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Compression Molding Characteristics of Seed Cotton and Damage from Cottonseed Crushing

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Abstract: This study investigated the impact of compression molding parameters on the post-molding characteristics of machine-harvested seed cotton and aimed to determine the optimal compression molding parameters. The closed compression test of seed cotton and force analysis on a single cottonseed clarified the boundary conditions for cottonseed crushing and the relationship between crushing rate and compressive force. A seed cotton compression test bench facilitated single-factor and four-factor, three-level quadratic regression orthogonal experiments, varying the moisture content, initial density, compression force, and holding time. Variance analysis revealed each factor's influence on the dimensional stability coefficient. Utilizing Design Expert 13.0.5, the optimal compression molding parameter ranges were identified: 6–11.7% moisture content, 47.87–74.84 kg/m^3 initial density, 3–5.32 kN compression force, and 50–239.75 s holding time. Software predictions within this range indicated an optimal cottonseed crushing rate and dimensional stability coefficient of 2.853% and 3.274, respectively. Further verification experiments yielded a cottonseed crushing rate and dimensional stability coefficient of 2.888% and 3.282, respectively, with a maximum error of 3.85%, validating the model and optimized parameters. Therefore, strictly controlling seed cotton compression molding parameters was shown to reduce the cottonseed crushing rate and dimensional stability coefficient. These findings offer crucial theoretical insights for developing seed cotton compression processes and selecting parameters for cotton harvesting and packing devices.

Keywords: seed cotton; compression; molding characteristics; cottonseed damage; expression

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1. Introduction

China is one of the largest cotton-producing countries in the world. The cotton production in China accounts for over 20% of the total global production [1]. Xinjiang ranks first in China for cotton production and planting area; its cotton production accounts for over 90%, and its planting area accounts for over 80%, making the cotton industry an important economic pillar industry in Xinjiang. In recent years, with the continuous improvement of the agricultural mechanization level and the widespread adoption of machined-harvested cotton technology, the mechanized harvesting of cotton has become a trend [2–4].

Seed cotton is cotton whose cottonseeds have not been removed. Seed cotton has a low bulk density and a large volume [5]. After seed cotton is compressed and shaped, its volume decreases, and its shape remains fixed, which can effectively reduce transportation and storage costs. To address the aforementioned issues, some advanced cotton pickers, such as the John Deere CP690 and Case IH630, have integrated the packaging device with the cotton picker, enabling the high-density compression molding of cotton harvesting and seed cotton.

Currently, cotton pickers are moving toward integrated harvesting and packing [6,7], and they will move toward digitization and intelligence in the future [8]. Determining the compression molding characteristics of seed cotton and designing optimal seed cotton compression molding processes would play a vital role in the integrated development of cotton pickers and provide a boost for their digitalization and intellectualization.

The fibers and seeds in seed cotton have industrial value, and unreasonable compression molding processes may decrease the fiber and seed quality. Nur and Mark et al. found that the excessive compression of seed cotton adversely affects cotton fibers and cottonseeds [9,10]. Van der Sluijs et al. compared the quality of cotton modules produced by bale cotton pickers with that of seed cotton after secondary molding and found that the former have a slightly lower micronaire [11]. Anthony and Columbus et al. found that a high moisture content reduces the quality of cottonseeds after picking and ginning [12,13]. When compressing seed cotton, examining its quality first and then assessing its compression molding performance is crucial. To sum up, the key to designing a seed cotton compression molding process is to enhance the seed cotton's compression molding quality without significantly reducing its overall quality.

Currently, scholars have conducted preliminary research on the compression molding characteristics of seed cotton and materials similar to seed cotton. Wang et al., Jing et al., and Li et al. studied the compression characteristics of lint and cotton fibers and established a formula for compression characteristics [14–16]. Xu et al. conducted finite element analysis on the compression of cotton fibers and revealed patterns of pressure variations during compression [17]. Tian conducted compression molding experiments on residual films and determined the optimal compression parameters based on the relaxation ratio and specific energy consumption as response indicators [18]. Chen et al. developed an optimal compression process based on the rheological properties of corn straw with the dimensional stability coefficient as a response indicator [19]. Zhang et al. performed the baling and molding of tobacco straw and found that compression density decreases and then increases with an increase in straw feeding mass, and the relaxation ratio decreases and then increases with an increase in relaxation density [20]. Tumuluru et al. measured the density of wheat and other straws after two days of storage following compression and found that moisture content has a negative effect on relaxation density [21].

In summary, when seeking the optimal ranges of compression parameter combinations for superior compressive forming characteristics, scholars have conducted experiments with moisture content, compressive force, feeding mass, compression speed, and holding time as factors and the dimensional stability coefficient/resilience, density, firmness, durability, and impact resistance as indicators. Their work provided useful references for the present paper. To study the compression molding characteristics and post-compression molding quality of seed cotton, a seed cotton compression molding experimental platform was constructed. Through analyzing the force acting on a single cottonseed, the boundary conditions for cottonseed crushing were determined, and a relationship curve between the cottonseed crushing rate and compression force was obtained. Furthermore, experimental factors including moisture content, initial density, compression force, and holding time were selected, and we investigated their relationship with the cottonseed crushing rate and dimensional stability coefficient. Ultimately, the optimal ranges of the compression molding parameters were determined using Design Expert 13.0.5 for parameter optimization and validation tests. These findings could serve as a reference for the development of seed cotton compression processes and the selection of operating parameters for packing devices.

2. Materials and Methods

2.1. Experimental Materials

The main machine-harvested cotton variety in the Shihezi area of Xinjiang, China, namely Huiyuan 720, was used as the experimental material in this study. A total of 3000 cotton plants with good growth and no diseases or pests were collected from the experimental field of Shihezi University on 15 October 2022. Then, the cotton plants were wrapped in black plastic bags and sealed for transportation to the laboratory. The seed cotton was obtained by indoor picking using the self-built CPT-02 cotton-picking performance test bench, as shown in Figure 1, and the natural bulk density of the seed cotton was measured using the fixed volume method as 38.95 kg/m^3. The remaining seed cotton was naturally air-dried for 5–7 days at a temperature of 20 ± 2 °C and a relative humidity of 60 ± 3%.

