Cotton stalk restitution coefficient determination tests based on the binocular high-speed camera technology

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Abstract: The restitution coefficient (RC) of cotton stalks is an important elementary physical parameter that is required to establish the crushing mechanical model and research the film residue separation machinery. In this study, the calculation method of restitution coefficient considering the rotation motion of stalk-shaped agricultural materials was derived based on the principle of kinematics and the energy restitution coefficient method, and a test bench for measuring the RC was designed and built. The effects of collision material, moisture content, length, diameter, release height, and collision angle respectively on the RC were investigated by single-factor experiments and orthogonal experiments, and the regression models between influence factors and the RC were established. The results showed that Q235 showed the highest value of the RC, and it was followed by cotton stalks and soil lumps, sequentially. The RC of cotton stalks decreased with the increase of moisture content and diameter, while it increased at first and then decreased with the increase of length. As the release height was less than 500 mm, the RC increased with the increased release height. As the collision angle was less than 40°, the RC showed a linear increasing trend. The significance of the effects of factors on RC decreased with the following sequence: collision angle, length, release height, diameter, and moisture content. Length, collision angle, and release height were extremely significant. The contrast test results showed that the values based on Newton's restitution coefficient method were smaller than that based on the energy restitution coefficient method. The verification test showed that the predicted rebound height of cotton stalks calculated based on the energy restitution coefficient method was closer to the actual rebound height, and the relative error was less than 5%.

Keywords: high-speed camera technology, cotton stalk, collision, restitution coefficient, determination test
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1 Introduction

China is one of the major cotton-producing countries in the world, and Xinjiang is the main cotton-producing area in China[1,2]. At present, the mode of film-covering planting is adopted in cotton planting in Xinjiang, increasing crop yield and bringing greater economic benefits to farmers[3], but the problem of residual film pollution has become increasingly serious. In order to solve the problem of residual film pollution in farmland, a large amount of residual film was mechanically recovered and utilized every year, but a large number of cotton stalks, soil, cotton mass, and other impurities were wrapped in the mechanically recovered residual film. With the lack of efficient film residue separation equipment, the difficulty in the resource utilization of residual film has increased[4-6]. The cotton stalk is the main component of film residue mixtures, and its basic physical characteristics are the basic data for the design and performance analysis of the key components for cotton stalk crushing and separation of the film from stalks. The restitution coefficient (RC) is one of the important basic material characteristics of cotton stalks, and its accurate setting is of great significance to both theoretical calculation and simulation boundary condition setting. Therefore, some exploratory research on the RC of cotton stalks was conducted.

The restitution coefficient is one of the important mechanical properties of agricultural materials. Measurement methods are mainly based on the principle of dynamics, the principle of kinematics, and the energy perspective[7,8]. Research on the RC of agricultural materials is relatively extensive, and domestic and foreign scholars have conducted some cumulative exploratory studies. Yang et al.[9] studied the effects of grain shape, moisture content, release height, and collision angle on the rebound characteristics and restitution coefficient of grains. Hurmuzlu et al.[10] proposed a new method to solve the problem of the collision between slender stalks with materials by revising the definition of restitution coefficient. Ozturk et al.[11] studied the effects of the

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shape of chickpeas and lentils, moisture content, collision material, and release height on restitution coefficient. González et al.[11] respectively measured the restitution coefficient between corn and olive nuclei and collision material, and the results showed that the corn and olive nuclei were accompanied by rotation in the non-vertical rebound process, resulting in a large error in the measured RC. Wang et al.[13] and Huang et al.[14] built a restitution coefficient test device based on the principle of kinematics, and analyzed the elastic properties of granular materials and the influence law between the main factors. Hastie et al.[15] deduced the calculation equation for the RC of polyethylene particles colliding with a plane, and proposed a method for measuring the RC of irregular particles under three-dimensional motion based on high-speed photography. Wang et al.[16] measured the collision restitution coefficient of corn kernels of different shapes, and analyzed the effect of different impact angles and reflection angles on the RC. Based on the dynamics theory of collision between particles and fixed surfaces, Feng et al.[17] measured the collision restitution coefficient of potato tubers during harvesting. Based on the mirror reflection theory, Wang et al.[18] built a restitution coefficient test bench, measured the RC between corn seeds and soils in 3D space under different collision conditions, and obtained the law of the effect of each factor on the restitution coefficient. Liu et al.[19,20] used the discrete element method (DEM) to calibrate the collision restitution coefficient of granular materials. Liu et al.[21] determined the RC of sunflower grains by using high-speed photography technology, and analyzed the difference between the values of the restitution coefficient calculated based on the classical Newton method and energy-based. Yang et al.[22] predicted the RC of castor seed using the restitution coefficient model based on material properties and collision theory. Wang et al.[23] constructed the theoretical model of RC of corn particles based on the energy method, verified the theoretical model by numerical simulation and physical tests, and obtained the differences between the theoretical value, the simulated value, and the test value. Yu et al.[24] analyzed the elastoplastic deformation, kinematics characteristics, and contact damage during bulb collision by using high-speed photography, and investigated the effects of bulb mass, collision material, moisture content, material thickness, and release height on the RC. As mentioned above, domestic and foreign scholars have conducted a large number of studies on the RC of different agricultural materials, but the irregular materials were often regarded as spherical particles in the research process, which simplifies the collision models. In addition, to the best knowledge of the authors, domestic and foreign scholars have carried out obviously few measurements and experiments on the RC of rod-shaped materials, and there is no publication of research on the RC of cotton stalks.

