters of micro-potatoes by combining experimental measurements and simulation tests. Santos *et al*. (2015) used the DEM to measure the repose angle of a cherry using a central combination test design and experiment; they then optimized the relevant parameters of the DEM simulation. Coetzee *et al*. (2010) determined the particle stiffness through compression tests and obtained relevant parameters by trial. The DEM modeling process can be simplified by calibrated simulation parameters.

In summary, several researchers have conducted parameter calibration for wheat, potato, cherry, and other foods. However, most of the existing studies have been conducted on materials having relatively regular shapes and uniform compositions. The composition of ginkgo kernels and shells varies greatly. Meanwhile, due to the gap between the kernel and shell, they can move relative to each other. Therefore, compared to the existing research objects, the properties of ginkgo nut are more complex. There have been few studies on ginkgo nuts. Ch'ng *et al*. (2013) tested some physical characteristics data of ginkgo nuts at a moisture content of 45.53% (±2.07) (wet basis) and ginkgo kernels at 60.13% (±2.00) (wet basis). At the same time, the coefficient of static friction for nuts and kernels was determined by using plywood, glass, rubber, and galvanized steel sheet. The study provided useful inputs for this study.

In this study, the ginkgo nut discrete element simulation parameters were calibrated by comparing the simulated value and the physical value of the stacking angle in order to improve the reliability of the simulation test of ginkgo nut shelling process. It is important for the design and optimization of the key components of the sheller, which is conducive to improving the quality and efficiency of shelling. There are two main contributions: (1) Compared with materials with uniform composition, the properties of ginkgo nut are more complex, and the parameter calibration study has been rarely reported. This paper provides a useful reference for the study of materials having such complex aspects. (2) Due to the special properties of ginkgo nut, there is a large error in measuring the restitution coefficient using the traditional oblique collision method. In this paper, with the help of a high-speed camera, the velocities of ginkgo nuts before and after collision with the horizontal contact surface were measured, which could significantly reduce the calculation error.

EXPERIMENTAL

Materials

The ginkgo nut breed selected for this study was "Da Fo Zhi". It was obtained from Liuchen Town, Taixing City, Jiangsu Province, China. Taixing is a famous ginkgo-producing area and plays a vital role in China. The growth period of ginkgo nuts is about 90 days. In this study, ginkgo nuts were selected for the experiment after 85 days of growth. When the fruit had matured, it was harvested manually, peeled, and dried. The selected nuts are spindle-shaped, and their coated shells are compact. The chemical composition of the shell of ginkgo nut used in this study is shown in Table 1. The results differed from other studies due to differences in varieties, growth periods, *etc.*

Table 1. Chemical Composition of the Ginkgo Nutshell

Composition	Cellulose (wt%)	Lignin (wt%)	Hemicellulose (wt%)
Ginkgo nutshell	41.37±1.52	48.61±0.94	6.85±0.75

Measurement of Physical Parameters

Measurement of basic physical parameters

A thousand ginkgo nuts were selected randomly. Then, the characteristic dimensions were measured by a vernier caliper (Harbin Measuring & Cutting Tool Group Company Ltd., Harbin, China). The test method drew on the relevant studies (Hou *et al*. 2020). The characteristic dimensions of the ginkgo nut are shown in Fig. 1.

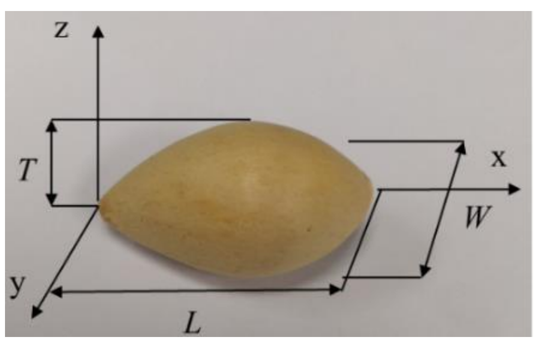

Fig. 1. Characteristic dimensions of the ginkgo nut

The thousand grain mass of the ginkgo nut was measured according to GB/T 5519 (2018) standard. Five hundred intact ginkgo nuts were randomly selected and weighed with an electronic balance (Puchun Measure Instrument Co., Ltd., Shanghai, China). The moisture content was measured using an electronic balance and an electric convection oven (Nanjing Experimental Instrument Factory, Nanjing, China) according to GB/T 3543.6 (1995) standard. The particle density was obtained using an electronic balance and a measuring cylinder (Jiangsu Sanaisi scientific Co., Ltd., Yancheng, China). Each parameter was tested ten times and averaged. The results are presented in Table 2.