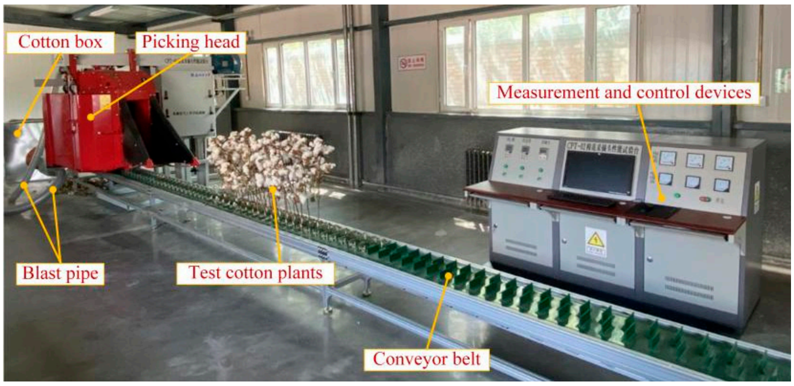


Figure 1. Cotton-picking performance test bench.

2.2. Experimental Instruments

The instruments used for the test were as follows: the seed cotton compression molding test bench shown in Figure 2, a MA100 rapid moisture meter (Sartorius, Göttingen, Germany) (range of 0–100 g and accuracy of 0.1 mg), a 101-1BS electric blast dryer (Tianyu Experimental Instrument and Equipment, Tianjin City, China), an MJSY-18 saw-tooth-type clothes parting test gin (Henan Jianghe Machinery Factory, Jiaozuo, China), an SX-5 body vision microscope imaging system (Shanghai Optical Instruments I Factory, Shanghai, China), an SPS402F precision electronic balance(OHAUS, Parsippany, NJ, USA) (range of 0–400 g and accuracy of 0.01 g), a steel plate ruler, and a height ruler.

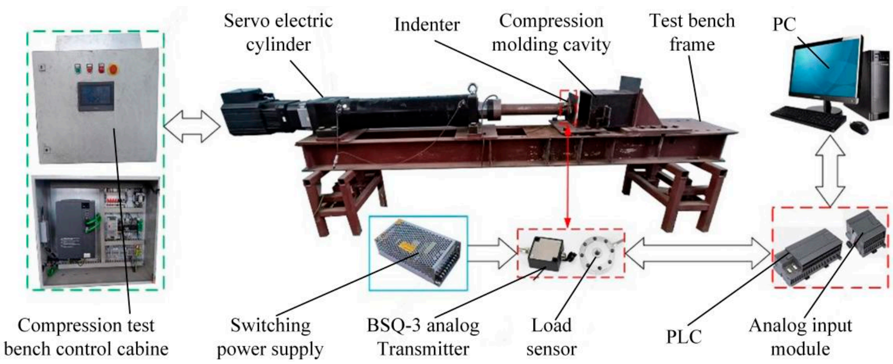


Figure 2. Seed cotton compression molding test bench.

The seed cotton compression molding test bench was composed of a servo-electric cylinder with a maximum extension displacement of 600 mm, a frame, an electrical control cabinet, a press head, a self-made square compression chamber (200 mm × 200 mm × 300 mm), a load sensor (measuring range of 0–20 kN and accuracy of 0.2%), a PLC, an analog input module, and auxiliary installation components. The compression force and compressed amount of seed cotton were recorded in real time using LabVIEW and the touch screen of the electrical control cabinet.

2.3. Experimental Method

To eliminate the influence of temperature differences and humidity in the experimental environment, the sample was placed in the test environment for at least 3 h before the experiment. Then, based on the levels of experimental factors, the cottonseeds were weighed and randomly placed in the compression cavity without pressing. The compression head was moved to align with the left end face of the compression cavity, and then the compression speed, compression force, holding time, and return speed were set. The compression and return speeds were 150 and 500 mm/min, respectively, and the compression force and holding time were based on the experimental design. Subsequently, the compression was stopped when the set compression force was reached, and the molding stage began. After reaching the holding time, the compression head returned, and then the cottonseed was quickly removed and placed in the test environment for 2 h for the subsequent measurement of the cotton module and the calculation of the cottonseed crushing rate.

The cotton module size was primarily divided into two stages: the size at the end of compression and the size after standing for 2 h following demolding. The former could be directly obtained based on the compression cavity and experimental data, whereas the latter needed to be measured. Given that the size of the seed cotton along its uncompressed direction had a small, constant recovery, the height gauge was used to measure each surface along the compression direction five times, and the average value was taken as the experimental data for the subsequent calculation to scientifically characterize the size of the cotton module after standing for 2 h following demolding.

After measuring the dimensions, the seed cotton was processed using a saw-type gin for ginning, chemical delinting, and drying to acquire the ginned cottonseeds. The obtained cottonseeds were sampled for testing, and five groups were randomly selected, with a single sampling weight of no less than 20 g (the thousand-seed weight of Huiyuan 720 cottonseed obtained before the experiment was approximately 83 g). Initially, the cottonseed was artificially screened to remove immature, broken, and crushed cottonseed. Then, the microcracked cottonseed was sorted out using a stereo microscope, as shown in Figure 3a. The cottonseed crushing and damage are shown in Figure 3b–d.

