Experimental study and simulation on the creep characteristics of machine-harvested seed cotton

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Abstract: In view of the unclear understanding of the basic scientific problems such as the rheological mechanism of seed cotton, especially the lack of research on the creep characteristics of seed cotton, the machine-harvested seed cotton in the Xinjiang region was taken as the research object to find out the compression creep characteristics. The universal material testing machine was used to carry out a one-factor creep test, taking moisture content, feed quality, compression times, and trash content as test factors and instantaneous elastic modulus, hysteretic elastic modulus, viscosity coefficient, and delay time as test indicators. The ANOVA and correlation were analyzed by SPSS, and the creep process of the seed cotton was simulated by ADAMS. Results show that moisture content significantly affects the instantaneous elastic modulus, hysteretic elastic modulus, and viscosity coefficient (p<0.01). In addition, each value of which decreases with the increase in moisture content. Feed quality significantly affects the hysteretic elastic modulus and viscosity coefficient (p<0.05). Moreover, the hysteretic elastic modulus and viscosity coefficient increase with the increase in feed quality. The compression times significantly influence the instantaneous elastic modulus, hysteretic elastic modulus, and viscosity coefficient (p<0.01), each value of which increases with the increase of compression times. Furthermore, the trash content significantly influenced the hysteretic elastic modulus and viscosity coefficient (p<0.05). The absolute error between the simulated and experimental values e_k is within −0.011-0.030 mm, and the relative error φ_k is less than 7%. The experimental results can provide theoretical and data support for the study of rheological characteristics of machine-harvested seed cotton, the design of seed cotton packing devices, and the molding quality of cotton bale (mold).

Keywords: creep characteristics, machine-harvested seed cotton, analysis of ANOVA, one-factor tests, ADAMS
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1 Introduction

Seed cotton belongs to agricultural fiber materials. It is light-weight, low-density, large volume, and is difficult to transport and store. Therefore, compression treatment has become an important part of agricultural fiber material densification molding technology and an effective way to utilize agricultural fiber material resources[1,2]. At present, bulk, palletizing, and baling are the primary harvesting, storage, and transportation methods for agricultural fiber materials, baling has become an important development and research direction because of its easier movement and stacking, and higher efficiency[3-5]. Compression is crucial in the baling of cotton. Fiber materials exhibit viscoelastic behavior during deformation[6]. Seed cotton has viscoelastic behavior such as stress relaxation, creep, and spring back during post-processing, such as compression molding and packaging, which change the size and shape of the baler compared with the initial baler, thereby resulting in poor morphological stability. Therefore, the rheological properties such as stress relaxation, creep, and recovery of seed cotton have an important influence on the process optimization, power consumption, and morphological stability of the cotton baler[7].

At present, the research objects on rheological properties are mostly focused on forage materials such as pasture, straw, and alfalfa[8-11]. Tang et al.[12] indicated that moisture content and density affected the internal characteristics of wheat bales. Chen et al.[13] found that the magnitude of the creep and relaxation curves increased and decreased with the increase of moisture contents, respectively. In addition, Xiao et al.[8] described the creep properties of rice seedlings by the Burgers model, showing that different loading levels affect creep parameters. Moreover, Peng et al.[14] showed that the creep strain rate under constant and cyclic humidity conditions is linearly related to the applied load level. Furthermore, Klinge et al.[15] found that the particle size and compression speed were related to the model parameters. Yan et al.[16] studied the stress-strain law of stress relaxation and the creep law of rice, wheat, and corn straw under different experimental conditions. Zou et al.[17] simulated the feeding process of green leafy vegetables based on Burgers creep theory and ADAMS simulation model. Wang et al.[18] concluded that higher moisture content is needed to lower the energy consumption for ladder forage compression. Du et al.[2,19] obtained the minimum specific energy consumption through the parameter optimization test when the moisture content was 57%. The above research shows that the stress and stress variation law in

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the compression molding process of agricultural materials is affected by many factors such as moisture content, compression times, initial density, load, etc., and exploring the creep characteristics is of great significance to the optimization and energy consumption of material compression equipment.

At present, the research on the rheological properties of cotton is mostly focused on cotton fiber, while the research on the rheological properties of seed cotton is relatively few. Wilkes et al.[20] pointed out that the compression density does not affect the fiber quality when the moisture content of the seed cotton is less than 10%; Husin et al.[21] concluded that a compression density greater than 384 kg/m^3 would cause cracks in cottonseed; Li et al.[22] showed that the nonlinear viscoelastic model can better characterize the creep recovery and stress relaxation of cotton fiber in Xinjiang; Kong et al.[23] pointed out that compressive stress and stress relaxation were positively correlated with moisture content and feed quality.

In summary, in view of the unclear understanding of the basic scientific problems such as the rheological mechanism of seed cotton, especially the lack of research on the creep characteristics of seed cotton, a combined method of experimental, theoretical, and numerical simulation was adopted to conduct a one-factor creep test on machine-harvested seed cotton to reveal the influence of various experimental factors on creep and its parameters. Taking moisture content, feed quality, compression times, and trash content as test factors and instantaneous elastic modulus E_0, hysteretic elastic modulus E_r, viscosity coefficient η, and delay time τ_r as test indicators. The purpose of this paper is to reveal the influence of various experimental factors on creep and its parameters and to provide theoretical and data support for the design of seed cotton packaging devices and the study of the molding mechanism of cotton bales (molds).

2 Materials and methods

2.1 Test materials

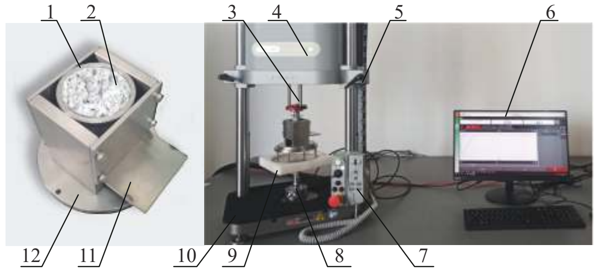
The test took Huiyuan 720, the main cotton-picking variety in the Xinjiang region, as the test raw material. The sample was taken from the test field of Shihezi University, sown on April 10, 2021. A total of 800 healthy cotton plants with no disease and pests were selected on October 10, 2021. Samples were then cut from the roots of the cotton plants with fruit branches and shears. After sampling, they were sealed and transported back to the laboratory with a single plant wrapped in black plastic bags. Samples were harvested through the cotton-picking performance test bench, built by the laboratory, and stored in a black sealed bag for backup.

