Stress Relaxation Characteristics and Influencing Factors of Sweet Sorghum: Experimental Study

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Compression of biological materials facilitates their transport and storage. The compressive rheological properties of silage sweet sorghum were studied *via* stress relaxation test with an electronic creep universal testing machine and a self-made adjustable compression device. The moisture content, compression density, cutting length, and compression speed were analyzed. Relaxation characteristics of sweet sorghum stalk were evaluated in terms of the stress decay time and the equilibrium elastic modulus. The stress relaxation characteristics of sweet sorghum stalks were consistent with the two Maxwell models, and the relevant parameters of the model at different levels were obtained. The rapid stress decay time first increased and then decreased with the increase of compression density, and the length of the smashed sorghum. The moisture content and the compression speed had greater fluctuations. The equilibrium elastic modulus increased with increasing straw compression density and the length of the shredding segment, and the equilibrium elastic modulus gradually decreased with increasing moisture content. The compression speed had little effect on the equilibrium elastic modulus. The research results lay a theoretical foundation and a basis for further study on the stress relaxation characteristics of sweet sorghum.

Keywords: Sweet sorghum; Silage; Stress relaxation; Models; Experiment

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INTRODUCTION

Sweet sorghum is a crop with high economic value. Its biological output and sugar content are very high (Han *et al*. 2012; Thomas *et al*. 2013; Zhang *et al*. 2014; Harper *et al*. 2017). Sweet sorghum has higher bio-productivity than green-fed maize (*Zea mays*), and can save arable land, reduce production costs, and increase agricultural production efficiency (Li *et al*. 2016; Shao *et al*. 2016). When sweet sorghum is used as silage, it can be stored for a long time without reduction of its nutrient content and palatability. It can also promote the secretion of digestive glands of livestock, enhance animal immunity, improve digestibility, prevent livestock constipation, *etc*. (He *et al*. 2017; Huang *et al*. 2017). However, sweet sorghum stalks are too loose and inconvenient to collect and transport. It is necessary to increase the density of the sorghum stalks by compressing them prior to mechanized collection and silage. At present, research on sweet sorghum silage is limited to the research of fermentation and other aspects. Research on silage compression and bale coating has been rarely reported.

Sweet sorghum is an agricultural fiber material, and the compression rheological properties of sweet sorghum will inevitably affect the working performance of compression equipment (Du *et al*. 2006; Zhu and Niu 2014; Lei *et al*. 2015). While there have been few studies on the compressive rheological properties of silage sweet sorghum, similar research on corn, alfalfa, and rice straw is common. Nona *et al*. (2014) used the compression times and moisture content as test factors, and they used straw and hay as the test objects. Through the fitting of the data it was found that the Peleg model had better relaxation characteristics than the Maxwell model. However, the generalized Maxwell model could be replaced with the fractional model without losing accuracy, which was useful for the reduction of viscoelastic parameters in the data processing of stress relaxation tests (Guo *et al*. 2017). There are some studies on the compressive and relaxing properties of compressed materials. The compression density, moisture content, material type, initial density (feeding amount), and compression speed have a significant influence on the rheological properties of the compressed material (Wang *et al*. 1997; Li *et al*. 2014; Yan *et al*. 2015; Guo *et al*. 2016; Ma *et al*. 2016).

In this study the stress relaxation test of sweet sorghum was conducted using a universal computer-controlled electronic tester and a self-made adjustable compression discharge device to obtain the stress relaxation characteristics, model, and corresponding rheological parameters of sweet sorghum stalks. The influence of moisture content, compressive density, length of chopping section, and compression speed of sweet sorghum stalk on its stress relaxation law was analyzed. This data provides the necessary theoretical basis and technical basis for the design of sweet sorghum baled silage and harvesting machinery in practical production.

EXPERIMENTAL

Material

Sweet sorghum was obtained from the suburbs of Hohhot, China. The average height was between 2000 and 4000 mm, and the average diameter was between 10 and 15 mm. Sweet sorghum straw is rich in cellulose, lignin, hemicellulose, pectin and crude protein, and also contains traces of tannins, crude fats and minerals. Compared with corn straw, the nitrogen-free extract of sweet sorghum straw was 40% to 50%, which was 64.2% higher than corn; the crude ash was 82.5% higher than corn, the crude protein was 3% to 5%, and the crude fat content was about 1% (Shao *et al*. 2016). It has been determined that the density of sweet sorghum straw was 20-40 kg/m^3 in natural loose state.