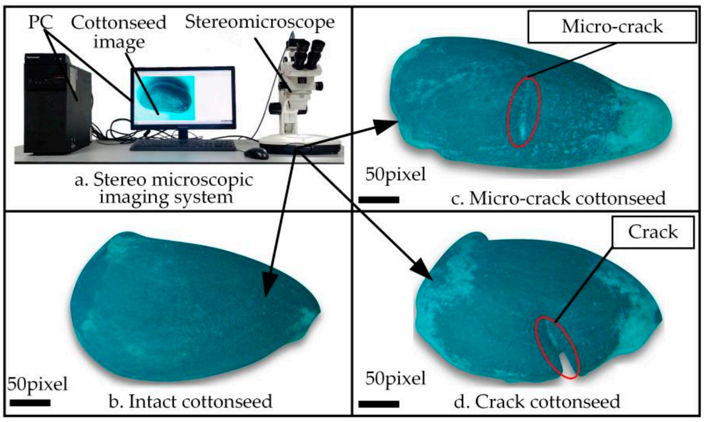


Figure 3. A case of cottonseed crushing damage. Note: The observation of cottonseed through the stereo microscope revealed no cracks on the surface for intact cottonseed, cracks on the surface but no visible cottonseed kernels for microcracked cottonseed, and evident rupture on the surface for visible cottonseed kernels or incomplete cottonseeds for broken cottonseed.

Ginning and chemical delinting were performed by one person, and the operation time was kept consistent to avoid interference from unknown factors during the cottonseed acquisition.

2.4. Test Evaluation Criteria

Compression molding characteristics include the dimensional stability coefficient, bulk density after relaxation, impact resistance, and specific energy consumption [18,19]. However, for seed cotton, excessive compression can cause the severe crushing of the cottonseeds, which affects the quality of the seed cotton. Therefore, for the compression molding of seed cotton, it is necessary to ensure that the intrinsic quality of the seed cotton does not decrease significantly while obtaining better compression molding characteristics. Based on this, the cottonseed crushing rate and dimensional stability coefficient were selected as the evaluation indicators.

When calculating the cottonseed crushing rate, the compressed seed cotton samples and the initial seed cotton samples had to be processed using identical procedures. The resulting linted cottonseeds were then used for further calculations, following the guidelines specified in GB/T 25416-2010 [22]. The calculation is shown in Equation (1). Seed cotton undergoes crushing during harvesting, compression, and processing. Therefore, by subtracting the cottonseed crushing rate due to harvesting and ginning from the total cottonseed crushing rate, the actual cottonseed crushing rate due to compression could be obtained, as shown in Equation (2).

$$Q_s = \frac{G_s}{G_q} \times 100\% \tag{1}$$

$$Q_y = Q_s - Q_s' \tag{2}$$

where Q_s is the cottonseed crushing rate, %; G_s is the mass of broken cottonseeds, g; G_q is the total mass of selected cottonseeds, g; Q_y is the cottonseed crushing rate due to compression, g; and Q_s' is the cottonseed crushing rate due to mechanical harvesting and ginning, %.

Based on the nature of the seed cotton and the post-compression state, the ratio of the height of the seed cotton after 2 h of resting in the compression direction and the height at compression termination was used as the dimensional stability factor, as shown in Equation (3).

$$\alpha = \frac{h_1}{h_0} \tag{3}$$

where α is the dimensional stability coefficient; h_1 is the height after 2 h of static settling, mm; and h_0 is the height at the end of compression, mm.

3. Analysis of Cottonseed Force during Compression

The compression of seed cotton can be divided into three stages: linear, transitional, and intensification. In the linear stage, the internal voids are compressed. In the transitional stage, the voids are eliminated, and the stress gradually becomes nonlinear. In the intensification stage, the stress increases dramatically, and the seed cotton is gradually compacted [15,23]. Seed cotton is a mixture of cottonseed and cotton fiber. Each flap of seed cotton contains about 7–8 cottonseeds, which are all wrapped in cotton fibers. During compression, the cottonseeds are randomly distributed among the cotton fibers. For a single cottonseed in the seed cotton, its force model is consistent, as shown in Figure 4.

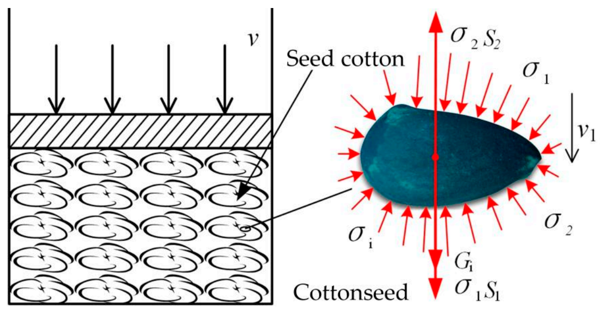


Figure 4. Schematic diagram of single cottonseed stress model. Note: G_i is the gravity of the cottonseed, N; v is the compression speed of the seed cotton aggregate, mm/s; v_1 is the speed of movement of a single cottonseed during compression, mm/s; σ_1 and σ_2 are the stresses on the upper and lower parts of cottonseed during compression, respectively, MPa; and S_1 and S_2 are the contact areas of the upper and lower parts of the cottonseed, respectively, mm^2.

When the seed cotton is not compressed, for the force analysis of a single cottonseed, it is subjected to stress σ_i from all directions [24], generating a combined force F_1, representing a pair of equilibrium forces with the gravity G_i of a single cottonseed, and the cottonseed is stationary. When the seed cotton assembly is compressed at speed v, in a truly brief time, in addition to its own gravity G_i, the single cottonseed is subjected to stresses σ_1 and σ_2 from the upper and lower parts, respectively, generating a resultant force F_1. The size of F_1 is unequal to the gravity G_i of a single cottonseed, causing the cottonseed to move in the compression direction at speed v_1 [25]. The seed cotton aggregate is gradually densified from being loose, and the stress σ_i on the cottonseed increases with the increase in the compression density of the seed cotton aggregate; when the combined force on the cottonseed is greater than the crushing force F_b that the cottonseed can withstand, the cottonseed breaks, as shown in Equation (4), and the force F_b that makes the cottonseed break is much greater than the gravity G_i [13,26]. Thus, the gravity can be neglected, and the cottonseed breaking condition can be simplified as in Equation (5).

$$\begin{cases} |F_1| = |\sigma_1 S_1 - \sigma_2 S_2| \\ |F_1 - G_i| > |F_b| \end{cases} \tag{4}$$

$$|F_1| > |F_b| \tag{5}$$

where F_1 is the resultant force exerted on the cottonseed by the surrounding cotton fibers during compression, N; σ_1 and σ_2 are the stresses experienced by the upper and lower portions of the cottonseed during compression, respectively, MPa; S_1 and S_2 are the contact areas between the cottonseed and the upper and lower portions, respectively, mm^2; G_i is the gravitational force acting on any individual cottonseed, N; and F_b is the breaking force of the cottonseed, N.