In this study, considering the anisotropy of materials and the rotational movement after the collision, the calculation method of the restitution coefficient of cotton stalks was derived based on the principle of kinematics and the energy restitution coefficient method. A test bench for measuring the RC was designed and built. By combining with binocular high-speed photography, the spatial velocity of cotton stalks was analyzed and measured, and the RC of cotton stalks collision under different conditions was determined. The effects of collision material, moisture content, length, diameter, release height, and collision angle respectively on the RC were investigated, and the regression model between influence factors and the RC was established. It can provide data support for the separation technology research and equipment development of film residue mixtures in Xinjiang, China.

2 Materials and methods

2.1 Test materials

The cotton stalks were selected from cotton fields around Shihezi City, Xinjiang, and the sampling time was October 2020, and the cultivar was Xinluzao series No.45. The moisture content of the fresh cotton stalks was (46.13±1.50)% to (69.80±1.50)%. Cylindrical cotton stalks with a length of 10-20 mm and a diameter of 5-10 mm were selected as the test materials. The diameter of the whole cotton stalk decreases gradually from top to bottom, but the length of the cotton stalk used in the test was short, so it was regarded as a cylindrical material of equal diameter stalk. During the sampling process, the selected cotton stalk samples were required no external damage and to be free of damage by worms.

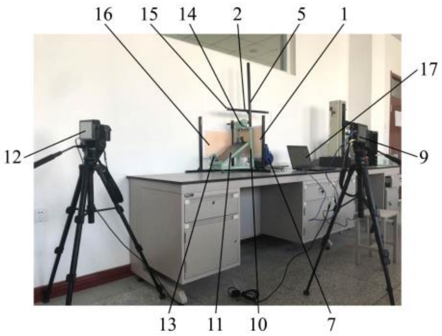
In order to obtain cotton stalk samples with different moisture content, the prepared cotton stalk samples were subjected to moisture content adjustment with reference to GB/T 1928-2009, GB/T 1931-2009, and References [25] and [26]. When the moisture content of the cotton stalks was adjusted, the samples were placed in an electric drying oven with forced convection and dried at (103±2) ℃ for 8 h. Then, the samples were weighed with a JMB5003 electronic balance, which was repeated after 2 h. In addition, the mass of the samples twice weighed was compared. If the relative error was no more than 0.50%, the moisture content of the samples was considered to be 0. The dried samples were soaked in water for 24 h to absorb water to be saturated state. The moisture content of the samples was adjusted via an electrothermal blowing dry box at (45±2) ℃ according to the set moisture content gradient before they were stored in an artificial climate chamber at 30 ℃ with a relative humidity of 95%.

The instruments and equipment in the test mainly included Sartorius MA100 electronic moisture analyzer (mass accuracy: 0.001g, moisture content accuracy: 0.01%, supplier: Shanghai Beiman Biological Technology Development Co., Ltd., China), JMB5003 electronic balance (measurement range: 0-500 g, measurement accuracy: 0.001 g, supplier: Zhejiang Yuyao Jiming Weighing Calibration Equipment Co., Ltd., China), electric drying oven with forced convection, DL91150 digital caliper (maximum measuring length: 150 mm, measuring accuracy: 0.01 mm, supplier: Zhejiang Ningbo Deli Group Co., Ltd., China) and other auxiliary tools such as electronic protractor (accuracy: 0.01°), trimming pliers, FASTEC-TS4 high-speed camera (U.S. Fastec Imaging Company, 510 fps), 3D ProAnalyst analysis software, standard scale paper with an accuracy of 1 mm (reading estimated to 0.1 mm) and vacuum pump.

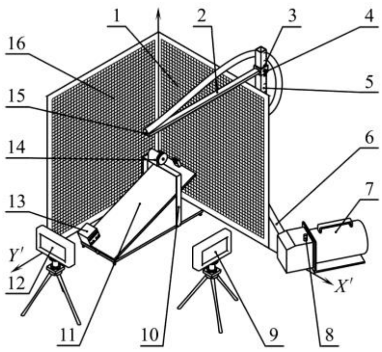
2.2 Test system and method

In order to determine the RC of cotton stalks, the kinematic model of cotton stalks in the falling and impacting processes was developed, and the restitution coefficient test bench was designed and built referring to References [15], [16] and [27]. The velocities for impacting cotton stalks were measured and analyzed in a three-dimensional space via high-speed photography. As shown in Figure 1.