Table 2. Basic Physical Parameters of the Ginkgo Nut

Parameter	Maximum	Minimum	Mean	Standard Deviation
Length (mm)	25.3	24.4	24.9	0.31
Width (mm)	15.6	14.5	15.1	0.38
Thickness (mm)	13.6	12.1	12.8	0.45
Thousand grain mass (g)	2087.9	1965.7	2031.6	26.4
Moisture content (%)	28.8	27.6	28.3	0.35
Density (kgm^{-3})	897.9	857.5	875.4	15.2

Measurement of Poisson's Ratio

Poisson's ratio was measured according to GB/T 22315 (2008). Ten ginkgo nuts were randomly selected, and their original dimensions in the Z and X directions were recorded. An extrusion test of the ginkgo nuts was carried out using an electronic universal testing machine (Shenzhen Suns Technology Stock Co., Ltd., Shenzhen, China). The Poisson's ratio was obtained by testing the dimensional change of a ginkgo nut at the cracking limit in the Z and X directions before and after pressure. In the test, the plane indenter was used to pressure along the X-axis direction at a constant speed (0.2 mm/s), and the pressure was stopped when the ginkgo shell broke. The vernier caliper recorded the deformation at the load crack limit along the Z-axis direction, and the universal testing machine recorded the deformation along the X-axis direction. The changes in X-axis and Z-axis directions were measured individually with a testing accuracy of 0.02 mm. The Poisson's ratio of ginkgo nuts was obtained using Eq. 1,

$$\mu=\left|\frac{\varepsilon_x}{\varepsilon_z}\right|=\frac{\Delta X / X}{\Delta Z / Z} \tag{1}$$

where μ is the Poisson's ratio, ε_x is the X-axis strain, ε_z is the Z-axis strain, ΔX is the X-axis deformation (mm), X is the X-axis dimension (mm), ΔZ is the Z-axis deformation (mm), and Z is the Z-axis dimension (mm). The Poisson's ratio was tested ten times and averaged. The Poisson's ratio was 0.34 and the standard deviation was 0.018. Poisson's ratio is an important property of agricultural materials, usually within a certain range that varies with the type and condition of the material. Therefore, the Poisson's ratio obtained in this study differs from other agricultural materials (Liu *et al*. 2018b; Hou *et al*. 2020).

Measurement of elastic modulus and shear modulus

The Hertz contact stress method was used to determine the elastic modulus of ginkgo nuts according to ASAE S368.4 (2017). Ten ginkgo nuts were randomly selected, and their characteristic dimensions were tested before the experiment. During the test, the chosen sample was put on the working plane of the electronic tester and compressed along the X-axis direction. The pressing speed was maintained at 0.1 mm/s. The loading time was set 10 s. The elastic modulus of the ginkgo nuts was calculated using the Hertz formula,

$$E=\frac{0.338F(1-\mu^2)}{D^{3/2}}[K_U(\frac{1}{R_U}+\frac{1}{R_U^{'}})^{1/3}+K_L(\frac{1}{R_L}+\frac{1}{R_L^{'}})^{1/3}]^{3/2} \tag{2}$$

$$\cos\theta=(\frac{1}{R_U}-\frac{1}{R_U^{'}})/(\frac{1}{R_U}+\frac{1}{R_U^{'}}) \tag{3}$$

where E is the elastic modulus (MPa), F is the compression force (N), D is the dimensional change of the ginkgo nut (mm), μ is the Poisson's ratio, R_U is the minimum radius of curvature of the convex surface of the sample at the point of contact with the upper plate (mm), $R_U^{'}$ is the maximum radius of curvature of the convex surface of the sample at the point of contact with the upper plate (mm), R_L is the minimum radius of curvature of the convex surface of the sample at the point of contact with the lower plate (mm), $R_L^{'}$ is the maximum radius of curvature of the convex surface of the sample at the point of contact with the lower plate (mm), K_U is a constant related to principal curvature radius, K_L is a constant related to principal curvature radius, and θ is the angle between the contact surface of the ginkgo nut and the contact surface of the probe (°).

K_U and K_L can be retrieved from the ASAE S368.4 (2017) standard by calculating cos θ. As the radius of curvature of the ginkgo nut is almost the same as that of the upper and lower contact surfaces, Eq. 2 can be simplified as

$$E = \frac{0.338F(1-\mu^2)}{D^{3/2}}[2K_U(\frac{1}{R_U}+\frac{1}{R_U^{'}})^{1/3}]^{3/2} \tag{4}$$

where $R_U = T/2$, $R_U^{'} = [T^2 + (L/2)^2]/2T$.

The mean elastic modulus of the ginkgo nut was 18.92 MPa and the standard deviation was 1.91. Therefore, the shear modulus was obtained as 7.09 MPa using Eq. 5,

$$G = \frac{E}{2(1+\mu)} \tag{5}$$

where G is the shear modulus (MPa).

Measurement of Contact Parameters

Measurement of restitution coefficient

The restitution coefficient is the ratio of the post-collision rebound normal velocity to the pre-collision normal velocity. The oblique collision method is usually used to measure the restitution coefficient, which is calculated by manually measuring the drop and rebound distances of particles (Wang *et al*. 2021). The conventional method has problems such as large measurement errors (Wang *et al*. 2021). The method seems to be mainly suitable for materials with relatively regular shape and uniform composition. Ginkgo kernels and shells are highly variable in composition and can move relative to each other. In order to minimize the error, a camera was used to record the collision process of a vertically falling ginkgo nut and a horizontal contact material, and the normal velocities before and after the collision were calculated. Then, the restitution coefficient was calculated. This method can effectively reduce the measurement error.