To determine the relationship between the cottonseed crushing rate and compression force after compression molding, compression tests were conducted at compression forces of 2, 4, 6, 8, 10, and 12 kN (corresponding to compression densities of 230, 285, 326, 355, 380, and 402 kg/m^3, respectively) to obtain cottonseeds and calculate the cottonseed crushing rate based on the above test method. The results are shown in Figure 5.

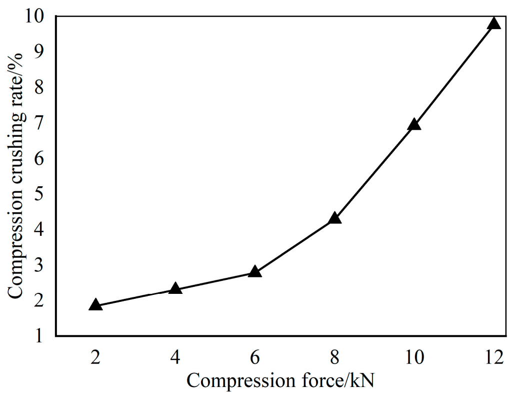


Figure 5. Relationship curve between cottonseed crushing rate and compression force.

Figure 5 shows that the cottonseed crushing rate gradually increased nonlinearly with the increase in compression force. When the compression force was in the range of 2–6 kN, the cottonseed crushing rate was less than 3% but not 0, corresponding to a compression density of approximately 300 kg/m^3. When the compression force exceeded 6 kN, the cottonseed crushing rate gradually increased, and the results were consistent with previous studies [8,11]. Therefore, an appropriate compression force should be selected for further study.

4. Seed Cotton Compression Molding Test

4.1. Single-Factor Test

4.1.1. Test Design

In the northern Xinjiang region of China, cotton harvesting is concentrated from late September to early November. During the harvesting period, the environment and operating parameters of cotton pickers vary greatly, resulting in an unstable moisture content for seed cotton [27,28]. As the moisture content increases, the adhesion force between impurities and cotton fibers increases significantly. A moisture content greater than 12% affects seed cotton processing [22]. During the harvesting period, the moisture content of seed cotton is generally high, reaching a maximum of 18–20% [29,30]. The preliminary experiment obtained a moisture content distribution range of approximately 7–11% for seed cotton. Therefore, in order to include the moisture content range obtained from the literature and the pre-experiment investigations into the study, the moisture content range was expanded on the basis of the known moisture content range, and test levels for the moisture content of 6%, 10%, 14%, 18%, and 22% were selected. Prior to the experiment, the moisture content of the test samples was measured as 4.72% according to the moisture determination method for seed cotton in ASABE standard S358.2, based on ASTM D2495 [31], and subsequently adjusted. Compression forces of 2, 4, 6, 8, and 10 kN were selected based on the relationship between the seed cotton crushing rate and compression force. Initial densities of 40, 50, 60, 70, and 80 kg/m^3 were selected based on the natural stacking density and common feeding density of seed cotton [22], and the corresponding feeding qualities were 480, 600, 720, 840, and 960 g per feeding, respectively. In addition, holding times of 50, 100, 150, 200, and 250 s were selected based on the stress relaxation characteristics of seed cotton according to the literature [19,23]. Finally, a single-factor test was performed with the dimensional stability coefficient as the indicator and five repetitions per group, and the average value was analyzed.

4.1.2. Analysis of Test Results

The obtained test data were subjected to variance analysis, and the results are shown in Table 1. Each factor had an extremely significant effect on the dimensional stability coefficient (p < 0.01).

Table 1. Analysis of variance of dimensional stability coefficient.

Factor	Variance Sources	Sum of Squares	Degrees of Freedom	Mean Square	*F*	*p*
Moisture content	Between groups	0.616	4	0.154	9.589	<0.001 **
	Within groups	0.321	20	0.016		
	Total	0.937	24			
Initial density	Between groups	4.402	4	1.101	29.490	<0.001 **
	Within groups	0.746	20	0.037		
	Total	5.149	24			
Compression force	Between groups	1.963	4	0.491	19.136	<0.001 **
	Within groups	0.513	20	0.026		
	Total	2.476	24			
Holding time	Between groups	0.494	4	0.123	11.578	<0.001 **
	Within groups	0.213	20	0.011		
	Total	0.707	24			

Note: ** indicates extremely significant (p < 0.01).

(1) Moisture content

The relationship between the dimensional stability coefficient and the moisture content is shown in Figure 6. Table 1 reveals that the moisture content had an extremely significant influence on the dimensional stability coefficient (p < 0.01). The dimensional stability coefficient decreased as the moisture content increased. When the moisture content was between 6% and 18%, the decrease was slow. When the moisture content reached 22%, a sharp decline was observed. An increase in moisture content makes seed cotton more viscous and adversely affects its flowability. Moreover, the impurities become more adhesive when wet [31,32], resulting in less springback for seed cotton after compression.

