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Experimental Study and Simulation of the Stress Relaxation Characteristics of Machine-Harvested Seed Cotton

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Abstract: Seed cotton compression molding solves the inconvenience of seed cotton transportation and storage after mechanical harvesting. Stress relaxation is closely related to the performance of the compressed seed cotton. In this study, an electronic universal testing machine with a homemade compression device was used to study the stress relaxation characteristics of machine-harvested seed cotton. The stress relaxation model of machine-harvested seed cotton was established, the influence of test factors on the response indexes was analyzed and, finally, stress relaxation characteristics of machine-harvested seed cotton were simulated. Results show that machine-harvested seed cotton stress relaxation characteristics can be described by the five-element Maxwell model. The equilibrium elastic modulus is negatively correlated with moisture content and cross-section dimensions, and the equilibrium elastic modulus is positively correlated with trash content and compression density. The rapid decay time and the residual stress ratio are negatively correlated with moisture content and compression density, but the influence of trash content and cross-section dimensions are limited. The stress relaxation process of machine-harvested seed cotton was simulated using virtual prototype technology, and the maximum error between the experimental and simulated values was obtained as 4.96%. The feasibility of the virtual prototype technique for the viscoelastic simulation of biomaterials was demonstrated.

Keywords: stress relaxation; machine-harvested seed cotton; rheological properties; experiment; mathematical models; simulation of virtual prototype

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1. Introduction

Cotton, flax and hemp plants are the main textile materials in the world [1]. While cotton is not only an important material, it is also one of the most important economic crops in Xinjiang, China, where the main planting of cotton is upland cotton [2,3]. Its planting area and output have ranked first in China for many years [4]. With the development of agricultural mechanization, cotton's mechanized harvesting has become a trend [5]. Cotton harvested by cotton pickers is collectively referred to as machine-harvested seed cotton, which has a small bulk density and belongs to a loose agricultural fiber material [6]. However, because the integration rate of cotton pickers in China is low, machine-harvested seed cotton requires secondary processing, resulting in its expensive costs of storage and transportation [7,8]. Therefore, machine-harvested seed cotton is compressed into modules of certain shapes, sizes, and densities before storing and transporting them [9]. Advanced cotton pickers have integrated compression molding equipment with cotton pickers, which can make mechanical harvest and compression molding continuous, solving the problems effectively [10,11].

At present, the compression and stress relaxation characteristics of fiber materials have been more widely examined [12]. The compression characteristics of cotton fibers and lint have been studied, while the relationship between compression density and compression force and compression modulus during compression has been derived, and the characteristics of each process has been described [13–18]. A finite element model of the cotton fiber was developed and the stress changes during compression of the cotton fiber were simulated [19]. However, the research on seed cotton compression and stress relaxation is at the initial stage. Hardin studied the compression and creep of seed cotton at small compression densities and established a creep model for seed cotton compression [20–22]; Kong Ft studied the effect of moisture content and feeding quality on the compression characteristics of seed cotton and established a stress relaxation model for seed cotton [23,24]. Husin concluded that the cottonseeds breaking rate has increased significantly when the compression density was greater than 400 kg/m^3 [25]. And now research on the stress relaxation characteristics of common agricultural fiber materials has matured. The compression, stress relaxation and creep of the material have been investigated, and rheological models have been developed to analyze the effects of moisture content and compression force on their rheological properties [26–30]. Rheological properties of the agricultural material have also been studied in terms of material type, initial density, compression speed and cross-sectional dimensions, which could provide implications for the successful development of this study [31–37]. The lack of understanding on stress relaxation characteristics of seed cotton restricted us from revealing the compression molding mechanism.

In previous studies on the factors influencing the compression and stress relaxation characteristics of seed cotton, the effects of seed cotton as a mixture and the physical properties of seed cotton on compression and stress relaxation parameters were ignored. In this paper, we investigated the effect of moisture content, trash content, compression density and cross-sectional dimensions on the stress relaxation characteristics of machine-harvested seed cotton through stress relaxation tests during the harvest period.