2.2 Test instruments and equipment

Instron E-1000 universal material testing machine (maximum static load and stroke of 700 N and 60 mm, respectively), Shengbo SB 5002-R precision electronic balance (measuring range of 0-500 g and accuracy of 0.01 g), MA45 moisture analyzer (measuring range, accuracy, and readability of 0-45 g, 1 mg, and 0.01%, respectively), DHG-9070A drying box (Shanghai Yiheng Technology Co, Ltd., China), indenter, self-made bottom plate, self-made compression chamber, sealing bag, and so on.

The creep process is the law of strain change with time when the load is unchanged[24]. The connection, installation method, and working status of each component in the compression process of this test are shown in Figure 1.

The self-made compression chamber and the bottom plate are adopted and installed on the universal material testing machine, which provides the compression power and matches the indenter, supporting the universal material testing machine to complete the test. The indenter and corresponding compression chamber are 50 mm and 52 mm in diameter, respectively, and the thickness is 4 mm. Moreover, the material is a seamless stainless-steel tube to ensure the stability of the piston in a forward direction. Considering that the maximum compression stroke of the universal material testing machine is 60 mm, the selected chamber depth is 60 mm, which can be well coordinated with the cavity. The surface polishing treatment of the chamber wall is done to reduce the impact of friction resistance during compression. The bottom of the compression chamber is in the form of a detachable bottom plate, connected to the box through the groove, which is convenient to complete the discharge after compression.



1. Compression chamber 2. Seed cotton 3. Lifting rod A 4. Status indicator 5. Lifting rod B 6. Computer 7. Test console 8. Force sensor 9. Tray 10. Chassis 11. Discharge plate 12. Connected components

Figure 1 Compression process diagram of machine-harvested seed cotton

2.3 Experimental factors

Affected by the working parameters of the cotton picker, the harvest period, and other factors, the moisture and trash contents of the machine-harvested seed cotton randomly change and are greatly unstable[25]. The cotton mechanization harvesting process has certain requirements for the moisture and trash contents of the cotton[26]. Combined with the actual moisture content and trash of machine-harvested cotton[27,28], the moisture content range was 6%, 10%, 14%, 18%, and 22%; meanwhile, the trash content interval was 8%, 10%, 12%, 14%, and 16%. Considering that compression of 3-4 times is required to complete a round baler in the field of a cotton picker, the whole baling process can be regarded as multiple continuous compressions. Therefore, the compression times were 1, 2, 3, 4, and 5 times. Furthermore, the seed cotton has been pre-compressed before the cotton picker reaches the baling stage. Thus, the initial density range was selected as 100, 105, 110, 115, and 120 kg/m^3, correspondingly, the feed quality range was 12.45, 13.07, 13.70, 14.32, and 14.94 g, respectively. Therefore, this paper selected the moisture content, feed quality, compression times, and trash content to conduct a one-factor experimental study on the compressive creep characteristics of the machine-harvested seed cotton, and the compression creep law of the machine-harvested seed cotton during the test observed.

2.4 Experimental methods

2.4.1 Sample configuration

The initial moisture content of machine-harvested seed cotton was determined by an MA45 moisture content analyzer. The upper, middle, and lower layers of samples were selected to measure the moisture content, and the average value of the three measurements was taken as the initial moisture content of the machine-harvested seed cotton. Finally, the initial moisture and initial trash contents were (5.62±0.09)% and (8.86±1.36)%, respectively.

Before the experiment, the machine-harvested seed cotton was uniformly treated. The trash such as bell shells and cotton rods was removed. Then, the remaining machine-harvested seed cotton was selected with forceps to a relatively clean state. The rehydration (miscellaneous) method[29,30] was used to calculate the quality of the deionized water (trash) that needs to be added by Equation (1), and the deionized water (trash) that needs to be added was taken in a layered manner, a small amount, and many times. Samples were added while stirring to ensure uniformity, and all samples were stirred every 3-4 h to adjust the moisture content to the desired level. Then, the samples are quantitatively loaded into the self-sealing bag. It was then placed in a well-sealed drying box for 3 d, and shaken 3-5 times a day to ensure the uniformity of water absorption of the machine-harvested seed cotton.

$$M = m\frac{(H_2 - H_1)}{(1 - H_2)} \tag{1}$$

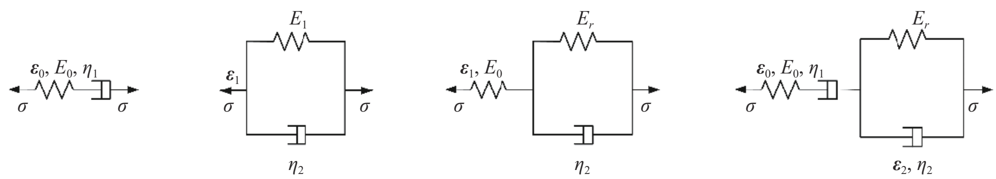
where, M is the mass of deionized water (trash) needed to be added, g; m is the mass of the test sample, g; H_1 is the initial moisture content (trash) of the test sample, %; H_2 is the moisture content (trash) of the sample to be obtained, %.

2.4.2 Experimental design

The one-factor compression creep test of machine-harvested seed cotton was carried out, taking moisture content, feed quality, compression times, and trash content as test factors, and the instantaneous elastic modulus E_0, hysteretic elastic modulus E_r, viscosity coefficient η and delay time τ_r as test indicators. During the test, the indenter and the self-made compression device were installed on the universal material testing machine. After the operation was stable, the corresponding quality of seed cotton was uniformly fed in a random arrangement, and the test bench was lifted to the target position. In the creep test, the selection of stress level should be based on the static strength value or creep characteristics of the material, a stress level based on the static strength of 50%-70% range could be selected[31]. It took approximately 5 min to complete a round baler in the field of a cotton picker. Thus, the creep test setting parameters were as follows: force control was set at 1 N/mm, the target control force was 420 N, and the load holding time was 300 s.

3 Comparison and determination of creep models

Generalized Kelvin and Burgers models are commonly used in agricultural materials to describe creep characteristics[32]. As shown in Figure 2, the generalized Kelvin model is formed in series by the spring and the Kelvin model, and it exhibits the properties of instantaneous and delayed elastic deformation under the action of external forces, of which the Kelvin model is made of elastic elements and a viscous component in parallel. Meanwhile, the Burgers model is formed by a Maxwell model and a Kelvin model in series, it can simultaneously present the properties of instantaneous elastic deformation, delayed elastic deformation, and viscous flow under the action of external forces, of which the Maxwell model consists of elastic and viscous elements in series. Both two models can reflect the creep characteristics of the materials.



a. Maxwell model b. Kelvin model c. GeneralizedKelvin model d. Burgers model

Figure 2 Model and constituent elements

The equation of the Burgers model is shown in Equation (2):

$$\varepsilon = \frac{\sigma}{E_0} + \frac{\sigma}{E_1}\left(1 - e^{-\frac{E_r}{\eta_2}t}\right) \tag{2}$$

where, ε is the total strain, N; t is the time, s; σ is the total stress, N; E_0 is the strain of the modulus of elasticity, MPa; E_r and η_2 are the elastic modulus and viscosity coefficient of Kelvin body, MPa and MPa·s, respectively.