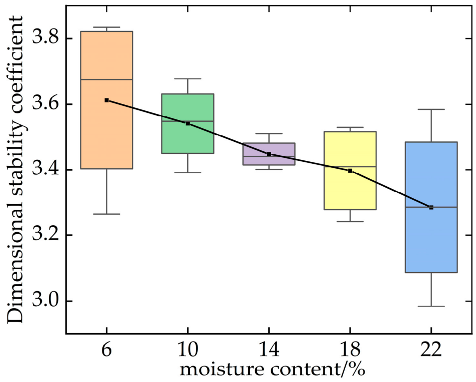


Figure 6. Boxplot of dimensional stability coefficient and moisture content.

(2) Initial Density

The relationship between the dimensional stability coefficient and initial density is shown in Figure 7. Based on Table 1, the initial density had an extremely significant effect on the dimensional stability coefficient ($p < 0.01$), which decreased with an increase in the initial density. Under the same compression force, the density of seed cotton with a lower initial density is smaller than that of seed cotton with a higher initial density after compression molding [23]. The plastic deformation of seed cotton with a lower initial density is small, the contact between the cotton fibers is less extensive, the elastic potential energy is more abundant, and the compressed height is smaller, resulting in a greater springback space during the static process. Therefore, the dimensional stability coefficient decreases as the initial density increases.

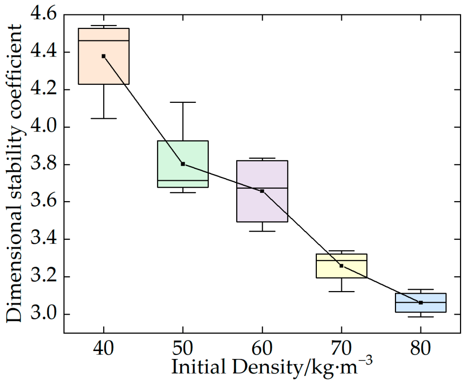


Figure 7. Boxplot of dimensional stability coefficient and initial density.

(3) Compression Force

The relationship between the dimensional stability coefficient and the compression force is shown in Figure 8. Based on Table 1, the compression force had a significant effect on the dimensional stability coefficient ($p < 0.01$), and the dimensional stability coefficient increased with an increase in compression force; however, the rate of increase gradually decreased. Due to the increase in compression force, the compressed density of the seed cotton increases, resulting in an increase in the amount of compressed seed cotton and its residual stress [33]. This outcome leads to an increase in the springback height. Moreover, the increase in the amount of compressed seed cotton reduces the number of internal voids and increases the entanglement between fibers [31], which slows down the rate of increase in the springback height and raises the dimensional stability coefficient, while gradually decreasing the growth rate of the dimensional stability coefficient.

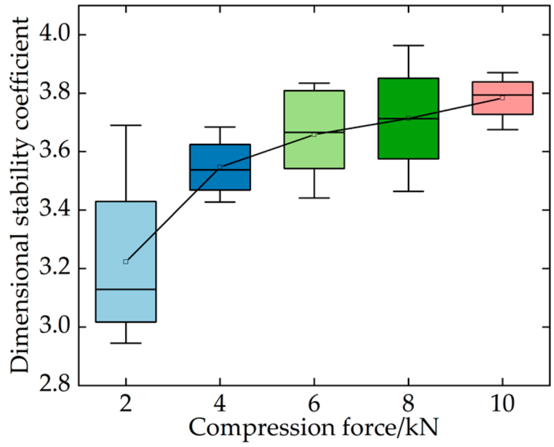


Figure 8. Boxplot of dimensional stability coefficient and compression force.

(4) Holding Time

The relationship of the dimensional stability coefficient and the holding time is shown in Figure 9. Based on Table 1, the holding time had an extremely significant effect on the dimensional stability coefficient ($p < 0.01$), and the dimensional stability coefficient decreased with an increase in the holding time. During shape retention, as the holding time increases, the residual stress in the seed cotton decreases and stabilizes, but the stress reduction rate gradually slows down [34,35]. This outcome causes the springback height to decrease gradually, and the rate of decrease in the dimensional stability coefficient slows down.

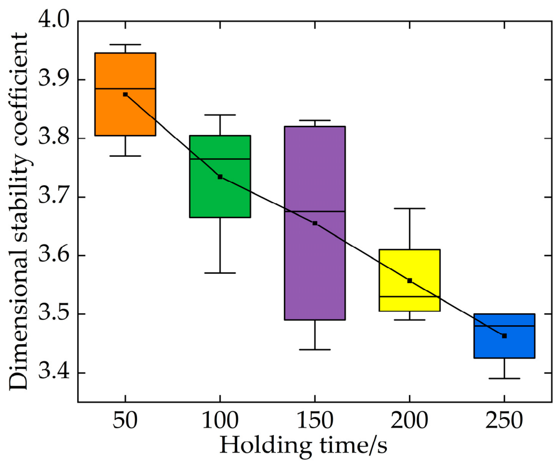


Figure 9. Boxplot of dimensional stability coefficient and holding time.

4.2. Multifactor Combination Test

4.2.1. Test Design

The results of the single-factor experiment indicated that moisture content, initial density, compression force, and holding time had extremely significant effects on the dimensional stability coefficient. Based on the previous research results, a multifactor combination experiment with four factors and three levels was conducted using the cottonseed crushing rate and dimensional stability coefficient as the evaluation criteria. The levels of experimental factors are shown in Table 2.

Table 2. Factors and levels of experiment.

Level	Moisture Content (X_1/%)	Initial Density (X_2/kg·m^{-3})	Compression Force (X_3/kN)	Holding Time (X_4/s)
−1	6	40	2	50
0	10	60	5	150
1	14	80	8	250

A total of 29 sets of experiments were conducted, each set was repeated thrice, and the average of the three trials was taken as the experimental result. The experimental protocol was designed using Design Expert.V13.0.5 software, and the results are shown in Table 3.

Table 3. Experimental design and results.