The RC test bench was composed of measuring equipment (two FASTEC-TS4 high-speed cameras, etc.), a simulated space coordinate system device, a material release device, and a collision platform (with an adjustable angle range of 0°-45°). The two high-speed cameras were fixed in a horizontal position at 90° and maintained the same height. By controlling the switch, the high-speed cameras can record the movement trajectories of cotton stalks on two planes at the same time. The simulated space coordinate system device was composed of graduated plates A and B that were perpendicular to each other. Standard scale paper was pasted on the two plates, which was used as the calibration reference size. The shooting surfaces of the two high-speed cameras were kept perpendicular to the graduated plates A and B during the test. The material release device was composed of a vacuum pump, a lifting device, and a release platform. Cotton stalks were placed at the suction port of the vacuum pump. Through the air pump switch to control the air flow break, the cotton stalks fell freely and vertically without initial speed, reducing the cotton stalk rotation in the falling process. Meanwhile, the release height can be adjusted by the lifting device, and the collision angle can be adjusted by the angle regulator.



a. Photo of the test bench for RC measurement



b. Schematic of the test bench for RC measurement

1. Graduated plate A 2. Release platform 3. Reading pointer 4. Locking device 5. Graduated lifting rod 6. Air pipe 7. Air pump 8. Air pump switch 9. High-speed camera 1 10. Collision table 11. Collision material placement platform 12. High-speed camera 2 13. Electronic protractor 14. Angle adjuster 15. Cotton stalk release outlet 16. Graduated plate B 17. PC-Computer

Figure 1 Restitution coefficient test bench

During the analysis of the cotton stalks collision test process, the 3D ProAnalyst analysis software was used to establish rectangular coordinate systems in Planes A and B respectively to simulate the *XOZ* plane and the *YOZ* plane. By calibrating the position of the cotton stalks, the origin position of the two rectangular coordinate systems was the same, so as to obtain the velocities of the cotton stalks in three-dimensional space from these images according to the principle of kinematics.

2.3 Theoretical analysis

The collision of materials is a complex energy transfer process, which has gone through the elastic deformation stage, the elastoplastic deformation stage, and the elastic recovery stage. The energy between different stages is transformed. In the case of ignoring the effect of air resistance and friction force, the laws of momentum conservation and energy conservation should be observed in the collision process. According to the observation and analysis of the movement process of the cotton stalks in high-speed videos, the cotton stalk inevitably had rotational motion and linear motion after a collision. Therefore, linear and rotational kinetic energy must be considered.

A cotton stalk was released at the height H, and it came into contact with a collision material after release freely, the position was recorded as the initial coordinate of the centroid at the moment of the impending bounce. The initial coordinate value of the cotton stalk was calibrated as (x_0, z_0) in XOZ plane and as (y_0, z_0) in the YOZ plane. At this time, the recording time was t_0. When the cotton stalk rebounded for t_n seconds after contacting the collision material, the coordinates of the centroid could be recorded as (x_n, z_n), (y_n, z_n) in the same way. After the collision, the material moved at a uniform speed in the X-axis and Y-axis directions, and at a uniform deceleration on the Z-axis. According to the kinematics principle, the motion velocities of the cotton stalk before and after colliding with the collision material could be calculated.

When the material fell freely from the height H (ignoring air resistance), the instantaneous approaching velocity before colliding with the collision material could be obtained from the equation as follows:

$$V_0 = \sqrt{2gH} \tag{1}$$

where, V_0 is the instantaneous approaching velocity before the material collides with the collision material, m/s; g is the acceleration of gravity, g=9.8 m/s^2 in this study; H is the material's release height, mm.

After the collision, the instantaneous velocities v_x (m/s) and v_y (m/s) along the X-axis and Y-axis respectively could be calculated as follows:

$$v_x = \frac{x_n - x_0}{t_n - t_0} \tag{2}$$

$$v_y = \frac{y_n - y_0}{t_n - t_0} \tag{3}$$

where, t_0 and t_n are the recorded values at the moment of collision and at a certain time after the collision respectively, s.

The cotton stalk moved at a uniform deceleration in the Z-axis direction. According to the law of uniform deceleration motion, the instantaneous velocity in the Z-axis direction (v_z, m/s) could be derived as:

$$\begin{cases} \bar{v} = \dfrac{z_n - z_0}{t_n - t_0} \\ v_z = \bar{v} + \dfrac{1}{2} g(t_n - t_0)^2 \end{cases} \Rightarrow v_z = \frac{z_n - z_0}{t_n - t_0} + \frac{1}{2} g(t_n - t_0)^2 \tag{4}$$

where, $\bar{v}$ is the average velocity in the Z-axis direction, m/s.

In the space coordinate system, the rebound velocity of the material after colliding is the resultant velocity in the X-axis, Y-axis, and Z-axis directions. The resultant velocity equation is as follows:

$$V_t = \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} \tag{5}$$

where, V_t is the rebound velocity of the material after colliding, m/s.

The shapes of agricultural materials are mostly irregular, with great morphological differences and anisotropic characteristics. In the process of collision, elastic-plastic deformation, sliding, and friction effects occur, which lead to a random movement of materials and obvious rotational movement during separation, especially the rotation of stalk-shaped materials is more obvious.

Therefore, based on the actual situation of cotton stalk rotation during the rebound process after the collision, the calculation method of restitution coefficient considering the rotational movement of stalk-shaped agricultural materials was derived based on the principle of kinematics and the restitution coefficient of energy[28]. The RC is shown in Equation (6).

$$e=\sqrt{\frac{\sum E_{k,o}}{\sum E_{k,i}}}=\sqrt{\frac{\sum E_{k,i}-\sum E_{k,a}}{\sum E_{k,i}}} \tag{6}$$

where, e is RC; $\sum E_{k,i}$ is the total kinetic energy before the collision; $\sum E_{k,o}$ is the total kinetic energy after a collision; $\sum E_{k,a}$ is the total kinetic energy lost in the collision.