The straw of the stem was cut using a 9Z-6A silage mower (China Agricultural Machinery North China Group Co., Ltd., Henan, China), and the length of the shredding segment was controlled by changing the number of gears of the silage mower and the number of moving blades. The straw was classified by the standard sieve to ensure that the length of the shredding section of the material was less than 40 mm, as shown in Fig. 1. The moisture content of the straw was tested by moisture meters (Hebi Electronic Research Institute Co., Ltd., DYSF-8000W automatic moisture analyzer, Henan, China). The initial average moisture content of the straw was 22.6%. According to the test requirements, each of the ground straws was conditioned to moisture contents of 50%, 57%, 64%, 71%, and 78% (w.b) by adding appropriate amounts of distilled water to the samples contained in Ziploc bags and stored in a cool room at 4 °C for 24 h. The calculation formula of the moisture content of the material was as shown in Eq. 1. The stress relaxation test was performed after the moisture of the straw was uniform.

$$M_W = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

In Eq. 1, M_w is wet basis moisture content (%), m_1 is the quality of fresh materials (g), and m_2 is the quality of dry materials (g).

Fig. 1. Test samples

Device

The experimental device was a DDL-200 universal computer-controlled electronic tester produced by the Changchun Research Institute for Mechanical Science Co., LTD, China and a self-made adjustable compression discharge device. The device is hydraulically powered, as shown in Fig. 2. Its force sensor range is 0.4% to 100% FS, and its displacement rate adjustment range is 0.005 to 500 mm/min. The error is controlled at ± 0.5%, and the test process can be controlled by the computer to complete the force, displacement, time, and other data collection. The self-made adjustable compression discharge device is mainly composed of a pressure cylinder and a discharge plate. The pressure cylinder has an internal diameter of 98 mm and a length of 300 mm. The movable beam is moved up and down by the beam of the universal computer-controlled electronic tester to complete the compression process.

Fig. 2. Experimental device. 1. Discharge port; 2. compression device; 3. movable beam; 4. force sensor; 5. hand control box; 6. EDC controller; 7. computer

Experimental Method

The compressive rheological properties of sweet sorghum stalks are affected by many factors. The stress relaxation characteristics are mainly related to factors such as compression density, moisture content, compression speed, and length of the shredding segment. This was done to satisfy the requirements of sweet sorghum silage for baling and livestock for palatability (Bai 2015; Li *et al*. 2016a, b). Experiments were conducted with the goal of rapidly decaying stress and equilibrium elastic modulus (Lei *et al*. 2015). The selected experimental factors and levels are shown in Table 1. Each test was replicated 5 times, and the results were averaged.

Table 1. Test Factors and Levels

Factors / Levels	Compressed Density (kg/m³)	Moisture Content (%)	Compression Speed (mm/min)	Cutting Length (mm)
1	400	50	100	<10
2	500	57	200	10-20
3	600	64	300	20-30
4	700	71	400	30-40
5	800	78	500	

During testing, the materials were uniformly fed into the self-made adjustable compression device in a randomly disordered manner. The test was conducted in accordance with the test factors and levels in Table 1. The material was pressed to the target density and held for 900 seconds. Furthermore, the stress relaxation curve of sweet sorghum straw compression process was obtained. The experimental data was analyzed using MATLAB 2014 (MathWorks, Natick, MA, USA). The compression models were fitted to the experimental data using Origin software 8.5 (OriginLab, Northampton, MA, USA).