2. Materials and Methods

2.1. Test Materials and Devices

Machine-harvested seed cotton is a mixed fiber material with a wide range of constituents as one of its main characteristics. In this paper, the main planted machine-harvested cotton variety Huiyuan 720 in the Shihezi region was used as the research object, taken from the experimental field of Shihezi University, as shown in Figure 1. It was harvested by a John Deere 7660 cotton picker on 10 October 2020, brought back to the laboratory, dried naturally for one month, and then measured for its bulk density, which was $40\sim 50 \text{ kg/m}^3$.

Test equipment: Changchun Testing Machine Research Institute CSS-44300 electronic universal material testing machine, Germany Sartorius MA 100 rapid moisture meter, SPS402F precision electronic balance, steel plate ruler, and self-made compression device. The self-made compression device includes a compression chamber with a circular cross-sectional shape, an inner diameter of 100, 150, and 200 mm a height of 270 mm, the compression piston with a radius of 49.5, 74.5, and 99.5 mm, and the demold device.

Figure 1. The situation of the experiment filed. (a) the specific geographical location of the experimental field, in which is 88.99° E, 44.31° N; (b) Experimental cotton field.

2.2. Experimental Method

2.2.1. Experimental Factors

Cotton harvesting in Xinjiang is concentrated from mid-September to early November every year, and the seed cotton moisture content and trash content are often affected by the working conditions of cotton pickers during harvesting, which are random and highly variable [38–40], while the compression density and cross-sectional dimensions are usually correlated with compression power consumption. Therefore, the stress relaxation characteristics of seed cotton were investigated by using seed cotton moisture content, trash content, compression density, and cross-section dimensions as test factors. The moisture content of seed cotton is generally 6~22%, and the trash content is 8~16% during the harvest period. Meanwhile, when seed cotton is compressed to 400 kg/m³, the cottonseeds are broken violently, while the seed cotton compression equipment can compress the seed cotton to 200 kg/m³ [8,25]. The cross-sectional shape is selected as circular. The moisture content of machine-harvested seed cotton was selected as 6%, 10%, 14%, 18% and 22%; trash content was 8%, 10%, 12%, 14% and 16%; compression density was 200 kg/m³, 250 kg/m³, 300 kg/m³, 350 kg/m³, and 400 kg/m³; the cross-section dimensions of the compression chamber was selected as 100 mm, 150 mm and 200 mm. And the levels of experimental factors are shown in Table 1.

Table 1. The levels of experimental factors.

Levels	Compression Density (kg·m ⁻³)	Moisture Content (%)	Trash Content (%)	Cross-Sectional Dimension (mm)
1	200	6	8	100
2	250	10	10	150
3	300	14	12	200
4	350	18	14	
5	400	22	16	

2.2.2. Specimen Preparation

The experiment procedures are shown in Figure 2. The average moisture content of seed cotton specimens was 4.7% the trash content was 11.62%, and the moisture content and trash content were adjusted to the desired level using the rehydration method according to Equation (1) [41]. To ensure the uniformity of the trash content, impurities of the corresponding proportional mass were added or removed; the moisture content was added

to water at the desired level, placed into sealed bags, and stored in the laboratory for more than 48 h.

$$m_d = m_o \times \frac{|d_1 - d_0|}{1 - d_1}, \quad (1)$$

where

m_d = the added (remove) impurities (water) mass (g)

m_o = the required modulation specimen mass (g)

d_0 = the trash (moisture) content of specimen (%)

d_1 = the specimen required to adjust the trash (moisture) content of specimen (%).

Figure 2. The experiment procedures. (a) mechanized harvesting; (b) machine-harvested seed cotton sampling; (c) rehydration (adding impurities) treatment machine-harvested seed cotton samples; (d) processed samples; (e) feeding quality control; (f) guarantee of initial density; (g) machine-harvested seed cotton compresses and strain remains 300 s; (h) machine-harvested seed cotton molding.