According to the kinetic energy conservation of the system as shown in Equation (7).

$$\sum E_{k,i}=\sum E_{k,o}+\sum E_{k,a} \tag{7}$$

If the rotational motion is considered along with the linear motion of the cotton stalk before and after the collision, then both linear and rotational kinetic energy must be considered, as shown in Equation (8).

$$\sum E_k=\sum E_{k,l}+\sum E_{k,r}=\frac{1}{2}mv^2+\frac{1}{2}J\omega^2 \tag{8}$$

where, $\sum E_k$ is the total kinetic energy; $\sum E_{k,l}$ is linear kinetic energy; $\sum E_{k,r}$ is the rotational kinetic energy; m is the mass of the material, g; v is the motion velocity of the material, m/s; ω is the angular velocity the material, rad/s; l is the length of the material, mm; J is the moment of rotary inertia, kg m^2.

According to the relationship between angular velocity and velocity:

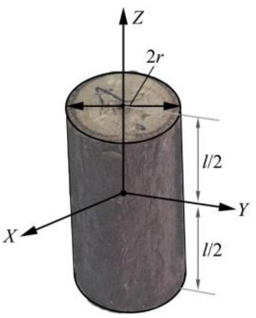
$$v=\omega\cdot r \quad \Rightarrow \quad \omega=\frac{v}{r} \tag{9}$$

where, r is the diameter of the material, mm.

The randomness of the rebound direction of the cotton stalk after the collision caused the simultaneous longitudinal rotation and radial rotation (Figure 2). The calculation equation for the longitudinal and radial rotary inertia is as follows:

$$\begin{cases} J_{x,y}=J_x=J_y=\dfrac{m}{12}(3r^2+l^2) \\ J_z=\dfrac{1}{2}mr^2 \end{cases} \tag{10}$$

where, J_x, J_y, and $J_{x,y}$ are the longitudinal rotary inertia, kg m^2; J_z is the radial rotary inertia, kg m^2.



Note: r is the diameter of the material, mm; l is the length of the material, mm.

Figure 2 Rotary inertia of cotton stalk

Therefore, the rotational kinetic energy is shown in Equation (11).

$$\sum E_{k,r}=\frac{1}{2}J_{x,y}\omega_1^2+\frac{1}{2}J_z\omega_2^2 \tag{11}$$

where, ω_1 and ω_2 are the longitudinal and radial angular velocities during material rotation, rad/s.

It is difficult to analyze longitudinal rotation and radial rotation, so the calculation of the angular velocity in the radial and longitudinal directions was compromised, and the angular velocity was evenly distributed, as shown in Equation (12).

$$\omega_1=\omega_2=\frac{\omega}{2}=\frac{v}{2r} \tag{12}$$

From Equations (10) and (12), the rotational kinetic energy can be calculated as:

$$\begin{aligned}\sum E_{k,r}&=\frac{1}{8}J_{x,y}\omega^2+\frac{1}{8}J_z\omega^2=\frac{1}{8}\cdot\frac{v^2}{r^2}\left[\frac{1}{12}m(3r^2+l^2)+\frac{1}{2}mr^2\right]\\&=\frac{1}{96}mv^2\left(9+\frac{l^2}{r^2}\right)\end{aligned} \tag{13}$$

The total kinetic energy of the cotton stalk after collision is

$$\begin{aligned}\sum E_{k,o}&=\frac{1}{2}mV_t^2+\sum E_{k,r}=\frac{1}{2}mV_t^2+\frac{1}{96}mV_t^2\left(9+\frac{l^2}{r^2}\right)\\&=\frac{1}{96}mV_t^2\left(57+\frac{l^2}{r^2}\right)\end{aligned} \tag{14}$$

According to the kinematics equation, the total kinetic energy of the cotton stalk before collision is

$$\sum E_{k,i}=\frac{1}{2}mV_0^2 \tag{15}$$

Then, from Equations (14) and (15), the RC of the cotton stalk can be expressed as:

$$e=\sqrt{\frac{\sum E_{k,o}}{\sum E_{k,i}}}=\sqrt{\frac{\frac{1}{96}mV_t^2\left(57+\frac{l^2}{r^2}\right)}{\frac{1}{2}mV_0^2}}=\sqrt{\frac{V_t^2\left(57+\frac{l^2}{r^2}\right)}{48V_0^2}} \tag{16}$$

2.4 Test design

2.4.1 Test factors

The restitution coefficient of agricultural materials is related to their own characteristics, moisture content, collision angle and collision material type, and other factors[10,22,27]. Therefore, the moisture content, length, diameter, collision angle, and release height of cotton stalks were selected as the test factors. The collision materials were selected from the common contact materials that interact with cotton stalks during processing: Q235, cotton stalks, and soil lumps.

2.4.2 Single-factor test design

In order to analyze the influence law of various factors on the RC, cotton stalks were used as the samples to conduct a single-factor test, and the regression equation determination coefficient was obtained. The variation range of five factors was determined based on the above-mentioned theoretical analysis and the contact and interaction between each machine and cotton stalks during actual working. The test factors and their level are listed in Table 1. Each group of tests was repeated five times, and the average value was calculated.