The test principle of the restitution coefficient is shown in Fig. 2. The ginkgo nut falls freely from the placement hole of a drop frame. The vertical displacement and corresponding instant time before the collision with the contact material are recorded with the aid of a background plate and a high-speed camera. Then, the pre-collision normal velocity (v_0) is calculated. The same method is used to record the vertical displacement and corresponding time of the ginkgo nut before it reaches the highest point after collision with the contact material. The next step is to calculate the post-collision normal velocity (v_z), which is the velocity of the post-collision velocity (v) in the z-direction. The restitution coefficient can be calculated using Eq. 6,

$$e = \frac{v_z}{v_0} \tag{6}$$

where e is the restitution coefficient; v_z is the post-collision normal velocity of ginkgo nut (m/s); and v_0 is the pre-collision normal velocity of ginkgo nut (m/s).

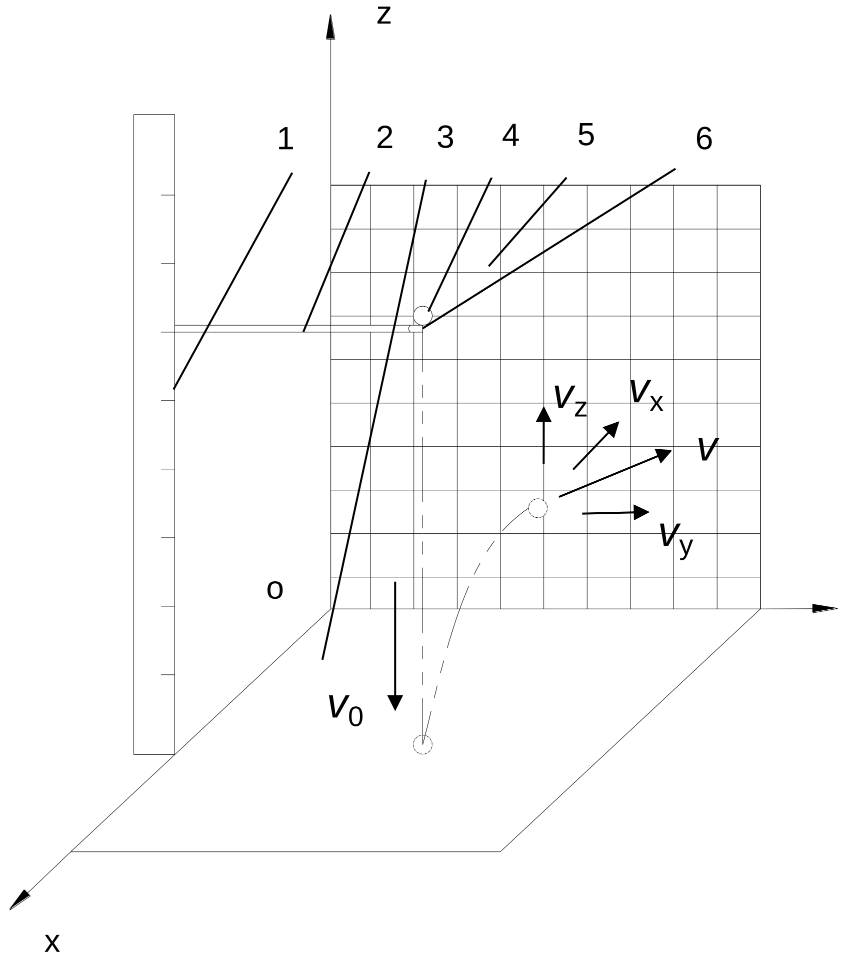

Fig. 2. Test principle of the restitution coefficient.1: Ruler; 2: Drop frame; 3: Contact material; 4: Ginkgo nut; 5:Background plate; 6: Placement hole
Note: v is the post-collision velocity; v_x, v_y, and v_z are the post-collision velocity in x-direction, y-direction, and z-direction, respectively.

According to the above principles, the restitution coefficients of the ginkgo nut–steel plate and ginkgo nut–ginkgo nut were tested. The measurement setup of the test is shown in Fig. 3, which mainly consists of a display, a drop frame, a background plate, a light source, a high-speed camera, and a base plate, *etc*. During the test, the contact material to be tested was placed on the base plate. The ginkgo nut was released from the placement hole with an initial velocity of 0 m/s and rebounded after colliding with the contact material. Videos and photographs of the ginkgo nut collision were captured using a high-speed camera (Fastec Imaging, San Diego, CA, USA). The camera was set at 800 f/s. Therefore, the time interval between each photo was 1.25 ms. Coordinate paper was taped to the background plate, and the falling distance could be obtained through the background plate. The pre-collision normal velocity (v_0) was calculated by measuring the falling distance of the particle before collision within 5 ms. Similarly, the post-collision normal velocity (v_z) was calculated by measuring the rise distance of the particle after collision within 5 ms. González-Montellano *et al*. (2012) utilized a similar method to measure restitution coefficients, and in order to avoid the particles from being subjected to other forces or rotating, the particles were released by changing the vacuum level. In this study, the ginkgo nut fell through the placement hole and was subjected only to gravity, avoiding other forces. Photographs of the bottom surface of the particle colliding with the contact material were selected. When the particles rotated so that the protruding prongs collided with the contact material, the direction of motion changed significantly, so these photographs were excluded. The restitution coefficient is an intrinsic property of granular materials and does not change due to the change in the drop height of the material. In this study, the height of the drop frame was set to 200 mm.