2.2.3. Compression Data Acquisition of Machine-Harvested Seed Cotton

Before the test, specimens were taken out in advance and placed in the test environment for more than three hours. Specimens were weighed and placed into the compression device naturally, to ensure the feeding density of 40 kg/m^3 , using an electronic material universal testing machine with a 50 mm/min compression speed to compress the seed cotton to the target compression density. The compression displacement was calculated according to Formula (2), and the compression displacement and compression speed were set before the test. After the test, the machine-harvested seed cotton that had been compressed were stored, and each group of tests was repeated three times.

$$l = l_0 - \frac{\rho_0 \times l_0}{\rho}, \quad (2)$$

where

l = the compression amount of machine-harvested seed cotton (mm)

l_0 = the initial height of machine-harvested seed cotton (mm)

ρ_0 = the initial density of machine-harvested seed cotton (kg/m^3)

ρ = the compression density during compression (kg/m^3).

3. Results and Discussion

3.1. Stress Relaxation Model for the Compression of Machine-Harvested Seed Cotton

Machine-harvested seed cotton is a common agricultural fiber material, and for the rheological properties of agricultural fiber material, scholars often use the Maxwell and Burgers models. Many studies have also shown that the Maxwell model can better describe the stress relaxation of agricultural materials. Therefore, in this study, the Maxwell model was chosen to characterize the stress relaxation properties of machine-harvested cotton

by comparing the obtained stress relaxation curves with common viscoelastic models. Although the Maxwell model can describe the stress relaxation process of machine-harvested cotton, the more Maxwell cells, the closer it is to the actual stress relaxation process of the material; it will introduce many variables, which is not conducive to the further solution of the model. And the stress rapid decay time T_1 is the time required for the stress to decrease to $1/e$ of the initial stress. The generalized Maxwell has multiple stress relaxation times that are equal to the time required for each Maxwell element to decrease to $1/e$ of their respective initial stresses. More importantly, due to the special nature of the Maxwell cells (which consists of a spring and a viscous pot), the initial stress on it does not eventually decay to zero, but to a stable value, which we call the equilibrium stress (or modulus).

The stress relaxation of machine-harvested seed cotton with 6% moisture content, 12% trash content and 300 kg/m^3 compression density were used as an example, and the stress variation curve of machine-harvested seed cotton with time is plotted when its strain remains 300 s. Using Origin 2017 to fit the regression to it using the Maxwell model and generalized Maxwell model, we can obtain the expression of stress relaxation characteristics of machine-harvested seed cotton, which can be used in 2 Maxwell cells and 1 equivalent spring parallel five-element model [23], as shown in Figure 3a, and the expression is shown in Equation (3).

$$E(t) = E_1 e^{-t/T_{s1}} + E_2 e^{-t/T_{s2}} + E_e, \quad (3)$$

where

$$T_{s1} = \eta_1 / E_1; T_{s2} = \eta_2 / E_2.$$

T_{s1}, T_{s2} = the rapid decay time of the stress, the slow decay time of the stress (s)

E_1, E_2 = the modulus of elasticity for the first Maxwell model, the modulus of elasticity for the second Maxwell model (MPa)

E_e = the equilibrium elastic modulus (MPa)

η_1, η_2 = the coefficients of viscosity for the first Maxwell model, the coefficients of viscosity for the second Maxwell model (MPa·s).

Figure 3. Stress relaxation model and fitting curve. (a) five-element Maxwell mode; (b) stress relaxation of machine-harvested cotton fitting curve.

The compression process of machine-harvested seed cotton is divided into two stages. The first stage is the compression, where with increasing compression displacement the compression density of machine-harvested seed cotton increases continuously; the second stage is the stress relaxation stage, in which the stress change in this stage also has two stages. In the initial of stress relaxation, stress decays rapidly to $1/e$ of the initial, which occurs within 10 s of stress relaxation; after that the stress decreases slowly and its value tends to a constant value. The proper equation is shown in Equation (4).

$$E(t) = 0.0706 e^{-t/4.9377} + 0.0368 e^{-t/98.8569} + 0.2005, \quad (4)$$

From Equation (4) and Figure 3b, the stress rapid decay time is 4.9377 s, the stress slow decay time is 98.8569 s, the equilibrium elastic modulus is 0.2005 MPa, and the fitted coefficient of determination $R^2 > 0.99$, indicating that the equation can better reflect the stress relaxation in the stress relaxation phase of machine harvested seed cotton.