Table 1 Test factors and their level

Level	Moisture content S/%	Length l/mm	Diameter d/mm	Release height H/mm	Collision angle C/(°)
1	10	10	6.00±0.23	300	0
2	20	15	7.00±0.12	400	10
3	30	20	8.00±0.16	500	20
4	40	25	9.00±0.15	600	30
5	50	30	10.00±0.20	700	40

2.4.3 Orthogonal test design

In order to determine the significant level of various factors that affected the RC and their sequence, orthogonal tests were conducted on the basis of the single factor test. The influencing factors and levels were listed in Table 2. The Q235 was selected as the collision material. Each group of tests was repeated five times, and the average value was calculated.

Table 2 Orthogonal test factors and their level

Level	Moisture content *S*/%	Length *l*/mm	Diameter *d*/mm	Release height *H*/mm	Collision angle *C*/(°)
1	10	10	6.00±0.16	400	20
2	30	15	8.00±0.21	500	30
3	50	20	10.00±0.33	600	40

2.4.4 Contrast test

Using the RC measurement test bench, combined with high-speed photography, the values based on Newton's restitution coefficient method and the energy restitution coefficient method were compared. Contrast tests were carried out for different release heights. Each group of tests was repeated five times, and the average value was calculated.

Newton's restitution coefficient is defined as the ratio of the velocity of the material before and after the collision, without considering the force of the material during the collision. The equation of the RC based on Newton's restitution coefficient method is as follows:

$$\begin{aligned} e &= \frac{v_t}{v_0} = \sqrt{\frac{{v_x}^2 + {v_y}^2 + {v_z}^2}{2gH}} \\ &= \sqrt{\frac{(x_n - x_0)^2 + (y_n - y_0)^2 + (z_n - z_0)^2}{2gH(t_n - t_0)^2} + \frac{z_n - z_0}{2H} + \frac{g(t_n - t_0)^2}{8H}} \end{aligned} \quad (17)$$

2.4.6 Verification test

In order to verify the reliability and accuracy of the values of the restitution coefficient obtained by the energy restitution coefficient method considering the rotation motion of cotton stalks, a verification test was conducted. According to the values of RC obtained by two different methods, their corresponding predicted rebound height were calculated respectively, and the values of actual rebound height and the predicted rebound height were compared. When measuring the actual rebound height h_1, the cotton stalk fell freely from different heights of H, and the actual rebound height was recorded and analyzed by high-speed photography. In the test, the vertical rebound of cotton stalk after collisions was identified as an effective test. Each group of tests was repeated five times, and the average value was calculated.

According to the definition of the RC, if the material rebounded vertically after the collision, the solution of the RC could be simplified to Equation (18).

$$e = \frac{v_1}{v_0} = \sqrt{\frac{2gh}{2gH}} = \sqrt{\frac{h}{H}} \quad (18)$$

Therefore, the predicted vertical rebound height h_2 after collision could be expressed as,

$$h_2 = He^2 \quad (19)$$

The actual rebound height was compared with the predicted rebound height, and the error between them was defined as the relative error δ (%), as shown in Equation (20).

$$\delta = \frac{|h_2 - h_1|}{h_1} \times 100\% \quad (20)$$

In the test, there were sliding motions in colliding progress and irregular collision, so this study defined it as invalid.

3 Results and analysis

3.1 Single-factor test analysis

Except for the factor of collision material, the test results of the quantifiable factors were analyzed. The regression equations of RC were calculated, and the determination coefficients were calculated. According to the phenomena and results in the test, the influence laws of various factors on the RC were discussed. The tendencies and corresponding regression equations of the restitution coefficient are shown in Figure 3.

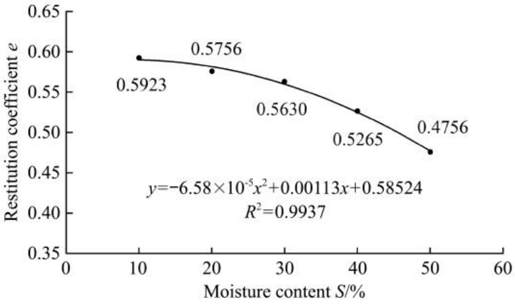
3.1.1 Effect of collision material on restitution coefficient

When the moisture content was 30%, the length was 15 mm, the diameter was 10 mm, the collision angle was 30° and the release height was 500 mm, the RCs between the cotton stalks and Q235, cotton stalk, and soil lump were 0.5681, 0.4876, 0.4346, respectively, and the restitution coefficient values decreased sequentially. By comparing the recovery coefficients between the three materials and the cotton stalks, it was found that the greater the hardness of collision material, the larger the RC between the cotton stalks and collision materials would be. The possible reason was that when the cotton stalks collide with the collision material, the greater the collision material hardness was, the smaller the plastic deformation of the cotton stalk would be, and the less the energy loss would be. During each collision test, the total energy of cotton stalk was the same and was equal to the sum of the plastic strain energy and the elastic strain energy. With the decreased plastic strain energy, the elastic strain energy increased, and in the rebound stage of cotton stalk after collisions, the elastic strain energy was transformed into linear kinetic energy and rotational kinetic energy. By observing the high-speed images, it was found that the rebound height and the rotation trend were more obvious when the cotton stalk collided with Q235, which also confirmed this inference. Therefore, the materials with larger RC should be selected under the condition of meeting strength in the design of film residue separation devices, so that cotton stalks can be better separated from other impurities.