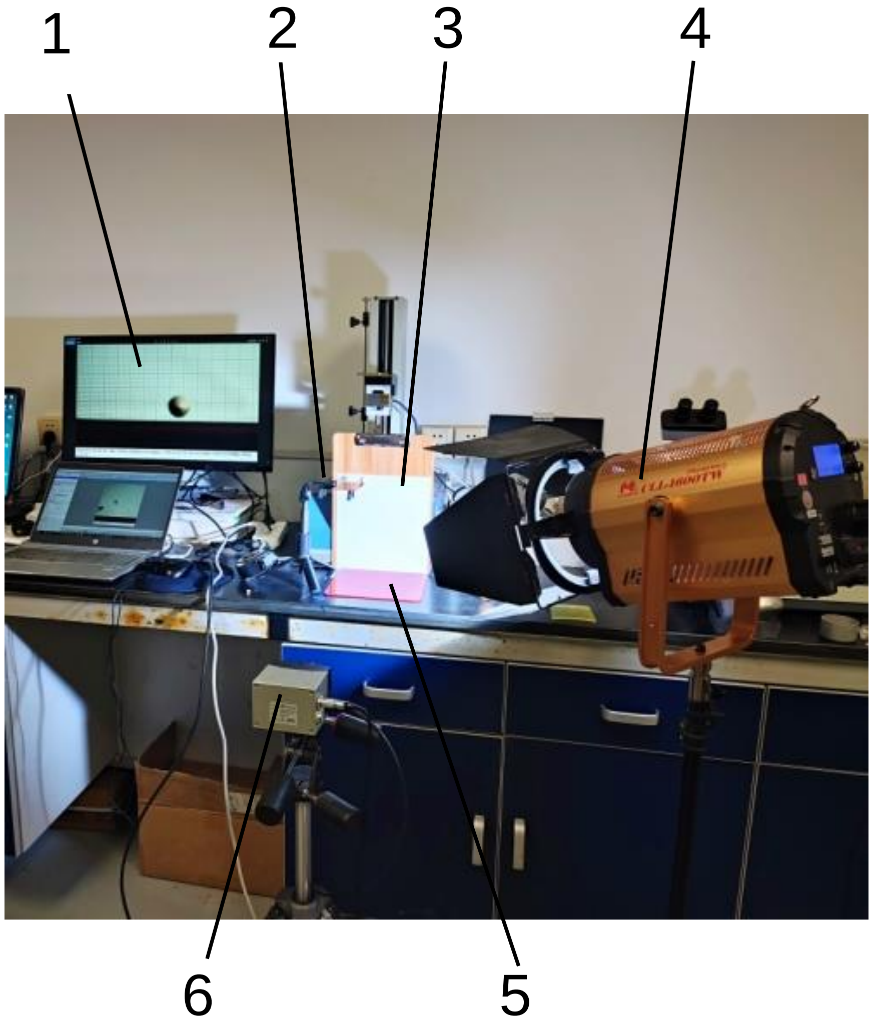

Fig. 3. Drop impact test.1: Display; 2: Drop frame; 3: Background plate; 4: Light source; 5: Base plate; 6: High-speed camera

The restitution coefficient was tested 20 times, and the calculation results of Eq. 6 were averaged. The restitution coefficients of the ginkgo nut–steel plate was 0.32 and the standard deviation was 0.022. The restitution coefficients of the ginkgo nut–ginkgo nut was 0.38 and the standard deviation was 0.034.

Measurement of static friction coefficient

In this study, the slope method was used to determine the coefficient between a ginkgo nut and different materials according to ASTM D4918-97(2002). The principle of measurement is presented in Fig. 4.

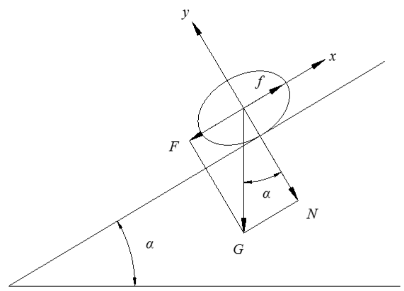

Fig. 4. Measurement principle of the static friction coefficient

When the ginkgo nut is in the critical state of downward sliding in the X direction,

$$F = f \tag{7}$$

where F is the component force of gravity on the ginkgo nut in the X direction, N; and f is the static friction between the two materials (N).

F and f were determined from Eqs. 8 and 9, respectively,

$$F = G \sin a \tag{8}$$

$$f = \gamma N = \gamma G \cos a \tag{9}$$

where G is the force of gravity (N); α is the angle of static friction, °; γ is the coefficient of static friction; and N is the component force of gravity (N).

In summary, Eq. 10 can be obtained.

$$\gamma = \tan a \tag{10}$$

When the ginkgo nut is in the critical state of downward sliding, the slope angle is the angle of static friction, and the coefficient of static friction can be obtained using Eq. 10. The dynamic friction coefficient is usually smaller than the static friction coefficient. When the particles are placed on an inclined plane and the angle of inclination is slowly raised, the particles roll before they begin to slide, making the static friction coefficient impossible to measure. Therefore, sticking ginkgo nuts together can avoid rolling and facilitate the testing of static friction coefficient. When testing the static friction coefficient of the ginkgo nut–steel plate, four ginkgo nuts were stuck and placed on the self-made inclinometer to prevent rolling. The inclinometer was slowly increased by lifting the handle until the ginkgo nuts exhibited a downward sliding trend. The angle of static friction was tested by an angle ruler (Deqing Shengtaixin Electronic Technology Co., Ltd, Huzhou, China). When measuring the static friction coefficient of ginkgo nut–ginkgo nut, the ginkgo nuts were arranged to form a material plate and pasted on the inclinometer. Then, four ginkgo nuts were stuck and placed on the material plate of ginkgo nuts. The test is presented in Fig. 5. The test was repeated 20 times, and the calculated results of Eq. 10 were averaged. The static friction coefficient of the ginkgo nut–steel plate was 0.58 and the standard deviation was 0.028. The static friction coefficient of the ginkgo nut–ginkgo nut was 0.73 and the standard deviation was 0.048.