Run	X_1	X_2	X_3	X_4	Cottonseed Crushing Rate (Y_1/%)	Dimensional Stability Coefficient (Y_2)
1	6	40	5	150	2.45	4.18
2	14	40	5	150	3.84	3.93
3	6	80	5	150	2.85	3.09
4	14	80	5	150	3.58	2.91
5	10	60	2	50	1.37	2.86
6	10	60	8	50	4.94	3.58
7	10	60	2	250	1.44	2.82
8	10	60	8	250	4.91	3.51
9	6	60	5	50	2.56	3.62
10	14	60	5	50	3.35	3.26
11	6	60	5	250	2.62	3.32
12	14	60	5	250	3.79	3.16
13	10	40	2	150	1.41	3.46
14	10	80	2	150	1.29	2.57
15	10	40	8	150	4.98	4.27
16	10	80	8	150	4.44	3.12
17	6	60	2	150	1.54	3.05
18	14	60	2	150	1.83	2.76
19	6	60	8	150	4.39	3.68
20	14	60	8	150	5.89	3.41
21	10	40	5	50	3.17	3.93
22	10	80	5	50	2.73	3.14
23	10	40	5	250	3.27	4.09
24	10	80	5	250	2.99	3.01
25	10	60	5	150	3.07	3.37
26	10	60	5	150	3.14	3.44
27	10	60	5	150	3.25	3.39
28	10	60	5	150	3.09	3.34
29	10	60	5	150	3.01	3.43

4.2.2. Analysis of Test Results

Quadratic polynomial regression models were established for the relationships between the initial moisture content, initial density, compression force, hold time, dimensional stability coefficient, and cottonseed crushing rate (Table 4). After eliminating insignificant factors, the regression equations were obtained, as shown in Equations (6) and (7).

$$Y_1 = 3.09 + 0.4892X_1 - 0.1033X_2 + 1.72X_3 - 0.165X_1X_2 + 0.3025X_1X_3 + 0.1359{X_1}^2 \quad (6)$$

$$Y_2 = 3.37 - 0.1258X_1 - 0.5017X_2 + 0.3375X_3 - 0.04X_4 - 0.065X_2X_3 - 0.0725X_2X_4 + 0.1578{X_2}^2 - 0.1685{X_3}^2 \quad (7)$$

Table 4. Variance analysis of regression models.

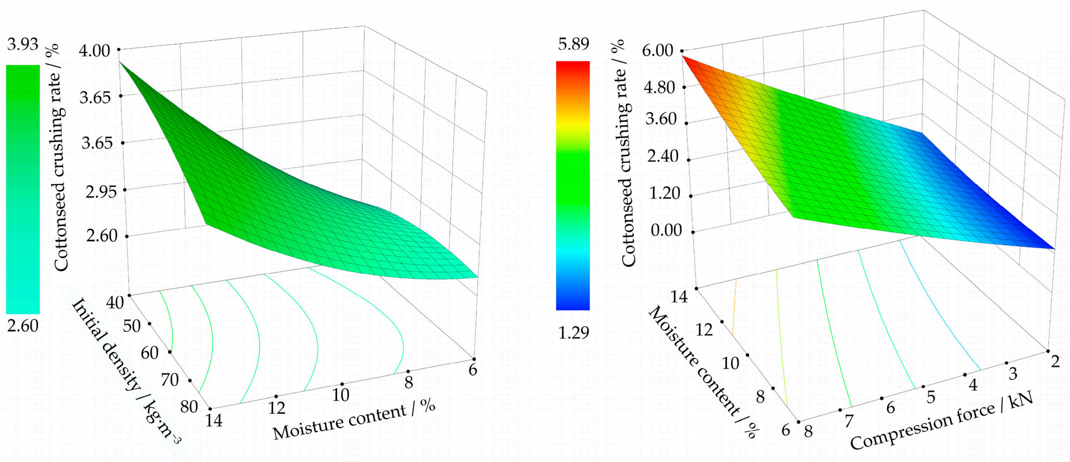
Variance Source	Degrees of Freedom	Cottonseed Crushing Rate (Y_1/%)				Dimensional Stability Coefficient (Y_2)			
		SS	MS	*F* Value	*p* Value	SS	MS	*F* Value	*p* Value
Model	14	39.52	2.82	121.67	<0.0001 **	5.08	0.36	104.92	<0.0001 **
X_1	1	2.87	2.87	123.75	<0.0001 **	0.19	0.19	54.99	<0.0001 **
X_2	1	0.13	0.13	5.52	0.0340 *	3.02	3.02	873.95	<0.0001 **
X_3	1	35.60	35.60	1534.48	<0.0001 **	1.37	1.37	395.55	<0.0001 **
X_4	1	0.068	0.068	2.91	0.1102	0.019	0.019	5.56	0.0335 *
X_1X_2	1	0.11	0.11	4.69	0.0480 *	0.0012	0.0012	0.35	0.5611
X_1X_3	1	0.37	0.37	15.78	0.0014 *	0.0001	0.0001	0.029	0.8674
X_1X_4	1	0.036	0.036	1.56	0.2327	0.010	0.010	2.89	0.1110
X_2X_3	1	0.044	0.044	1.90	0.1896	0.017	0.017	4.89	0.0441 *
X_2X_4	1	0.0064	0.0064	0.28	0.6077	0.021	0.021	6.08	0.0272 *
X_3X_4	1	0.0025	0.0025	0.11	0.7476	0.0002	0.0002	0.065	0.8023
X_1^2	1	0.11	0.11	4.65	0.0489 *	0.0014	0.0014	0.39	0.5400
X_2^2	1	0.044	0.044	1.89	0.1907	0.15	0.15	43.23	<0.0001 **
X_3^2	1	0.060	0.060	2.60	0.1289	0.20	0.20	57.16	<0.0001 **
X_4^2	1	0.027	0.027	1.17	0.2973	0.0035	0.0035	1.01	0.3309
Residuals	14	0.32	0.023			0.048	0.0035		
Lack of fit	10	0.29	0.029	3.60	0.1142	0.041	0.0041	2.40	0.2073
Pure error	4	0.032	0.0081			0.0069	0.0017		
Cor total	28	39.85				5.12	0.36		

Note: ** indicates extremely significant difference ($p < 0.01$); * indicates significant difference ($p < 0.05$).