RESULTS AND DISCUSSION

Stress Relaxation Models

According to current research practices, the stress relaxation characteristics of agricultural fiber materials were generally described by the generalized Maxwell model. By comparing the three-element Maxwell model, the five-element Maxwell model, and the burgers model (Alvarez and Canet 2000; Kaur *et al*. 2002; Kim *et al*. 2008), which were unsuccessful in explaining the stress relaxation characteristics of sweet sorghum stalks, low R^2 values were obtained when the stress relaxation models were fitted to the experimental data. Within the test factors, the expression of stress relaxation characteristics of sweet sorghum stalks can be described by using two Maxwell models in parallel with one equivalent spring (Fig. 3). Moreover, the fitting correlation coefficient (R^2) of each group of models was more than 0.99 (Fig. 4). The model expression equation is shown in Eq. 2,

$$E_{(t)} = E_1 e^{-t/T_1} + E_2 e^{-t/T_2} + E_e \qquad (2)$$

where $E_{(t)}$ is the instantaneous elastic modulus at any time t (kPa), E_1 is the relaxation elastic modulus of the first Maxwell model (kPa), E_2 is the relaxation elastic modulus of the second

Maxwell model (kPa), E_e is the equilibrium elastic modulus (kPa), T_1 is the rapid decay time of stress (s), and T_2 is the time of slow stress decay (s). The model parameter fitting results are shown in Table 2. The results showed that different experimental factors have certain influences on each parameter in the stress relaxation model, and the fitting coefficient was more than 0.997, which proved the rationality and feasibility of the model in the experimental range.

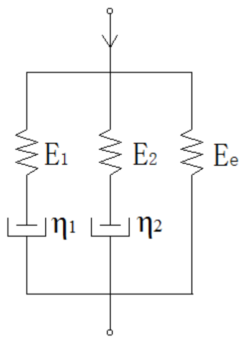


Fig. 3. Stress relaxation model. E_1 and E_2 are the elastic modulus of the first and second-order Maxwell model (kPa), respectively. E_e is the equilibrium elastic modulus (kPa), η_1 and η_2 are damping coefficients of the first and second-order Maxwell model, respectively.

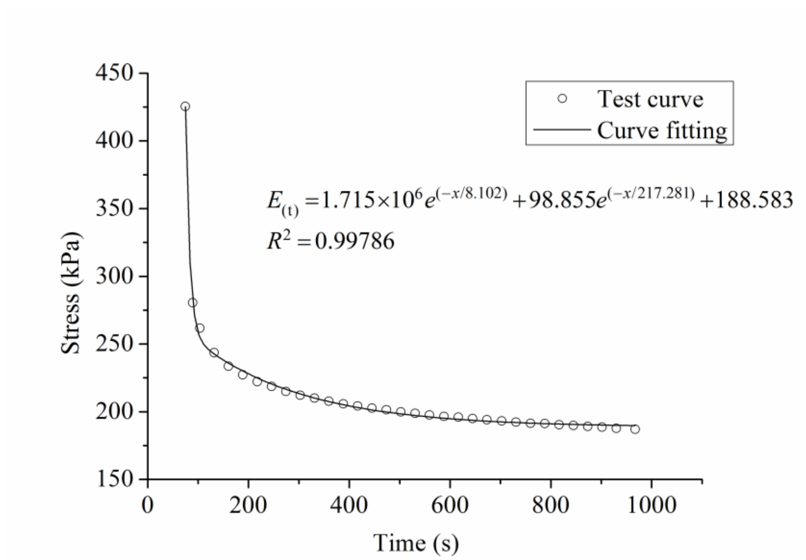


Fig. 4. Stress relaxation fitting curves

Stress Relaxation Characteristics

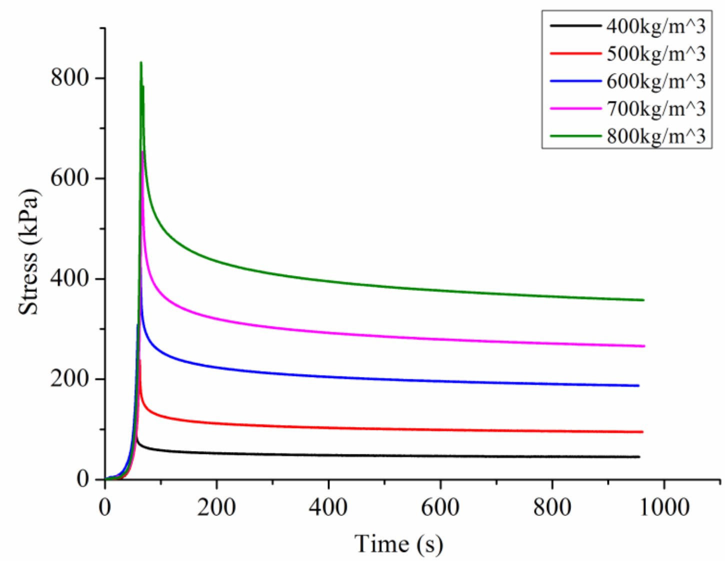
T_1 reflects the relaxation rate of the material in the relaxation process. The shorter T_1, the faster the relaxation rate of the material and the greater the relaxation elastic modulus of the material. In the actual production process, T_1 determines the optimal rope and wrap time; that is to say, the bundling and wrapping are performed after T_1, thereby reducing the impact on the bundling rope and film after the material forming of the relaxation process. E_e reflects the ability of the material to recover in the relaxation process. The smaller E_e, the less likely the material to break the actual production, and the phenomenon of broken and loose bundles. At the same time, it can decrease the thickness of the base layer and save costs.