The equation of the Burgers model is shown in Equation (3):

$$\varepsilon = \frac{\sigma}{E_0} + \frac{\sigma}{E_r}\left(1 - e^{-\frac{E_r}{\eta_2}t}\right) + \frac{\sigma}{\eta_1}t \tag{3}$$

where, η_1 is the elastic modulus and viscosity coefficient of Maxwell's body, MPa·s.

A set of data was selected to take the average to fit with the generalized Kelvin model and the Burgers model. When the moisture content was 14%, the feed quality and compression times were 13.70 g and 1 time, respectively. The corresponding fitting results of the two models are shown in Figure 3. As shown in the figure, both the generalized Kelvin and the Burgers models can be used to describe the compressive creep characteristics of the machine-harvested seed cotton, both of which have a high degree of fitting. However, the coefficients of determination of the two are 0.9695 and 0.9923, respectively. This is because the instantaneous deformation generated by the instantaneous elastic modulus can be fully recovered after unloading, and the deformation generated by the Kelvin model composed of hysteretic elastic modulus and coefficient of viscosity gradually recovers over time after the stress disappears. However, the viscosity flow of the coefficient of viscosity in a separate series will become the irretrievable permanent deformation of the machine-harvested seed cotton, and the machine-harvested seed cotton will produce permanent deformation during the compression creep process. In summary, the Burgers model can better describe the compression creep characteristics of machine-harvested seed cotton.

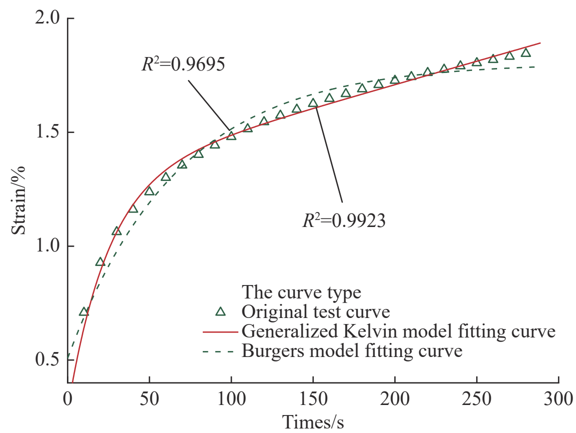


Figure 3 Comparison curve of the creep model

4 Results and analysis

The experiment obtained the creep characteristic curve of the machine-harvested seed cotton at different factor levels. Based on Equation (3), the creep model of the machine-harvested seed cotton at different test factor levels was fitted with OriginPro 2019b software. The fitting results are listed in Table 1, each set of tests was repeated 5 times, the average was taken as the test data for analysis, and the data were expressed in the form of mean±standard deviation. Thus, 0.05 is selected as the significance test criterion to study the influence of various factors on creep characteristic parameters[33].

Table 1 Fitting parameters of the creep model for each factor

Experimental factor	Level of factor	Instantaneous elasticity modulus E_0/MPa	Hysteretic elasticity modulus E_r/MPa	Coefficient of viscosity η/(MPa·s)	Relaxation time τ_r/s	R^2
Moisture content/%	6	1.91±0.10	0.29±0.00	158.32±2.72	27.33±0.51	0.993
	10	1.00±0.05	0.21±0.00	107.10±1.86	24.51±0.55	0.993
	14	1.03±0.05	0.20±0.00	101.23±1.80	25.12±0.57	0.991
	18	0.66±0.03	0.14±0.00	75.26±1.34	24.21±0.55	0.993
	22	0.41±0.02	0.13±0.00	74.06±1.56	18.81±0.53	0.987
Feed quality/g	12.45	0.40±0.02	0.12±0.00	69.75±1.46	19.06±0.55	0.985
	13.07	0.75±0.04	0.14±0.00	72.49±1.31	24.01±0.56	0.991
	13.70	0.66±0.03	0.14±0.00	74.42±1.31	23.92±0.55	0.993
	14.32	0.75±0.04	0.15±0.00	75.76±1.28	25.76±0.58	0.994
	14.94	0.66±0.03	0.16±0.00	85.06±1.57	23.09±0.57	0.991
Compression times/times	1	0.76±0.04	0.20±0.00	111.91±2.16	22.12±0.58	0.989
	2	1.15±0.05	0.34±0.00	177.99±3.33	21.58±0.59	0.989
	3	1.82±0.08	0.51±0.01	251.18±4.40	22.13±0.58	0.990
	4	2.06±0.10	0.63±0.01	315.60±5.63	20.29±0.57	0.989
	5	2.39±0.10	0.75±0.01	382.11±6.99	19.13±0.54	0.985
Trash content/%	8	1.06±0.05	0.19±0.00	99.69±1.65	26.60±0.56	0.994
	10	0.76±0.04	0.15±0.00	73.18±1.21	26.26±0.59	0.993
	12	0.78±0.04	0.15±0.00	76.11±1.25	26.78±0.58	0.994
	14	0.76±0.04	0.15±0.00	76.71±1.27	26.45±0.58	0.994
	16	0.75±0.04	0.15±0.00	77.36±1.32	26.01±0.58	0.994

Note: τ_r is Relaxation time, s, $\tau_r = \eta_2/E_r$.

SPSS software was used to analyze the correlation analysis of each creep characteristic parameter. The correlation analysis of each factor on the creep characteristic parameters of the machine-harvested seed cotton is listed in Table 2.

Table 2 Correlation analysis of creep characteristic parameters

Experimental factor	Instantaneous elasticity modulus E_0	Hysteretic elasticity modulus E_r	Coefficient of viscosity η	Relaxation time τ_r
Moisture content	−0.704**	−0.790**	−0.712**	−0.423*
Feed quality	0.210	0.603**	0.619**	0.286
Compression times	0.790**	0.963**	0.953**	−0.303
Trash content	−0.312	−0.458*	−0.498*	−0.420

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

4.1 Effect of moisture content on creep parameters

When the feed quality is 13.70 g, the compression times and trash content are 1% and 12%, respectively. The creep curves of the machine-harvested seed cotton corresponding to different moisture contents are shown in Figure 4. The variation trend of creep parameters of the machine-harvested seed cotton corresponding to different moisture contents is shown in Figure 5.