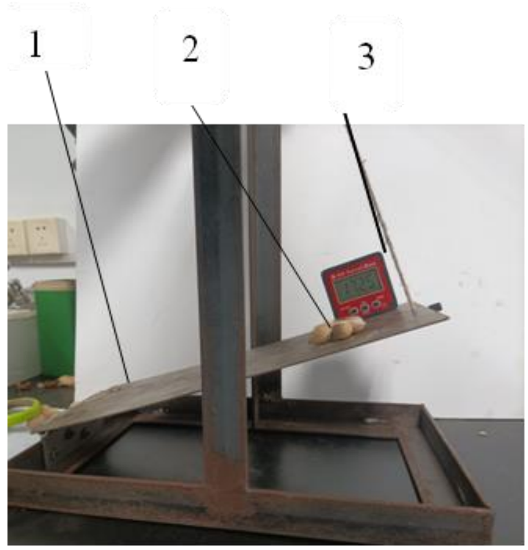

Fig. 5. Static friction coefficient test.1: Inclinometer; 2: Ginkgo nut; 3: Angle ruler

Measurement of dynamic friction coefficient

The dynamic friction coefficient, also known as the rolling friction coefficient, is tested in different ways. Wójcik *et al*. (2020) conducted tests on three plant particulate materials (peas, maize, triticale) to obtain a direct relationship between maximum static friction and mean dynamic friction. Khazaei *et al*. (2010) proposed a new method for simultaneous measurement of angle of repose and coefficient of friction of wheat grains based on the motion of the grains in a partially-filled horizontal rotating drum at the slumping and rolling modes of motion. Kweon *et al*. (2007) developed a device to measure the dynamic friction coefficient of particles accelerated in a tube rotating in a horizontal plane. Combarros *et al*. (2014) calibrated the dynamic friction coefficient by comparing the macroscopic behavior of granular matter in standard bulk experiments, which have the advantage of being highly repeatable and reliable. Liu *et al*. (2018a) calculated the dynamic friction coefficient by testing the rolling distance of the particles on inclined and horizontal planes. In this study, calculating the dynamic friction coefficient by measuring the angle of inclination of the inclined plane when the particles start rolling on the inclined plane is another common method, which can also be referred to relevant research (Hou *et al*. 2020). The method used to measure the dynamic friction coefficient can refer to that used to measure the static friction coefficient. When measuring the dynamic friction coefficient of ginkgo nut–steel plate, a ginkgo nut was placed on the steel inclinometer in the thickness direction. The inclined plane was raised slowly until the ginkgo nut rolled downward; the inclination angle of the inclined plane was the dynamic friction angle. The test is presented in Fig. 6. When measuring the dynamic friction coefficient of ginkgo nut–ginkgo nut, the ginkgo nuts were arranged to form a material plate and pasted on the inclinometer. Then, a ginkgo nut was placed on the material plate of ginkgo nuts. The results were averaged after 20 repetitions of the test. The dynamic friction coefficients of the ginkgo nut–steel plate was 0.46, and the standard deviation was 0.045. The mean dynamic friction coefficient of the ginkgo nut–ginkgo nut was 0.53, and the standard deviation was 0.061.

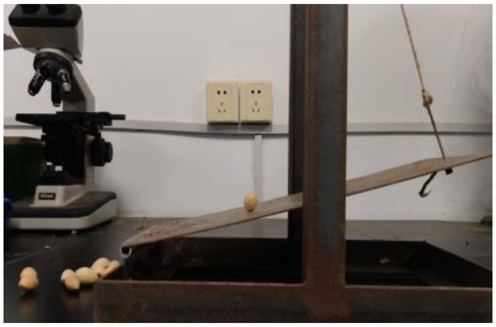

Fig. 6. Dynamic friction coefficient test

Calibration of Simulation Parameters

Measurement of stacking angle

Many scholars have carried out research on stacking angle testing methods. Du *et al*. (2023) measured the stacking angle of granular materials in DEM software based on Python's linear regression analysis and particle coordinate acquisition algorithm, and the consistency and stability of the measurement results were good. Madrid *et al*. (2022) calculated the stacking angle by measuring the height of the granular pile directly. In this study, the cylinder lifting method was chosen to measure the stacking angle. The height of the selected cylinder was 150 mm, and the diameter was 80 mm. During the test, the cylinder was placed on a steel plate chosen and filled with ginkgo nuts to be tested. It was lifted at a uniform speed of 0.05 m/s so that the ginkgo nuts formed a pile. A camera was used to take vertical photos of the ginkgo nut pile, and the photos were imported into computer aided design (CAD) software (Autodesk Inc., San Rafael, CA, USA) to measure the angle (Dai *et al*. 2019; Liao *et al*. 2020). The results were averaged after 20 repetitions of the test. The stacking angle measured was 39.59° and the standard deviation was 0.535.