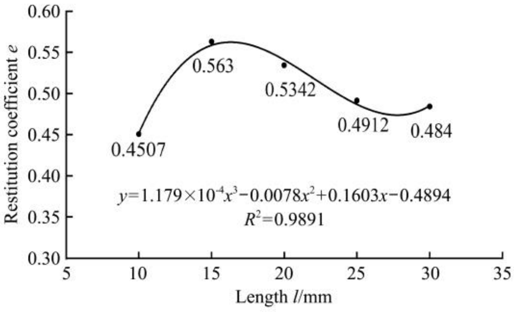
3.1.2 Effect of moisture content on restitution coefficient

The single-factor test results of different moisture contents are shown in Figure 3a. When the moisture content of cotton stalks was 10%-50%, the RC of cotton stalks decreased with the increase of moisture content. Under the condition with a length of 15 mm, a diameter of 10 mm, a collision angle of 30°, and a falling height of 500 mm, the determination coefficient R^2 of the regression equation of the RC variation with the moisture content was 0.9937.

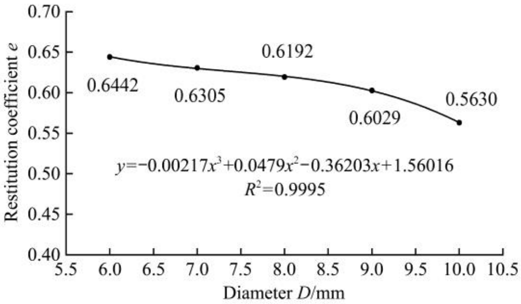
Through analysis, the RC of cotton stalks decreased with the increase of moisture content that related to the biological structure of cotton stalks. When sampling during cotton harvest, the lignification degree of the cotton stalk was high and the proportion of xylem was large. With the decrease in moisture content, the hardness of cotton stalks became higher. During the collision, the deformation of cotton stalks and the loss of plastic strain energy were smaller, and the rebound velocity was high. With the increase of moisture content, the moisture content of the pith core of the cotton stalk increased, the deformation was large when collisions occurred, and more energy was absorbed, resulting in a larger loss of elastic strain energy. Therefore, the moisture content should be considered when separating cotton stalks from the residual film. Drying film residue mixtures after recovery and thus reducing the moisture content of cotton stalks will facilitate the separation of film residue mixtures.



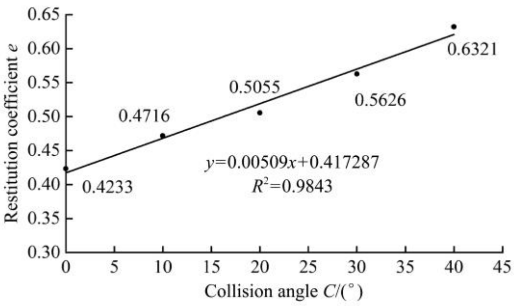
a. Effect of moisture content on restitution coefficient



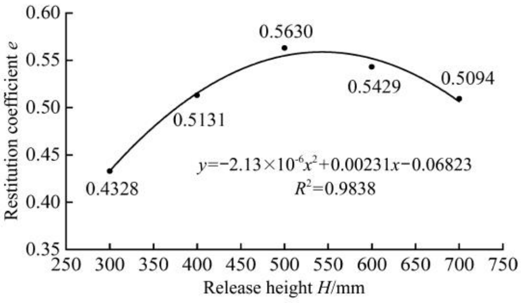
b. Effect of length on restitution coefficient



c. Effect of diameter on restitution coefficient



d. Effect of collision angle on restitution coefficient



e. Effect of release height on restitution coefficient

Figure 3 Effects of factors on restitution coefficient

3.1.3 Effect of length on restitution coefficient

The effects of different cotton stalk lengths on RC are shown in Figure 3b. The RC increased first and then decreased with the increase of the length as the length of the cotton stalks was 10-30 mm. The declining trend of the RC was relatively stable as the length was 25-30 mm. Under the condition with the release height of 500 mm, the moisture content of 30%, the collision angle of 30°, and the diameter of 10 mm, the determination coefficient R^2 of the regression equation of the RC variation with the length was 0.9891.

With the increase of cotton stalk length, its mass and surface area also increased. During the collision, the contact area between the cotton stalk and collision materials increased, and the plastic deformation increased, which resulted that energy dissipation increased and the RC decreased. The lengths have an important influence on the rotation of cotton stalks. When the lengths of cotton stalks were small, the rotation of cotton stalks along radial and longitudinal directions was more obvious. When the lengths of cotton stalks increased to a certain value, the rebound height and rotation trend of cotton stalks decreased after collisions, which corresponds to the decrease of RC with the increase of length. Therefore, cotton stalks should be crushed to an appropriate length when designing the crushing device for film residue mixtures, which is conducive to the separation of the cotton stalks from residual films.