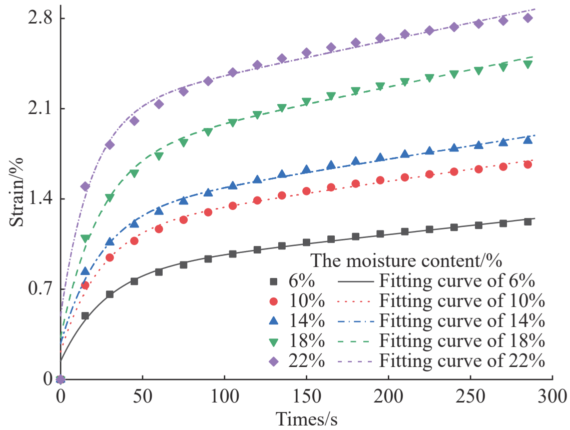


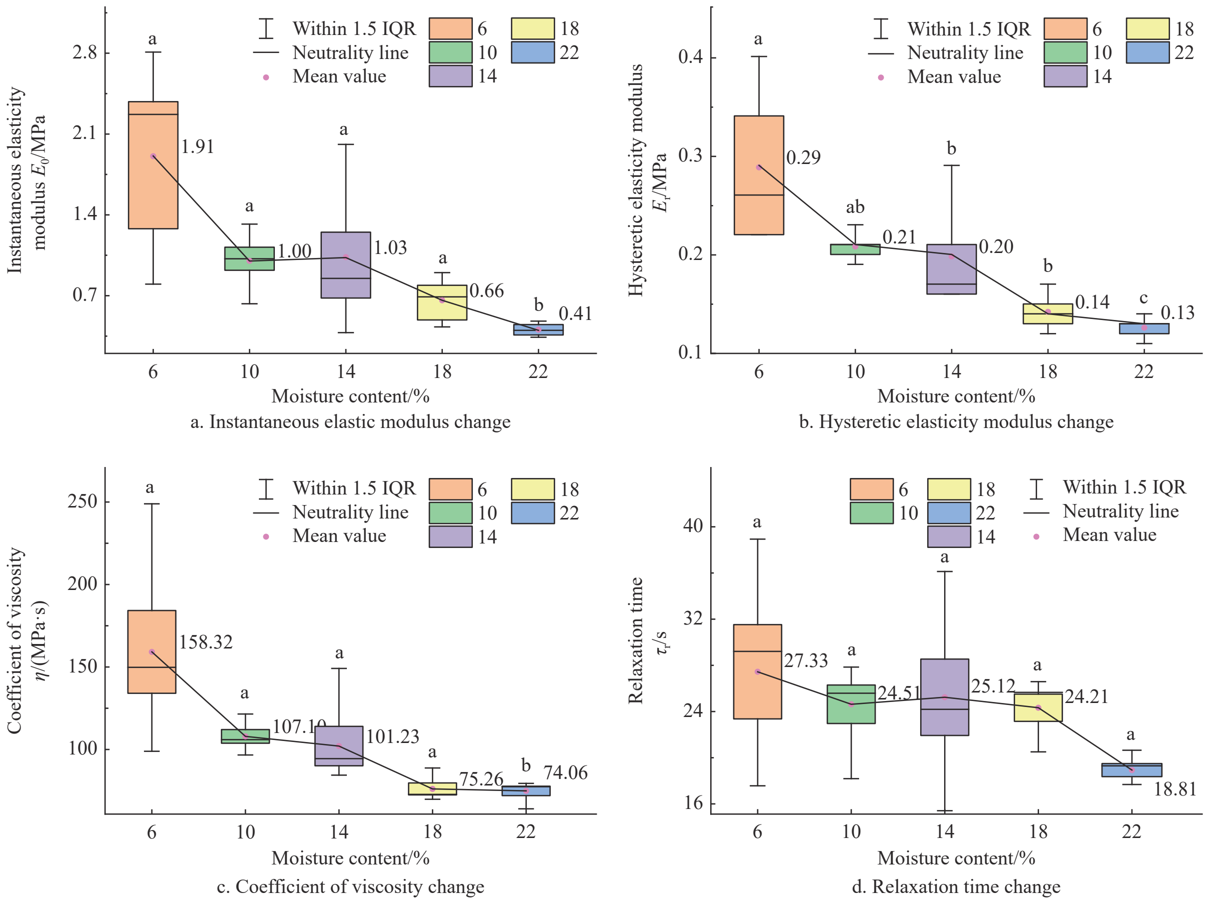
Figure 4 Creep curve with different moisture contents

Figure 4 shows the strain deformation increases with the increase of moisture content. As shown in Figure 5, the moisture content significantly affects the instantaneous elastic modulus E_0 (p<0.01), the hysteresis elastic modulus E_r (p<0.01), and the viscosity coefficient η (p<0.01), but the delay time τ_r is not significant. Figure 5a shows that the instantaneous elastic modulus E_0 decreases with the increase of moisture content. The instantaneous elastic modulus E_0 of the machine-harvested seed cotton with a moisture content of 22% is 0.41 MPa, which is significantly lower than 1.91 MPa of 6%, 1.00 MPa of 10%, 1.03 MPa of 14%, and 0.66 MPa of 18%, and the correlation coefficient is r=−0.704. Figure 5b shows that the hysteresis elastic modulus E_r decreases with the increase of moisture content. The hysteresis elastic modulus E_r with the moisture content of 6%, 10%, 14%, 18%, and 22% are 0.29 MPa, 0.21 MPa, 0.20 MPa, 0.14 MPa, and 0.13 MPa, respectively, and the correlation coefficient is r=−0.790. Figure 5c shows that the viscosity coefficient η decreases with the increase in moisture content. The viscosity coefficients η with the moisture content of 6%, 10%, 14%, 18%, and 22% are 158.32, 107.10, 101.23, 75.25, and 74.06 MPa·s, respectively, r=−0.712.

The instantaneous elastic modulus E_0 reflects the elastic deformability of the machine-harvested seed cotton. When the E_0 is higher, the elastic deformability is lower. The viscosity coefficient η reflects the anti-deformation viscosity of the machine-harvested seed cotton. The higher the viscosity coefficient η is, the stronger the anti-deformation ability is, and the worse the fluidity of the internal structure of the machine-harvested seed cotton will be. The instantaneous elastic modulus E_0, hysteresis elastic modulus E_r, and viscosity coefficient η of machine-harvested seed cotton decrease, thereby indicating that the higher the moisture content of machine-harvested seed cotton is in the creeping stage, the greater the instantaneous elastic deformation, the better the internal fluidity of machine-harvested seed cotton, and the greater the permanent deformation. Therefore, creep is more likely to occur after compression.