Fig. 7. Stacking angle test of ginkgo nuts

Simulation model establishment and simulation test

In this study, EDEM software (DEM Solutions Ltd., Edinburgh, UK) was used to carry out the simulation tests. Since the ginkgo nuts are spindle-shaped, if a single regular spherical particle model is used to build the simulation model, the characteristics of the material and its interaction will not be accurately reflected. Therefore, this study used the method of aggregating multiple spherical particles to build a model of the ginkgo nut to approximate its actual shape (Kruggel-Emden *et al*. 2008; Markauskas *et al*. 2010). The simulation model of the ginkgo nut is shown in Fig. 8. The coordinates and radius of each sphere are shown in Table 3.

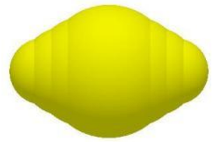

Fig. 8. Simulation model of a ginkgo nut

Table 3. Coordinates and Radius of Each Sphere of the Ginkgo Nut Model

Sphere	X	Y	Z	R (mm)
1	8.4	0	0	4
2	5.6	0	0	5
3	2.8	0	0	6.5
4	0	0	0	7.5
5	-2.8	0	0	6.5
6	-5.6	0	0	5
7	-8.4	0	0	4

The liquid bridge force and adhesion force between ginkgo nuts can be ignored, and the ginkgo nut can be regarded as a non-viscous body. Considering the calculation accuracy and simulation speed, the Hertz–Mindlin non-slip model was chosen. Based on the establishment of the model of the ginkgo nut, the stacking angle test model was established according to the stacking angle measuring device, and the lifting process of the cylinder was simulated. Then, a virtual face was built above the cylinder as a particle factory. The ginkgo nuts were dynamically generated in the particle factory, and the initial velocity was 0.5 m/s downward along the cylinder center. The size distribution of ginkgo nuts is normal, with a generation rate of 200 grains/s and a generation time of 2.5 s. A total of 500 ginkgo nut granules were generated. After the particles were stable, the cylinder moved uniformly upward along the center of the cylinder, so that the ginkgo nuts naturally formed a pile. The determination model of stacking angle is shown in Fig. 9.

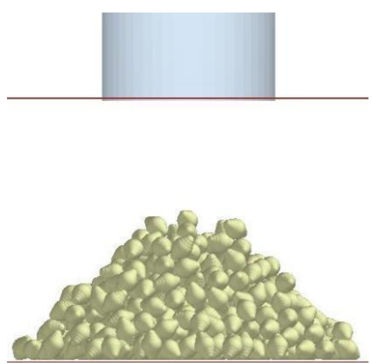

Fig. 9. Determination model of stacking angle

RESULTS AND DISCUSSION

Plackett–Burman test

The Plackett–Burman test design was developed using the Design-Expert software (Stas-Ease Inc., Minneapolis, MN, USA). The experimental parameters and ranges were selected based on the physical parameters measured in the early stages and related literature (Zhang *et al*. 2022b). The stacking angle of the ginkgo nuts was considered as the research object, and the factors that had an essential impact on the stacking angle were selected. The test factors and results are presented in the Tables below.

Table 4. Parameters of Plackett-Burman Test

Parameter	-1 level	+1 level
Poisson's ratio of ginkgo nut X_1	0.1	0.5
Shear modulus of ginkgo nut X_2 (MPa)	5	10
Restitution coefficient of ginkgo nut–ginkgo nut X_3	0.2	0.5
Static friction coefficient of ginkgo nut–ginkgo nut X_4	0.4	0.9
Dynamic friction coefficient of ginkgo nut–ginkgo nut X_5	0.3	0.8
Restitution coefficient of ginkgo nut–steel plate X_6	0.2	0.4
Static friction coefficient of ginkgo nut–steel plate X_7	0.4	0.7
Dynamic friction coefficient of ginkgo nut–steel plate X_8	0.4	0.6

Table 5. Factor Levels and Plackett-Burman Test Results

No.	Factor level								Stacking angle
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	θ (°)
1	0.5	10.00	0.50	0.40	0.30	0.20	0.70	0.40	40.29
2	0.10	10.00	0.50	0.40	0.80	0.40	0.70	0.40	43.19
3	0.50	10.00	0.20	0.40	0.30	0.40	0.40	0.60	32.60
4	0.10	5.00	0.20	0.40	0.30	0.20	0.40	0.40	33.95
5	0.50	5.00	0.50	0.90	0.80	0.20	0.40	0.40	73.67
6	0.10	5.00	0.50	0.40	0.80	0.40	0.40	0.60	41.91
7	0.50	5.00	0.50	0.90	0.30	0.40	0.70	0.60	50.11
8	0.50	10.00	0.20	0.90	0.80	0.40	0.40	0.40	61.20
9	0.10	5.00	0.20	0.90	0.30	0.40	0.70	0.40	44.64
10	0.10	10.00	0.50	0.90	0.30	0.20	0.40	0.60	49.06
11	0.50	5.00	0.20	0.40	0.80	0.20	0.70	0.60	46.95
12	0.10	10.00	0.20	0.90	0.80	0.20	0.70	0.60	63.68

The variance of the obtained results was analyzed using the Design-Expert software. The analysis results are presented in Table 6. The p-value corresponding to each factor can reflect the impact of the factor on the stacking angle. When $p < 0.01$, it indicates that the effect of the factor on the stacking angle is very significant. When $0.01 < p < 0.05$, it indicates that the effect of the factor on the stacking angle is significant. When $p > 0.05$, it indicates that the effect of the factor on stacking angle is not significant.