3.2. Stress Relaxation Characteristics of Machine-Harvested Seed Cotton

T_1 reflects the rapid decay rate of stress relaxation; The smaller T_1 is, the faster the stress decay of machine-harvested seed cotton changes. T_1 determines the optimal length of wrapping and winding time of machine-harvested seed cotton after baling [25]; E_e reflects the ability of machine-harvested seed cotton to recover in the process of stress relaxation; the smaller E_e is, the less loose wrapping and damage phenomenon of the machine-harvested seed cotton can be reduced after wrapping. ε reflects the residual stress ratio of machine-harvested seed cotton after stress relaxation, similar to E_e , which indicates the stress relaxation of machine-harvested seed cotton. The smaller ε is, the more it can be used to measure the effect of stress relaxation, and its calculation formula is shown in Equation (5):

$$\varepsilon = \frac{\sigma_s}{\sigma_0} \times 100, \quad (5)$$

where

σ_s = the stress after relaxation stabilization (MPa)

σ_0 = the stress after reaching the set strain (MPa)

ε = the residual stress ratio (%).

To reveal the effect of moisture content, trash content, compression density, and cross-sectional dimensions of machine-harvested seed cotton on stress relaxation characteristic parameters, the five-element Maxwell model was used to fit all stress relaxation curves of machine-harvested seed cotton, and the stress relaxation characteristic parameters were obtained, taking the average of the three groups of experiments, as shown in Table 2. A correlational analysis of stress relaxation characteristics parameters was conducted, as shown in Table 3.

Table 2. Parameters of stress relaxation of machine-harvested cotton.

Factors	Levels	E_1 (MPa)	E_2 (MPa)	E_e (MPa)	η_1 (MPa·s)	η_2 (MPa·s)	T_1 (s)	T_2 (s)	ε (%)	R^2
Moisture content (%)	6	0.0735	0.0378	0.1296	0.379	3.795	5.158	100.410	54.168	0.999
	10	0.0602	0.0317	0.1099	0.306	3.222	5.085	101.646	53.302	0.999
	14	0.0544	0.0284	0.0876	0.278	2.831	5.102	99.669	52.085	0.999
	18	0.0486	0.0249	0.0737	0.245	2.475	5.049	99.392	50.489	0.999
	22	0.0395	0.0219	0.0573	0.201	2.205	5.090	100.694	48.748	0.999
Trash content (%)	8	0.0691	0.0352	0.1843	0.348	3.546	5.031	100.735	64.173	0.999
	10	0.0696	0.0345	0.2049	0.343	3.446	4.934	99.884	66.578	0.999
	12	0.0844	0.0423	0.2055	0.412	4.231	4.884	100.035	62.207	0.999
	14	0.0919	0.0458	0.2187	0.451	4.604	4.912	100.524	61.810	0.999
	16	0.0868	0.0431	0.2331	0.431	4.334	4.966	100.562	64.526	0.999
Compression density (kg·m ⁻³)	200	0.0073	0.0057	0.0396	0.045	0.631	6.202	110.678	75.684	0.997
	250	0.0229	0.0165	0.0904	0.134	1.763	5.843	106.820	70.067	0.999
	300	0.0634	0.0326	0.1791	0.315	3.278	4.966	100.541	65.457	0.999
	350	0.1528	0.0718	0.3887	0.738	7.073	4.830	98.511	63.651	0.999
	400	0.3416	0.1528	0.7737	1.590	14.995	4.655	98.134	61.326	0.999
Cross-sectional dimensions (mm)	100	0.0394	0.0212	0.1238	0.204	2.168	5.179	102.282	67.511	0.999
	150	0.0334	0.0184	0.1046	0.173	1.822	5.167	99.032	67.106	0.999
	200	0.0299	0.0160	0.0929	0.151	1.624	5.051	101.477	67.243	0.999

Table 3. Correlation analysis of stress relaxation characteristics parameters.