4.2 Effect of feed quality on creep parameters

When the moisture content is 14%, the compression and trash content are 1 time and 12%, respectively. The creep curves of the machine-harvested seed cotton corresponding to different feed qualities are shown in Figure 6. As the feed quality increases, the strain deformation gradually decreases. The variation trends of creep parameters with different feed qualities are shown in Figure 7.



a. Instantaneous elastic modulus change

b. Hysteretic elasticity modulus change

c. Coefficient of viscosity change

d. Relaxation time change

Note: Different values after the same column of data indicate significant differences between data (p<0.05), the same as below.

Figure 5 Variation trend of creep fitting parameters with different moisture contents

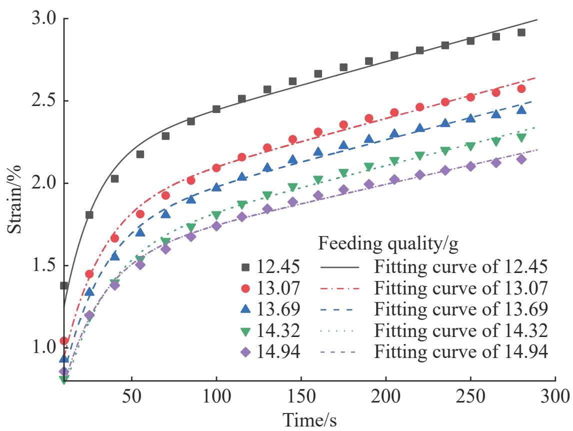


Figure 6 Creep curve with different feed qualities

As shown in Figure 7, the feed quality has a significant effect on the hysteresis elastic modulus E_r (p<0.05) and the viscosity coefficient η (p<0.05), but it has no significant effect on the instantaneous elastic modulus E_0 and the delay time τ_r (p>0.05). Figure 7b shows that the hysteresis elastic modulus E_r increases with the increase in feed quality. The hysteresis elastic modulus E_r with a feed quality of 12.45 g is 0.12 MPa, which is significantly lower than 0.16 MPa of 14.94 g, r=0.603. Figure 7c shows that the viscosity coefficient η increases with the increase in feed quality. Similarly, the viscosity coefficient η with feed quality of 14.94 g is 85.06 MPa·s, which is significantly higher than 69.75 MPa·s of 12.45 g, 72.49 MPa·s of 13.07 g, 74.42 MPa·s of 13.70 g, and 75.76 MPa·s of 14.32 g, r=0.619.

From Figures 7a and 7d, the instantaneous elastic modulus E_0 and delay time τ_r have no apparent trend with the increase of feed quality, and the correlation coefficients are r=0.210 and r=0.286, respectively. Similarly, the viscosity coefficient η shows an upward trend, thereby indicating that a smaller feed quality in the creeping stage will produce a more extensive permanent deformation and a greater amount of permanent deformation is more likely to occur after compression.

4.3 Effect of compression times on creep parameters

When the moisture content is 14%, the feed quality and trash content are 13.70 g and 12%, respectively. The creep curves of the machine-harvested seed cotton corresponding to different compression times are shown in Figure 8. The strain deformation of machine-harvested seed cotton decreases with the increase in compression times. The variation trend of creep parameters with different compression times is shown in Figure 9.

As shown in Figure 9, the compression times significantly affect the instantaneous elastic modulus E_0 (p<0.01), the hysteresis elastic modulus E_r (p<0.01), the viscosity coefficient η (p<0.01), and the delay time τ_r (p>0.05), r=−0.310. Figure 9a shows that the instantaneous elastic modulus E_0 increases with the increase of compression times. The instantaneous elastic modulus E_0 with compression times of 1 is 0.76 MPa, which is significantly lower than 1.82 MPa of 3 times, 2.06 MPa of 4 times, and 2.39 MPa of 5 times, r=0.844.

Meanwhile, Figure 9b shows that the hysteresis elastic modulus E_r increases with the increase of compression times. The hysteresis elastic modulus E_r with compression times of 1, 2, 3, 4, and 5 times is 0.20, 0.34, 0.51, 0.63, and 0.75 MPa, respectively, r=0.955. In addition, Figure 9c shows that the viscosity coefficient η shows an upward trend with the increase in compression times. The viscosity