Table 6. Analysis of Factors in Plackett-Burman Test

Factor	Sum of Squares	df	F	P
X_1	67.17	1	7.42	0.0723
X_2	0.12	1	0.013	0.9149
X_3	19.28	1	2.13	0.2406
X_4	892.17	1	98.52	0.0022**
X_5	532.67	1	58.82	0.0046**
X_6	96.05	1	10.61	0.0472*
X_7	1.04	1	0.11	0.7572
X_8	13.29	1	1.47	0.3124
Note: P < 0.01 (very important impact, **), P < 0.05 (important impact, *), the same below.				

According to Table 6, the static friction coefficient of ginkgo nut–ginkgo nut X_4 and the dynamic friction coefficient of ginkgo nut–ginkgo nut X_5 significantly affected the stacking angle of the ginkgo nuts ($P < 0.01$). The restitution coefficient of ginkgo nut–steel plate X_6 had an important effect on the stacking angle of the ginkgo nuts ($P < 0.05$). The effects of the remaining parameters on the response value were not significant ($P > 0.05$).

Steepest Climbing Test

The factors that have a significant impact on the stacking angle were determined using the Plackett–Burman test. These factors were studied using the steepest climbing test to obtain a range of values for each factor. The steepest climbing test is an optimization algorithm experiment that simulates the process of finding the steepest climbing in a curvilinear terrain, and gradually approximates the optimal solution by continuously adjusting the values of the parameters. In the simulation test, the average value was selected for other non-significant factors, that is, the Poisson's ratio of ginkgo nut is 0.3, the restitution coefficient of ginkgo nut–ginkgo nut is 0.35, the shear modulus of ginkgo nut is 7.5 MPa, the static friction coefficient of ginkgo nut–steel plate is 0.55, and the dynamic friction coefficient of ginkgo nut–steel plate is 0.5. The steepest climbing test scheme and results are presented in Table 7.

Table 7. Steepest Climbing Experimental Scheme and Results

No.	X_4	X_5	X_6	Stacking angle θ (°)	Relative error δ (%)
1	0.4	0.3	0.40	37.81	4.37
2	0.5	0.4	0.46	40.21	1.57
3	0.6	0.5	0.52	43.88	10.84
4	0.7	0.6	0.58	47.01	18.74
5	0.8	0.7	0.64	50.42	27.36
6	0.9	0.8	0.70	52.38	32.31

The results indicate that the relative error of the stacking angle was the smallest when the No. 2 test combination was used. It means that the simulated stacking angle obtained using No. 2 test combination was closest to the actual value, which ensures the accuracy of the simulation test. The relative errors of combinations No. 1 and No. 3 were closest to those of No. 2. Therefore, No. 2 was used as the intermediate value, and Nos. 1 and 3 were used as the low level and high level of the subsequent response surface test, respectively.

Box–Behnken Test

The Plackett-Burman test determined that the number of factors that significantly affect the stacking angle was three. They were the static friction coefficient of ginkgo nut–ginkgo nut X_4, the dynamic friction coefficient of ginkgo nut–ginkgo nut X_5, and the restitution coefficient of ginkgo nut–steel plate X_6. The steepest climbing test determined the intermediate value, low level, and high level of the significant influencing factors, so the level of each factor was three. Based on the previous test, the static friction coefficient of ginkgo nut–ginkgo nut X_4, the dynamic friction coefficient of ginkgo nut–ginkgo nut X_5, and the restitution coefficient of ginkgo nut–steel plate X_6. were considered as the factors of test. The stacking angle was used as an assessment index. A response surface test analysis was developed using the three-factor three-level quadratic regression test design scheme. The factors and levels of the response surface tests are shown in Table 8. The remaining factors were consistent with the previously performed climbing test values.

Table 8. Factors and Levels of Response Surface Test

Level	Factor		
	X_4	X_5	X_6
-1	0.4	0.3	0.40
0	0.5	0.4	0.46
1	0.6	0.5	0.52

The Box–Behnken test was carried out using the Design-Expert software. The total number of tests was 17, including 12 analysis tests and 5 estimation error tests. The design and results of the experiment are presented in Table 9.