Items	E_1	E_2	E_e	η_1	η_2	T_1	T_2	ε
Moisture content	−0.979 **	−0.981 **	−0.992 **	−0.981 **	−0.978 **	−0.672 **	−0.332	−0.899 **
Trash content	0.703 **	0.662 **	0.949 **	0.687 **	0.647 **	−0.316	0.035	−0.175
Compression density	0.913 **	0.920 **	0.929 **	0.918 **	0.920 **	−0.825 *	−0.579 *	−0.971 **
Cross-sectional dimensions	−0.692 *	−0.897 **	−0.895 **	−0.817 **	−0.887 **	−0.197	−0.194	−0.075

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

We fitted the stress relaxation characteristics of machine-harvested seed cotton under different conditions, and the results are shown in Table 2. The fitting coefficient of stress relaxation parameters $R^2 > 0.99$, indicating that the five-element Maxwell model can accurately describe the stress relaxation of machine-harvested seed cotton. Meanwhile, the correlation analysis results in Table 3 show that the equilibrium elastic modulus E_e is negatively correlated with moisture content and cross-sectional dimensions ($p < 0.01$), but is positively correlated with trash content and compression density ($p < 0.01$). The rapid decay time T_1 is negatively correlated with moisture content and compression density ($p < 0.05$), but is weakly correlated with trash content and cross-sectional dimensions. The residual stress ratio is negatively correlated with moisture content and compression density ($p < 0.01$), but is weakly correlated with trash content and Cross-sectional dimensions.

3.2.1. Effect of Moisture Content on Stress Relaxation Characteristics

As shown in Figure 4a, as the moisture content increases, a smaller compression force is required when the seed cotton is compressed to the same density [23,32]. The main reason for this phenomenon is that the cotton fiber, cottonseeds, cotton and other components of the water absorption are slightly different, the higher the moisture content of is, the smaller the elastic modulus is would be [25,42]. With the increase of seed cotton moisture content, it is easier for seed cotton to be densely compressed, and it requires less compression force. As shown in Figure 4b,c, the minimum value of T_1 appeared at 18% with increasing moisture content, and E_e and ε gradually decreased with moisture content increasing. This is due to the fact that the increasing moisture content disrupts the hydrogen bonds in the cell wall, shielding the interaction forces between macromolecules, and increasing intermolecular flexibility [41], thus making it easier to move, requiring less compression force, and the faster the stress relaxation rate, the smaller the residual stress ratio. It shows that seed cotton relaxes better at a high moisture content.

3.2.2. Effect of Trash Content on Stress Relaxation Characteristics

The trash content increases the bulk density of machine-harvested seed cotton, while the impurities are rich in the higher modulus of elasticity of wood fibers [42,43]. As shown in Figure 5a, the initial stress of seed cotton gradually increases with the increase of trash content. The main reason for this phenomenon is that the modulus of elasticity of wood fibers such as impurities is large, resulting in the need for a larger compression force for seed cotton at a high trash content [43]. As shown in Figure 5b,c, the E_e increases slightly with the trash content, and the main reason is that the compression force increases with the increase of trash content, and there is a certain transient drop under the larger compression force; while T_1 increases with the decrease of trash content, and the minimum value appears at 12%, which is explained by the proper increase of trash content, which can make the seed cotton and impurities easier to bond, but an excessively high or low trash content will hinder the close combination between seed cotton and the impurities [44]. With the increase of trash content, the ε shows a fluctuating decrease, and the main reason for this phenomenon is that the trash content of seed cotton is not uniform, and there will be certain pores in the compression process, which makes the ε decrease with the increase of trash content.

Figure 4. Stress relaxation characteristics at different moisture contents: (a) Stress relaxation curve; (b) Equilibrium elastic modulus E_e and rapid decay time T_1 ; (c) Residual stress ratio ϵ .

Figure 5. Stress relaxation characteristics at different trash contents: (a) Stress relaxation curve; (b) Equilibrium elastic modulus E_e and rapid decay time T_1 ; (c) Residual stress ratio ϵ .