3.1.4 Effect of diameter on restitution coefficient

The single-factor test results of different diameters are shown in Figure 3c, the RC of cotton stalks decreased with the increase of the diameter. Under the condition with the release height of 500 mm, the moisture content of 30%, the collision angle of 30°, and the length of 15 mm, the determination coefficient R^2 of the regression equation of the RC variation with the diameter was 0.9995.

The effect of diameter change on the RC was also related to the biological structure of cotton stalks. The greater the cotton stalk diameter was, the rougher the cotton stalk bark, which resulted that the increase of friction between cotton stalks and collision materials, and the energy dissipation increased during the collision, then the reflection velocity of cotton stalk decreased, and then the RC decreased.

3.1.5 Effect of collision angle on restitution coefficient

The effects of different collision angles on RC are shown in Figure 3d. The RC had a linearly increasing trend with the increase of collision angle. Under the condition with the release height of 500 mm, the moisture content of 30%, the diameter of 10 mm, and the length of 15 mm, the determination coefficient R^2 of the regression equation of the RC variation with the collision angle was 0.9843.

The results showed that the deformation, sliding, and rotation motion of cotton stalks during collisions were all related to the collision angle and the change in the collision angle made the motion of the cotton stalks in the test process more complex. The friction between collision material and cotton stalk, and the deformation and rotation motion of cotton stalk caused by linear contact and point contact were all involved in the collision process. When the collision angle was smaller, the cotton stalk collide with the collision material in linear contact, increasing the normal force of the cotton stalk. The energy loss was large and mainly dominated by plastic deformation. With the increase of the collision angle, the linear contact between the cotton stalk and collision material changed to point contact, which reduced the plastic deformation and energy loss in the collision, and then the RC increased.

3.1.6 Effect of release height on restitution coefficient

The effects of different release heights on RC are shown in Figure 3e. The RC increased with the release height increasing as the release height was 300-500 mm. The RC increased with the release height decreasing as the release height was bigger than 500 mm, and the changing trend of the RC was relatively stable. Under the condition with the moisture content of 30%, the diameter of 10 mm, the length of 15 mm, and the collision angle of 30°, the determination coefficient R^2 of the regression equation of the RC variation with the release height was 0.9838.

According to the corresponding phenomena and results, with the increase of the release height, the velocity and potential energy before the collision of cotton stalks increased continuously, which increased the rebound velocity and the angular velocity of rotation after the collision, and the RC increased continuously. The research on the RC of peanut pods also showed such a change in law[29]. When the release height reached a certain degree (>500 mm), with the increase in the release height, the plastic deformation of the cotton stalk after the collision was bigger, and the friction resistance between the cotton stalk and the air and the collision materials were also increased, resulting in greater energy loss and smaller RC. References [13] and [17] also described this change in the law in the study of the RC of wheat grains and potato tubers. Therefore, when designing the separation devices for the mixtures of cotton stalks and residual film, it should be considered to throw the mixture up to a greater extent to increase the spacing between them and the separation device, so as to improve the separation rate.

3.2 Analysis of orthogonal test

The test scheme and results of the orthogonal test are shown in Table 3. When the collision material was Q235, the results showed that the significant level of various factors that affected the RC and their sequence was collision angle, length, release height, diameter, and moisture content. In addition, the effect of the moisture content on the RC was the smallest, which was consistent with the laws obtained in References [13], [14], and, [21]. The variance analysis of the orthogonal test was listed in Table 4. The results showed that within the scope of the 95% confidence coefficient, length, collision angle, and release height were extremely significant for the effect on RC, and moisture content and diameter were significant.

Table 3 Orthogonal test scheme and results of the RC

No.	Moisture part	Length	Diameter	Collision angle	Release height	e
1	1	1	1	1	1	0.5574
2	1	1	1	1	2	0.4819
3	1	1	1	1	3	0.4645
4	1	2	2	2	1	0.5559
5	1	2	2	2	2	0.51644
6	1	2	2	2	3	0.5470
7	1	3	3	3	1	0.6219
8	1	3	3	3	2	0.5424
9	1	3	3	3	3	0.5304
10	2	1	2	3	1	0.5796
11	2	1	2	3	2	0.5691
12	2	1	2	3	3	0.5789
13	2	2	3	1	1	0.5489
14	2	2	3	1	2	0.4939
15	2	2	3	1	3	0.4288
16	2	3	1	2	1	0.4660
17	2	3	1	2	2	0.4432
18	2	3	1	2	3	0.4123
19	3	1	3	2	1	0.5528
20	3	1	3	2	2	0.5511
21	3	1	3	2	3	0.5207
22	3	2	1	3	1	0.5542
23	3	2	1	3	2	0.5450
24	3	2	1	3	3	0.5008
25	3	3	2	1	1	0.4359
26	3	3	2	1	2	0.4827
27	3	3	2	1	3	0.4033
k_1	0.5353	0.5396	0.4917	0.4775	0.5414	
k_2	0.5023	0.5212	0.5188	0.5073	0.5140	
k_3	0.5052	0.4820	0.5323	0.5580	0.4874	
R	0.0330	0.0575	0.0406	0.0805	0.0540	
Sequence of factors	Collision angle > Length > Falling height > Diameter > Moisture part					

Note: e is the restitution coefficient; k_1-k_3 are the comprehensive average of the restitution coefficient at various factors and levels; R is the range.