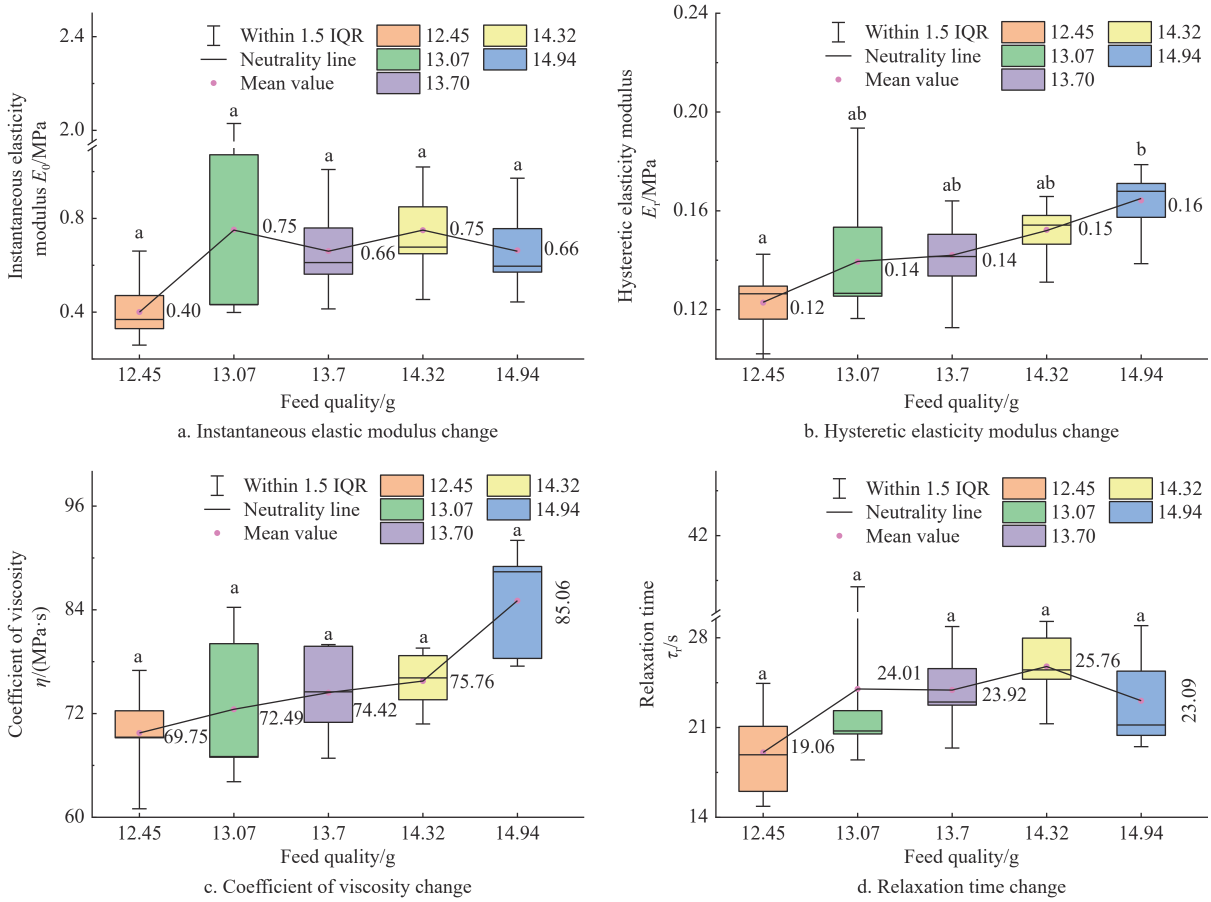


Figure 7 Variation trend of creep fitting parameters with different feed qualities

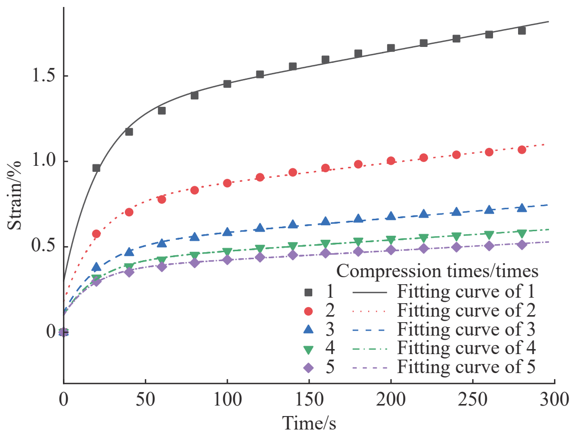


Figure 8 Creep curves of the machine-harvested seed cotton with different compression times

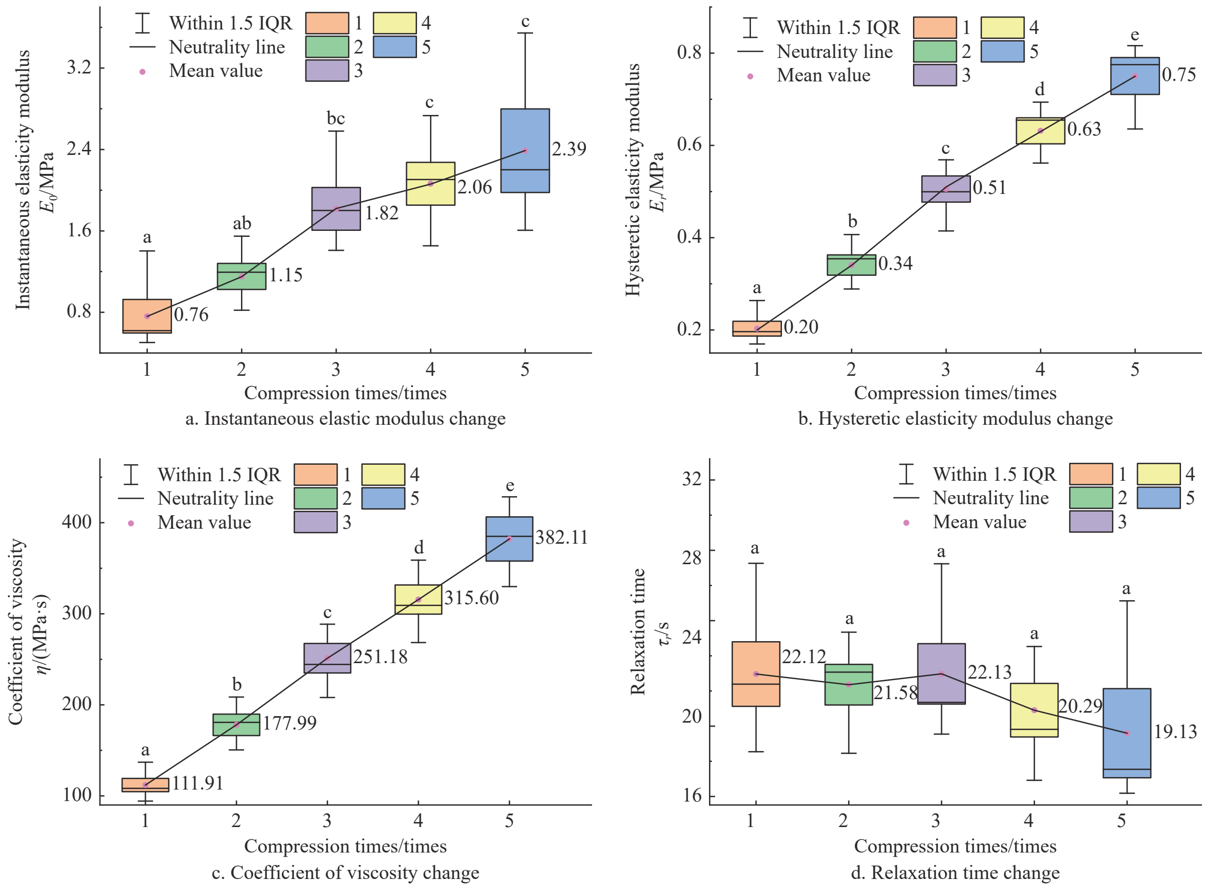
coefficients η with compressions of 1, 2, 3, 4, and 5 times are 111.91, 177.99, 251.18, 315.60, and 382.11 MPa·s, respectively, r=0.955. Similarly, the instantaneous elastic modulus E_0 and viscosity coefficient η gradually increase, thereby indicating that shorter compression times will produce higher instantaneous elastic deformation and more considerable permanent deformation in the creeping stage. Therefore, creep is more likely to occur after compression.

4.4 Effect of trash content on creep parameters

When the moisture content is 14%, the feeding quality and compression times are 13.70 g and 1, respectively. The creep curves of machine-harvested seed cotton with different trash content are shown in Figure 10. As shown, there is no apparent law of strain deformation with the increase in trash content.