Table 9. Experimental Design and Response Values

No.	Factor Level			Response Value
	X_4	X_5	X_6	Stacking angle θ (°)
1	-1	-1	0	37.93
2	1	-1	0	41.27
3	0	0	0	39.95
4	-1	0	-1	37.63
5	-1	0	1	38.54
6	1	0	-1	43.08
7	0	-1	1	39.56
8	0	0	0	40.93
9	0	0	0	40.18
10	0	-1	-1	38.27
11	0	0	0	40.88
12	0	1	-1	39.05
13	-1	1	0	38.76
14	1	0	1	43.24
15	0	0	0	40.29
16	1	1	0	43.55
17	0	1	1	40.21

According to the experimental results, a multiple regression fitting analysis was developed using the Design-Expert software. A quadratic polynomial regression model of the stacking angle θ on three independent variables (X_4, X_5, X_6) was obtained, as shown in Eq. 11. Then, a variance analysis of the obtained regression equation was carried out. The results obtained are presented in Table 10.

$$\theta = 40.45 + 2.28X_4 + 0.57X_5 + 0.44X_6 + 0.36X_4X_5 - 0.19X_4X_6 - 0.032X_5X_6 + 0.64X_4^2 - 0.71X_5^2 - 0.46X_6^2 \quad (11)$$

As shown in Table 10, the P value of the stacking angle response surface model was less than 0.01, indicating that the regression model was very significant. The P value of the misfit term was greater than 0.05, indicating a good fit of the regression equation. The model coefficient of determination R^2 was 0.9648, indicating that this model could explain more than 96% of the evaluation indicators, and less than 4% of the total variation could not be explained by the model, indicating a high correlation between the predicted value of the model and the actual value and a small experimental error. Therefore, it is feasible to predict the stacking angle θ of ginkgo nuts using the model.

Table 10. Variance Analysis of the Regression Equation

Source	Stacking angle θ (°)			
	Sum of squares	df	F	P
Model	51.15	9	21.34	0.0003**
X_4	41.77	1	156.81	< 0.0001**
X_5	2.58	1	9.67	0.0171*
X_6	1.55	1	5.81	0.0467*
X_4X_5	0.53	1	1.97	0.2029
X_4X_6	0.14	1	0.53	0.4911
X_5X_6	4.225E-003	1	0.016	0.9033
X_4^2	1.73	1	6.49	0.0382*
X_5^2	2.12	1	7.95	0.0258*
X_6^2	0.91	1	3.41	0.1074
Residual	1.86	7		
Lack of Fit	1.10	3	1.92	0.2676
Pure Error	0.76	4		
Cor Total	53.01	16		
R-Squared	0.9648			
Adj R-Squared	0.9196			
Note: P < 0.01 (highly significant, **); 0.01 ≤ P < 0.05 (significant, *).				

Table 10 shows that the P value of X_4 was less than 0.01, indicating that the effect of this factor on the model was highly significant. The P values of X_5, X_6, X_4^2, and E^2 were all less than 0.05, and these factors significantly influenced on the model. The effects of X_4X_5, X_4X_6, X_5X_6, and X_6^2 were not important. Different studies have shown that dynamic and static friction coefficients between the materials have extremely significant effect on the stacking angle (Fu *et al*. 2023; Lei *et al*. 2023), which is consistent with the results of this study. In addition, the friction coefficient and restitution coefficient between the particles and contact materials also have a significant effect on the stacking angle in different studies, which is related to the different particles as well as contact materials. By analyzing the coefficients of each regression term in the regression model, it was found that the strength of the influence of different factors on the stacking angle of ginkgo nuts was: $X_4>X_5>X_6$. The significant terms of the above model were retained, and the insignificant terms were eliminated to ensure that the model was highly significant and the lack-of-fit terms were not significant. The model was re-fitted to obtain the optimized regression model:

$$\theta = 40.25 + 2.28X_4 + 0.57X_5 + 0.44X_6 + 0.62X_4^2 - 0.73X_5^2 \quad (12)$$

Verification Test

The effects of the various factors are different. Regression Eq. 12 needs to be optimized so that the simulated value of the stacking angle is as close as possible to the experimental value. The optimized parameter combination was captured: the static friction coefficient of ginkgo nut–ginkgo nut, the dynamic friction coefficient of ginkgo nut–ginkgo nut, and the restitution coefficient of ginkgo nut–steel plate were 0.50, 0.36, and

0.42, respectively. Because the optimized optimal combination was not included in the response surface test, a DEM simulation test was developed using the combination determined above to test the reliability of the predicted value and the rationality of the test results. The results were averaged after five repetitions of the test. The simulated stacking angle was 41.12°. The standard deviation was 1.79°, and the relative error between the simulated and actual values was 3.86%. The comparison shows that the calibrated parameters are accurate and can be used for subsequent discrete element simulations test of ginkgo nut shelling.

CONCLUSIONS

In this study, three factors that had an essential impact on the stacking angle of the ginkgo nut were captured: the static friction coefficient of ginkgo nut–ginkgo nut, the dynamic friction coefficient of ginkgo nut–ginkgo nut, and the restitution coefficient of ginkgo nut–steel plate. A Box–Behnken experiment was conducted to obtain a quadratic polynomial regression model of the three factors on the stacking angle. The model was optimized, and the experimental value of 39.59° was used as the target. The optimal parameter combination was obtained as follows: the static friction coefficient of ginkgo nut–ginkgo nut, the dynamic friction coefficient of ginkgo nut–ginkgo nut, and the restitution coefficient of ginkgo nut–steel plate were 0.50, 0.36, and 0.42, respectively. The experiment was conducted using an optimal parameter combination. The simulated stacking angle obtained was 41.12°. The relative error between the simulated and actual values was 3.86%. This indicates that the model is reliable, and that the calibrated parameters can provide a useful reference for relevant research.

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