Table 4 Analysis of variance

Variance source	DOF	Sum of squares of deviations	F value	P value	Significance level
Moisture part	2	0.006	4.092	0.037	*
Length	2	0.016	10.563	0.001	**
Diameter	2	0.008	5.233	0.018	*
Collision angle	2	0.030	20.276	3.9×10^{-4}	**
Release height	2	0.013	8.902	0.003	**
Error	16	0.07			
Sum	26				

Note: p<0.01(Extremely,**); p<0.05(significant,*). DOF: Degree of freedom.

3.3 Analysis of contrast test

The contrast test results are shown in Figure 4. Under a condition with a moisture content of 30%, a diameter of 10 mm, a length of 15 mm, and a collision angle of 0°, contrast tests were carried out for different release heights. The RC values were calculated by the energy recovery coefficient method considering rotation motion was bigger than that calculated by Newton's restitution coefficient method. In the process of solving the RC based on the energy restitution coefficient method, the rotational movement of the stalk-shaped materials after the collision was considered, and the rotational kinetic energy along the longitudinal and radial direction was calculated, which conformed to the law of energy conservation. The research objects of Newton's restitution coefficient method were mainly approximate spherical materials, ignoring the anisotropy of stalk-shaped materials and the rotational kinetic energy along the radial and longitudinal directions.

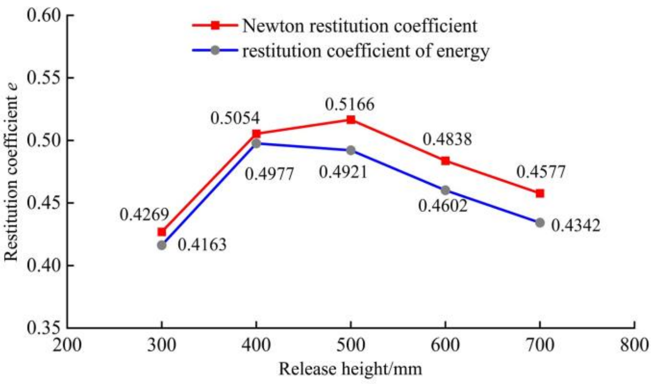


Figure 4 Contrast test results of the RC

3.4 Analysis of verification test

The verification test results are shown in Figure 5. According to the comparison of the values of actual rebound height and the predicted rebound height, when considering the rotation motion, it was found that the predicted rebound height calculated by the RC values based on the energy restitution coefficient method was closer to the actual rebound height, and the relative error was less than 5% (Relative error 1). The predicted rebound height curve calculated based on Newton's restitution coefficient method was far from the actual rebound height curve, and the relative error was more than 5% (Relative error 2). Therefore, the RC obtained by the energy restitution coefficient method considering rotation motion can better reflect the rebound characteristics of cotton stalks.

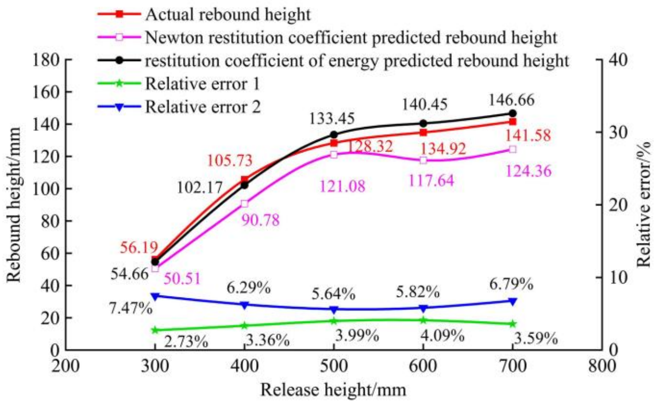


Figure 5 Verification test results of the RC

4 Conclusions

1) The calculation method of restitution coefficient considering the rotation motion of stalk-shaped agricultural materials was derived based on the principle of kinematics and the energy restitution coefficient method. Based on the binocular high-speed photography, a test bench for measuring the RC was built, and the RC values under different conditions were obtained.

2) According to the single-factor test, Q235 showed the highest value of the RC, followed by cotton stalks and soil lumps, sequentially. The RC of cotton stalks decreased with the increase of moisture content and diameter; in addition, with the increase of length, the values increased at first and then decreased. As the release height was less than 500 mm, the RC increased with the increased release height; as the collision angle was less than 40°, the RC showed a linear increasing trend.

3) According to the results of the orthogonal test and variance analysis, the significance of the effects of factors on RC decreased with the following sequence: collision angle, length, release height, diameter, and moisture content. Release height, collision angle, and length were extremely significant, and moisture content and diameter were significant.

4) The contrast test results showed that the RC values based on Newton's restitution coefficient method were smaller than that based on the energy restitution coefficient method. The verification test showed that the predicted rebound height of cotton stalks calculated based on the energy restitution coefficient method was closer to the actual rebound height, and the relative error was less than 5%.

This study can provide a method for measuring the restitution coefficient of stalk-shaped agricultural materials, and also provide data support for the separation technology research and equipment development of film residue mixtures in Xinjiang, China.

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