4.2.3. Impact of Factors on Corresponding Indicators

(1) Influence of the interaction of several factors on the cottonseed crushing rate

The response surface plot of the cottonseed crushing rate is shown in Figure 10. In Figure 10a, the cottonseed crushing rate gradually increased with the increase in moisture content and the decrease in initial density. As the moisture content increases, the strength of the cottonseed decreases, and it is more likely to deform under the same compression force, leading to crushing [36]. The decrease in initial density results in a larger compressed volume, leading to greater deformation, which also causes more severe crushing [37]. Therefore, the cottonseed crushing rate is higher.



a. Effect of X_1 and X_2 on Cottonseed crushing rate b. Effect of X_1 and X_3 on Cottonseed crushing rate

Figure 10. Effects of two factors on cottonseed crushing rate.

In Figure 10b, the cottonseed crushing rate increased significantly with an increasing moisture content and compressive force. The reason for this result lay in the increase in the moisture content of the cottonseeds, leading to a softer and more fragile texture, accompanied by an enlargement in the cottonseed volume. This increased softness and the expanded force-receiving area, under the influence of a gradually increasing compression force, results in a rapid rise in the cottonseed breakage rate [36]. Combined with the effect of the moisture content on the compression characteristics of cottonseed, a higher moisture content results in a lower compressive force being required to achieve the same compression density, meaning that greater deformation is incurred, leading to increased force distributed over individual cottonseed particles. These two factors jointly contribute to the increase in the cottonseed crushing rate.

(2) Influence of interactive factors on the dimensional stability coefficient

The response surface plot of the dimensional stability coefficient is shown in Figure 11. In Figure 10a, with an increasing initial density and decreasing compressive force, the dimensional stability coefficient decreased, indicating an improvement in the compression molding characteristics of the seed cotton. The higher the initial density, the smaller the compression displacement needed to achieve the same compressive force, and the smaller the springback height after unloading [31]. Therefore, the dimensional stability coefficient of the seed cotton is small. As the compression force increases, the compression displacement increases, allowing more height to springback, resulting in a larger dimensional stability coefficient.

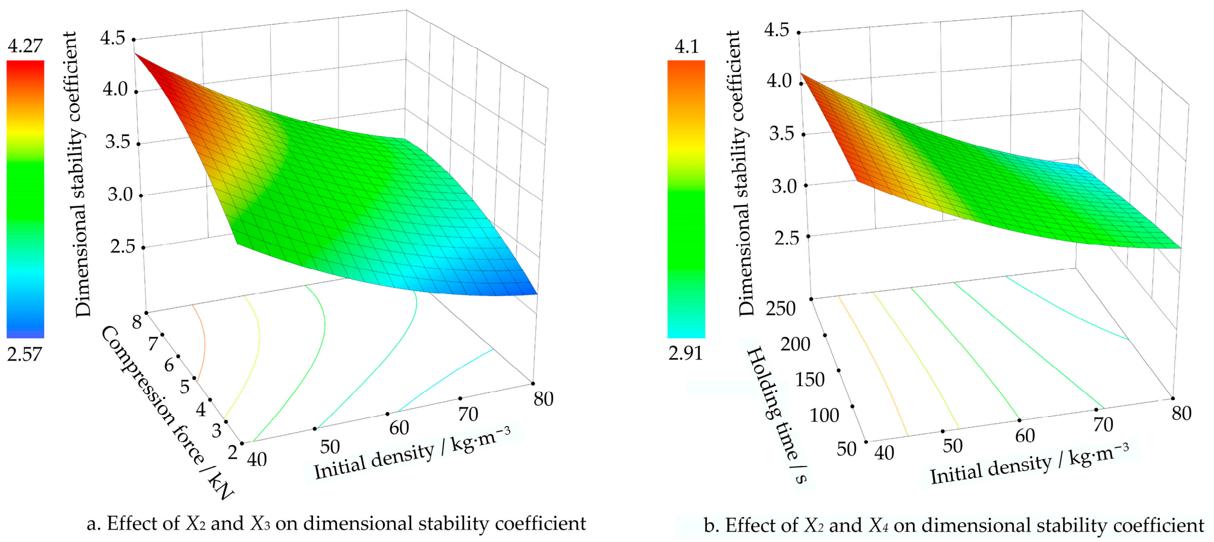


Figure 11. Effects of two factors on dimensional stability coefficient.

Figure 11b shows that with an increasing initial density, the dimensional stability coefficient decreased, indicating an improvement in the compression molding characteristics of the seed cotton. With a prolonged holding time, the dimensional stability coefficient decreased slowly, which was due to the reduction in residual stress during the shape retention process over time, allowing the stress to be distributed evenly and stabilized internally. Therefore, the compression molding characteristics of the seed cotton improved [19]. As the holding time increased, the increase in the amplitude of the dimensional stability coefficient continued to slow down.