3.2.3. Effect of Compression Density on Stress Relaxation Characteristics

The high density compression of seed cotton increases the required compression force [14,17,18,23]. Figure 6a shows the stress relaxation characteristics curves of machine-harvested seed cotton compressed to different compression densities. The trends of stress relaxation characteristics curves of machine-harvested seed cotton were basically similar at each compression density. Figure 6b,c show the curves of stress relaxation characteristics of parameters E_e , T_1 , and ε with the compression density of machine-harvested seed cotton under different compression densities, T_1 decreases with the increase of compression density, and the lowest point appears when the compression density is 400 kg/m³. The main reason is that the compression force of machine-harvested seed cotton at high density is large, and the stress exists transient drop, stress relaxation rate is fast; thus T_1 has the minimum value [36,41]. Moreover, the maximum value of E_e and the minimum value of ε were obtained at the compression density of 400 kg/m³. This is due to the fact that the higher the compression density is, the higher the compression force and the greater the corresponding stress are [23,32,35], while the stress relaxation process itself is a long process, and the rate of stress decrease becomes slower, in which there is a higher E_e at high compression density. Meanwhile, with the increase of compression density, the seed cotton pressure drops, while its equilibrium stress time T_2 is also larger, which means that the seed cotton under high compression density reaches the equilibrium modulus E_e rapidly, and there is more time for stress homogenization, thus there is smaller ε under high compression density, indicating a better stress relaxation effect.

Figure 6. Stress relaxation characteristics at different compression densities: (a) Stress relaxation curve; (b) Equilibrium elastic modulus E_e and rapid decay time T_1 , (c) Residual stress ratio ε .

3.2.4. Effect of Section Size on Stress Relaxation Characteristics

As shown in Figure 7a, the initial stress of seed cotton gradually decreases with the increase of cross-sectional dimensions. When the seed cotton is compressed to the same density, the initial stress gradually decreases with the increase of the cross-sectional dimensions. The stress can be gradually homogenized in the radial direction due to the larger cross-sectional dimensions, which made the compression force required decrease during the compression process [36]. Figure 7b,c show the curves of stress relaxation characteristics of parameters E_e , T_1 and ε with cross-sectional dimensions of machine-harvested seed cotton under different cross-sectional dimensions. E_e decreases gradually with the increase of cross-sectional dimensions, and there is a minimum value at of 200 mm. The primary reason is that the compression force decreases with the increase of cross-sectional dimensions [45], and the stress is easily homogenized along the direction of cross-sectional dimensions. Meanwhile, there is a larger compression force and a certain pressure transient drop at the small cross-sectional dimensions [26], therefore, the equilibrium elastic modulus firstly increases and then decreases with the increase of cross-sectional dimensions. However, the T_1 decreases slightly with the cross-sectional dimensions, and the decrease is limited, because in larger cross-sectional dimensions, the stress can be fully homogenized along the compression direction and radial direction. With the increase of cross-sectional dimensions, the ε shows a fluctuating decrease, and the reason for this phenomenon is that the larger the cross-sectional dimensions, the stress rapid decay time is smaller, and the seed cotton has a longer time for stress homogenization.

Figure 7. Stress relaxation characteristics at different cross-sectional dimensions: (a) Stress relaxation curve; (b) Equilibrium elastic modulus E_e and rapid decay time T_1 ; (c) Residual stress ratio ε .

4. Virtual Simulation of Stress Relaxation of Machine-Harvested Seed Cotton

Stress relaxation is the relationship between stress and time after the material has been compressed to a constant deformation, in which it can be reduced to a kinetic system and the process can be analyzed using virtual prototyping techniques. Some scholars used this

method to simulate viscoelastic materials with some success [46,47]. Stress relaxation is the relationship between stress and time after the material has been compressed to a constant deformation, so it can be reduced to a kinetic system and the process can be analyzed using virtual prototyping techniques. Some scholars used this method to simulate and analyze viscoelastic materials with some success [46,47]. This study uses this method to model and simulate the stress relaxation process of machine-harvested seed cotton in a virtual prototype. The five-element Maxwell model has been obtained in the previous paper to better characterize the stress relaxation process of machine harvested seed cotton, and the stress relaxation model constructed by it can be characterized by two Maxwell units, one equilibrium spring, and a five-element Maxwell model composed of three in parallel, as shown in Figure 3a, while the Maxwell unit can be composed of one Hooke body (spring) and one Newton body (viscous pot) in series, and they can be found in ADAMS with the corresponding actor, spring and damping. Therefore, the corresponding seed cotton stress relaxation model can be established in ADAMS, as shown in Figure 8a.