The variation trend of creep parameters of the machine-harvested seed cotton with different trash contents is shown in Figure 11. As shown in Figure 11, the trash content significantly affects the hysteresis elastic modulus E_r (p<0.05) and the viscosity coefficient η (p<0.05). Nevertheless, the trash content has no significant effect on the instantaneous elastic modulus E_0 and the delay time τ_r (p>0.05). Figure 11b shows that the hysteresis elastic modulus E_r decreases first and then tends to be stable with the increase of trash content. The hysteresis elastic modulus E_r with a trash content of 8% is 0.19 MPa, which is higher than 0.15 MPa of 10%, 12%, 14%, and 16%, r=−0.458. Figure 11c shows that the viscosity coefficient η decreases first and then increases with the increase in trash content. The viscosity coefficient η with trash content of 8% is 99.69 MPa·s, which is higher than 73.18 MPa·s of 10%, 76.11 MPa·s of 12%, 76.71 MPa·s of 14%, and 77.36 MPa·s of 16%, r=−0.498. Based on Figures 11a and 11d, the instantaneous elastic modulus E_0 gradually decreases with the increase of trash content, and the delay time τ_r has no noticeable trend with the increase of trash content. The correlation coefficients are r=−0.312 and r=−0.042.

In the range of trash content selected in this article, considering that only under highly heterogeneous conditions will have trash such as bell shells and cotton rods, and the mechanized harvesting process of cotton has certain requirements for the trash content of the cotton[27]. Thus, the bell shell and cotton rod are not counted as trash when selecting the factor level, but the results show that the trash content does not have noticeable regularity on the creep characteristics of the machine-harvested seed cotton. This may be because parts of trash are fragile such as cotton leaves, and small trash has little impact on the compression creep characteristics of machine-harvested seed cotton. In addition, although the total



a. Instantaneous elastic modulus change

b. Hysteretic elasticity modulus change

c. Coefficient of viscosity change

d. Relaxation time change

Figure 9 Variation trend of creep fitting parameters with different compression times

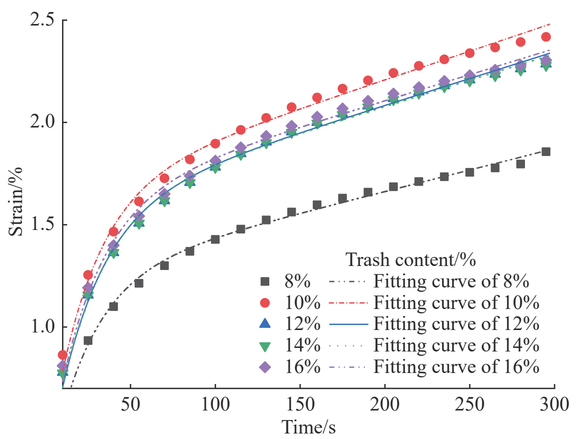


Figure 10 Creep curves of the machine-harvested seed cotton with different trash contents

quality of trash is different, it is difficult to ensure complete uniformity when filling in the trash. Moreover, in the case of certain feed quality, a higher proportion of trash will lead to a smaller proportion of seed cotton quality.

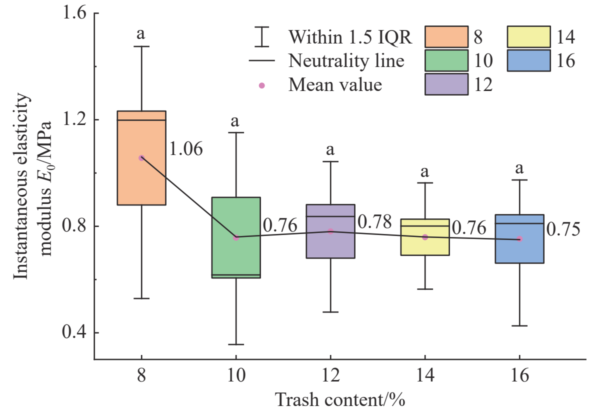
5 Implementation and analysis of ADAMS simulations

The previous text has shown that the Burgers model is suitable for describing the compression creep characteristics of machine-harvested seed cotton, which is composed of spring, damper, and Kelvin models in series, and these elements can be found in ADAMS. Thus, the Burgers model can be simplified as a power system, and the compression creep process can be analyzed by virtual prototype technology. In the ADAMS/View software environment, the Burgers model is constructed by adding connectors, tensile springs, and dampers, and then the creep process of machine-harvested seed cotton is realized by adding motion pairs and forces. Therefore, the creep virtual prototype model for the machine-harvested seed cotton is established. The connection and constraint methods of each component are shown in Figure 12.

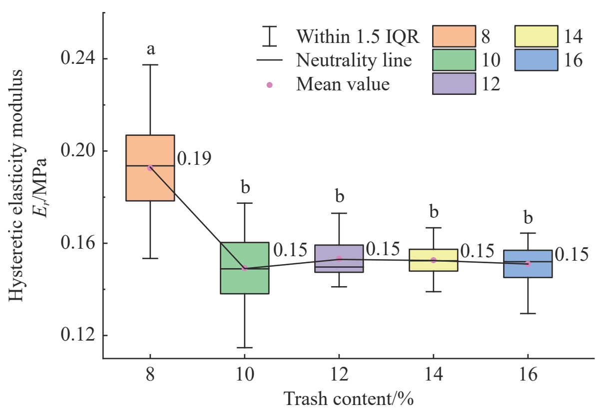
The virtual prototype model is set as follows: 1. Considering that the strain-time relationship curve of the creep process is independent of the gravity and mass of the machine-harvested seed cotton, the mass of each component is set as the default micro value when modeling and the modeling environment is set to a gravity-free state[34]. 2. The connecting plate c is consolidated with the earth, and the moving pairs are used to constrain the movement direction between the components to move along the vertical direction of the earth.

Based on the fitting parameters listed in Table 1, the parameters of the creep simulation model of the machine-harvested seed cotton can be set under different experimental conditions. The creep fitting parameters of the machine-harvested seed cotton with moisture content, load, and feed quality of 6%, 420 N, and 13.70 g/time, respectively, were selected as the simulation parameters corresponding to each component in ADAMS. Regarding the experimental data, the values of the corresponding components are set, where Tension spring a, Tension spring b, Damper a, and Damper b correspond to the instantaneous elastic modulus E_0, the hysteresis elastic modulus E_r, the viscosity coefficient η_1, and the viscosity coefficient η_2 in the creep model, respectively. When the force is 420 N, the corresponding stress is 0.197 MPa.