4.2.4. Solution and Verification of Improved Parameters

Considering that cottonseed crushing cannot be avoided during mechanical harvesting, compression molding, ginning, and linting [38], pursuing a cottonseed crushing rate of zero during compression molding is unrealistic. In actual production, a high cottonseed crushing rate is not conducive to the subsequent processing of seed cotton and affects the quality of the cotton fibers. Therefore, reducing the cottonseed crushing rate is highly significant for seed cotton processing. After processing, when cottonseed is used as seed, the cottonseed crushing rate should be less than 5–6%; when used for oil pressing, it should be less than 8%; and during mechanical harvesting and ginning observations, the cottonseed crushing rate is generally 2–3% [39,40]. The seed cotton aggregate inevitably rebounds because of the presence of residual stress. Therefore, the dimensional stability coefficient should also be within a certain range. Based on the results obtained earlier, the cottonseed crushing rate was between 2 and 3%, and the dimensional stability coefficient was between 3 and 3.5, with the constraints shown in Equation (8).

$$\begin{cases} 3 \leq Y_1 \leq 3.5 \\ 2 \leq Y_2 \leq 3 \end{cases}$$

$$where : \begin{cases} 6 \leq X_1 \leq 12 \\ 40 \leq X_2 \leq 80 \\ 2 \leq X_3 \leq 8 \\ 50 \leq X_4 \leq 250 \end{cases} \tag{8}$$

Using Design Expert 13.0.5 software with Equation (8) as the constraint, multiobjective optimization was performed, and the optimal results were obtained, as shown by the yellow region in Figure 12. The moisture content was 6–11.7%, the initial density was 47.87–74.84 kg/m^3, the compression force was 3–5.32 kN, and the holding time was 50–239.75 s. Further optimizing the compression parameters within this region yielded the optimal combination: a moisture content of 9.55%, initial density of 63.00 kg/m^3, compression force of 4.70 kN, holding time of 165 s, predicted cottonseed crushing rate (Y_1) of 2.853%, and predicted dimensional stability coefficient (Y_2) of 3.274.

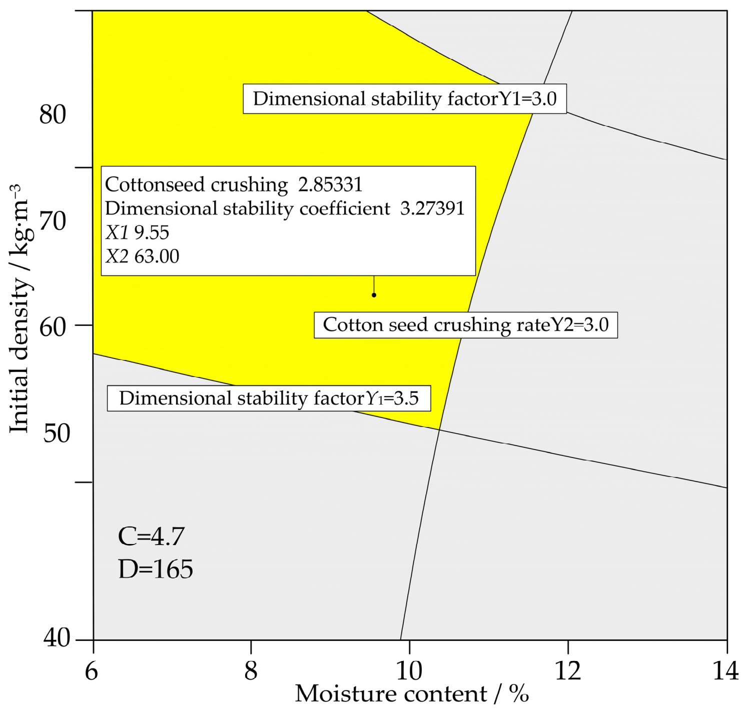


Figure 12. Optimal scheme of experiment. Note: the compression force was 4.7 kN, and the holding time was 165 s.

To validate the regression equations for the dimensional stability coefficient and cottonseed crushing rate after machine-harvested seed cotton compression molding, as well as the reliability of the optimization results, experiments were conducted using the optimal compression parameters. Five sets of experiments were conducted, and the results are shown in Table 5.

Table 5. Results of validation test.

No.	Cottonseed Crushing Rate (Y_1/%)	Error/%	Dimensional Stability Coefficient (Y_2)	Error/%
	Measured Values		Measured Values	
1	2.92	2.35	3.32	1.41
2	2.90	1.65	3.25	2.32
3	2.80	1.86	3.28	0.18
4	2.87	0.60	3.40	3.85
5	2.95	3.40	3.21	1.95
Average value	2.888	1.972	3.282	1.942

The maximum relative errors between the experimentally measured cottonseed crushing rate and dimensional stability coefficient and their predicted values were 3.40% and 3.85%, respectively. This indicated the reliability of the regression equations for both parameters. The validation results demonstrated that under the optimized experimental conditions, favorable compression molding parameters could be obtained, leading to superior seed cotton molding characteristics and a lower cottonseed crushing rate. These findings hold significant reference value for the formulation of seed cotton compression processes.

5. Conclusions

(1) A mechanical analysis of a single cottonseed during compression was conducted. This analysis yielded the conditions under which the cottonseed was crushed. The compression tests on seed cotton revealed a pattern whereby the cottonseed crushing rate increased with an increase in the compression force. Consequently, this provided the boundary conditions for studying the compression characteristics of seed cotton.

(2) The influence of the moisture content, initial density, compression force, and holding time on the dimensional stability coefficient was significant. Specifically, the dimensional stability coefficient decreased with an increase in the moisture content, initial density, and holding time, whereas it increased with an enhancement in the compression force.

(3) Through multifactor combination experiments and optimization using the response surface methodology, optimal ranges for the parameters were determined: a moisture content ranging from 6% to 11.7%, initial density between 47.87 kg/m^3 and 74.84 kg/m^3, compression force ranging from 3 kN to 5.32 kN, and holding time ranging from 50 s to 239.75 s.

The research findings hold theoretical value for determining the working conditions of cotton-picking machines, developing seed cotton compression processes, and designing compression molding devices.

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Data Availability Statement: The data used or generated during this study are available upon request from the corresponding author and are subject to privacy and ethical restrictions. As per our institution's guidelines, we are unable to publicly share the data due to these considerations. However, we encourage interested parties to contact the corresponding author to discuss the possibility of accessing the data and any related inquiries. We aim to foster open science principles and are committed to promoting transparency and collaboration in research.

Conflicts of Interest: The authors declare no conflict of interest.

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