After the virtual prototype model of stress relaxation of machine harvested seed cotton is established, the corresponding settings and descriptions are made: (1) Because the unit of force in ADAMS simulation analysis is N and the unit of stress is N/mm^2 , the force and stiffness can be used in ADAMS instead of stress and modulus of elasticity; (2) As stress relaxation is the law of change of stress with time at constant strain, independent of weight, the modeling environment is set to a gravity-free state; (3) Stress relaxation also requires constant strain, in which fixed constraints are used to cement upper pressure head, lower pressure head to the earth, and the springs and dampers in the Maxwell cell to movement along the vertical direction of the earth by prismatic pair 4 and 9; (4) The spring element preload in the model is also set to the initial stress of the stress relaxation as the stress values obtained from the aforementioned tests (σ_1 , σ_2 , σ_e).

After the setup is completed, the simulation analysis is conducted and the simulation time is set to 300 s, with a step size of 0.1 s with regard to the test data to obtain the curve of stress variation with time for the upper baffle [48]. In this section, the simulation test of stress relaxation of machine-harvested seed cotton with a moisture content of 14% and compression density of $300 \text{ kg}/\text{m}^3$ is carried out as an example, and the test results and simulation results are obtained, as shown in Figure 8b.

Figure 8. Stress relaxation virtual prototype model and test results: (a) Model: 1. upper pressure head 2. spring 1 3. spring 2 4. prismatic pair 1 5. damper 1 6. fixed constraint 1 7. lower pressure head 8. damper 2 9. prismatic pair 2 10. fixed constraint 2; (b) Curves comparison between simulation and test results.

The simulation results show that the test and simulation curves are consistent, with a maximum deviation of 4.96%. This shows that it is feasible to use the virtual prototype method to study and analyze the stress relaxation characteristics of seed cotton. And it also shows that the five-element Maxwell model can better describe the stress relaxation

characteristics of machine-harvested seed cotton. The possible reasons for the errors are: (1) the test of stress relaxation is affected by various uncertainties, which leads to errors caused by inaccurate calculation of model parameters; and (2) the ADAMS simulation, considering that stress relaxation is unrelated to material quality, sets the quality of each component to the minimum amount allowed by the software, which made the simulation results deviate.

5. Conclusions

(1) The stress relaxation model of machine-harvested seed cotton can be described by a five-element Maxwell model. The relevant parameters of the stress relaxation model were obtained for different moisture content, trash content, compression density and cross-sectional dimensions, and the $R^2 > 0.99$.

(2) All factors have a certain influence on the stress relaxation characteristics of machine-harvested cotton. Moisture content, cross-sectional dimensions and equilibrium elastic modulus are negatively correlated, while trash content, compression density and equilibrium elastic modulus are positively correlated. Moisture content and compression density are negatively correlated with rapid decay time and residual stress ratio. According to the relationship diagram between factors and response indexes, the fast decay time decreases and then increases with the increase of trash content, and slowly decreases with the cross-sectional dimensions. The residual stress ratio decreases with the trash content fluctuation, but the cross-sectional dimensions have little effect on it.

(3) A rheological model was used to simulate and analyze the stress relaxation process of seed cotton from a kinetic point of view. A stress relaxation intrinsic model based on ADAMS was established to simulate the stress relaxation process of seed cotton and the maximum deviation between the simulated and experimental values was 4.96%, indicating that the virtual prototype can be used to simulate and study the rheological process of seed cotton, thus broadening the research method of biomechanics.

The test results can provide some data and theoretical support for the study of stress relaxation and compression of seed cotton.

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