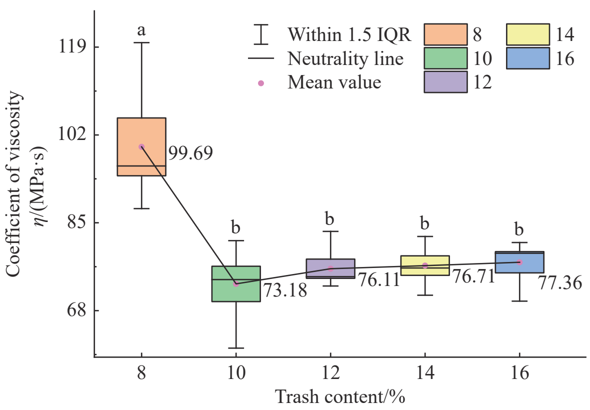
After passing the self-test, the simulation time was set to 300 s, the simulation step was 1 s, and the machine-harvested seed cotton creep ADAMS model was run. After the simulation test is



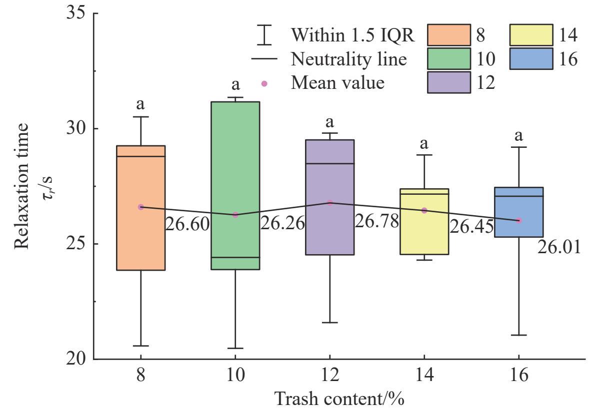
a. Instantaneous elastic modulus change



b. Hysteretic elasticity modulus change

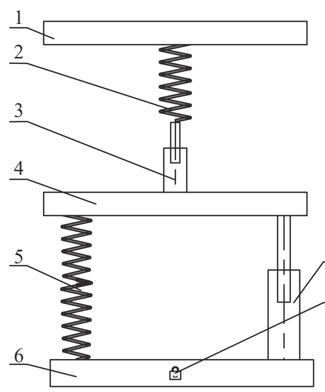


c. Coefficient of viscosity change



d. Relaxation time change

Figure 11 Variation trend of creep fitting parameters with different trash contents



1. Connecting plate a 2. Tension spring a 3. Damper a 4. Connecting plate b 5. Tension spring b 6. Connecting plate c 7. Fixed part 8. Damper b

Figure 12 Connection diagram of ADAMS components

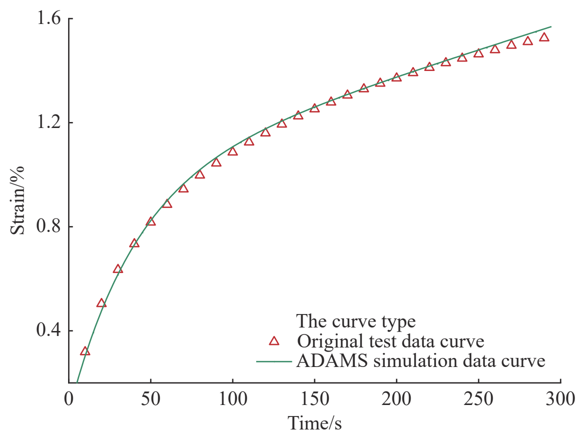


Figure 13 ADAMS simulation and test data comparison diagram

completed, the ADAMS/Post Processor module is entered, the simulation data is exported, and the simulation and test data are compared with OriginPro 2019b. Results are shown in Figure 13.

The absolute error e_k between the simulated measurement X_s and the test measurement X_t is as follows:

$$e_k = X_t - X_s \tag{4}$$

where, e_k is the absolute error, mm; X_s is the simulated measurement, mm; X_t is the test measurement, mm.

The relative error between simulated measurement X_s and the test measurement X_t is as follows:

$$\varphi_k = \frac{|e_k|}{X_t} \times 100\% \tag{5}$$

where, φ_k is the relative error, mm; e_k is the absolute error, mm; X_t is the test measurement, mm.

Obtained from Equations (4) and (5), the absolute error e_k, the simulated measurement X_s, and the test measurement X_t is e_k = −0.011~0.030 mm, and the relative error is $\varphi_k \leq 7\%$, thereby indicating that simulation and test curves are highly consistent, but there is also a small deviation. This is because the creep test is affected by uncertain factors, thereby resulting in inaccurate test data and calculation of model parameters, and the quality of the seed cotton is ignored in the simulation, which makes the simulation results biased.

6 Conclusions

In this study, the effects of different moisture contents, feed qualities, compression times, and trash contents on the compression rheological characteristics of the machine-harvested seed cotton were studied by a one-factor compression creep experiment, taking the instantaneous elastic modulus E_0, hysteretic elastic modulus E_r, viscosity coefficient η, and delay time τ_r as test indicators. The results are as follows:

1) The Burgers model is more suitable for describing the creep characteristics of machine-harvested seed cotton than the generalized Kelvin model. Different experimental factors have different influences on the creep curve fitting parameters of machine-harvested seed cotton;

2) At the significance level of 0.05, the moisture content significantly affects the instantaneous elastic modulus E_0, hysteretic elastic modulus E_r, and viscosity coefficient η (p<0.01). Each value decreases with the increase in moisture content. The feed quality has significant effects on hysteretic elastic modulus E_r and viscosity coefficient η (p<0.05). The hysteretic elastic modulus E_r and viscosity coefficient η increase with the increase in feed quality. The compression times significantly influence the instantaneous elastic modulus E_0, hysteretic elastic modulus E_r, and viscosity coefficient η (p<0.01), each value of which increases with the increase of compression times. The trash content has a significant influence on the hysteretic elastic modulus E_r and viscosity coefficient η (p<0.05);

3) In the level range selected by the test, higher moisture content, smaller feed quality, and fewer compression times will produce higher permanent deformation and a more likely to creep without considering factors such as power consumption and efficiency.

4) The absolute error e_k, the ADAMS simulated measurement X_s, and the test measurement X_t is $e_k = -0.011\sim0.030$ mm, and the relative error is $\varphi_k \leq 7\%$, which verifies the rationality and reliability of the established model and verifies the feasibility of using ADAMS simulation software to study the creep characteristics of machine-harvested seed cotton.

The results of this study show that various factors have different degrees of influence on the seed cotton, and the seed cotton baling process is a continuous and multiple-feeding process. The follow-up study will be more related to the actual process of seed cotton baling, and further explore the influence of the different loading methods and different parameters on the combination process on the rheological properties of the seed cotton, to provide theoretical and data support for the study of the rheological characteristics of machine-harvested seed cotton, the design of seed cotton baling devices, and the molding mechanism of molded cotton bales (molds).

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