Table 2. Parameters of Stress Relaxation Test of Sweet Sorghum Stalk

Factors	Levels	Stress relaxation parameters					Fitting coefficients R^2
		E_1/kPa	E_2 /kPa	E_e /kPa	T_1/s	T_2 /s	
Moisture content (%)	50	7.033×10^5	211.228	446.104	9.818	255.010	0.99786
	57	6.340×10^6	128.289	237.358	7.393	215.212	0.99817
	64	1.715×10^6	98.855	188.583	8.102	217.281	0.99786
	71	6.084×10^6	44.392	84.731	6.844	202.680	0.99842
	78	1.360×10^6	28.287	57.004	7.43	195.087	0.99823
Cutting length (mm)	>10	8.114×10^6	53.693	53.693	7.445	216.671	0.9983
	10-20	2.040×10^6	99.262	188.562	8.124	218.118	0.99782
	20-30	3.614×10^6	126.128	237.214	7.925	215.960	0.9979
	30-40	4.256×10^6	131.216	254.204	7.855	226.667	0.99794
Compressed density (kg/m^3)	400	3.391×10^5	20.535	45.394	7.501	213.112	0.99773
	500	1.672×10^6	46.775	95.612	6.924	211.627	0.99836
	600	4.364×10^6	103.199	183.961	6.818	205.347	0.99837
	700	1.292×10^6	140.895	267.705	7.919	221.469	0.99792
	800	2.682×10^5	197.412	359.079	9.940	230.061	0.99784
Compression speed (mm/min)	100	6.376×10^7	106.132	169.721	9.965	236.132	0.99796
	200	7.291×10^9	140.013	184.172	7.598	206.217	0.99854
	300	1.129×10^9	118.651	169.969	8.389	216.338	0.99837
	400	2.973×10^9	117.242	167.230	7.941	216.266	0.99843
	500	9.571×10^9	110.068	161.256	7.625	214.548	0.99883

Effect of Compression Density on the Stress Relaxation Characteristics

The compression density reflects the compressibility of the material. The results show that the density of compressed straw samples was significantly affected by the moisture content, hammer mill screen size, and compression pressure (Maniet *et al*. 2003; Adapa *et al*. 2009). Figure 4 shows the change curve of straw at different compression densities of 400, 500, 600, 700, and 800 kg/m^3, which are under the test conditions of moisture content of 64%, compression speed of 200 mm/min, and chopped section length of 10 to 20 mm. Figure 5(a) shows that with the compression density increases, the greater the force required for the compression process, the more pronounced the relaxation phenomenon during relaxation, and the slower the rate of stress relaxation (Ma *et al*. 2016), but the overall variation is consistent. Figure 5(b) shows the change curve of compressive density, T_1, and E_e. The analysis found that with the increase of the compression density, T_1 decreases first and then increases. When the density is 400 kg/m^3, T_1 is the lowest point. The main reason is that the sweet sorghum stalk has the maximum stress relaxation rate at this density, which shortens T_1. E_e increases with the increase of the compression density. When the density is 600 kg/m^3, E_e appears at the lowest point. The main reason is that the sweet sorghum stalks are subjected to a variety of force interactions at this density, such as the squeezing forces within the material, the compression resistance between the materials, and the compressive force of the indenter on the material. Under the interaction of each force, the elastic deformation restoring force (Ma *et al*. 2016) is reduced, and the shape and stability of the shaped block are easily maintained.



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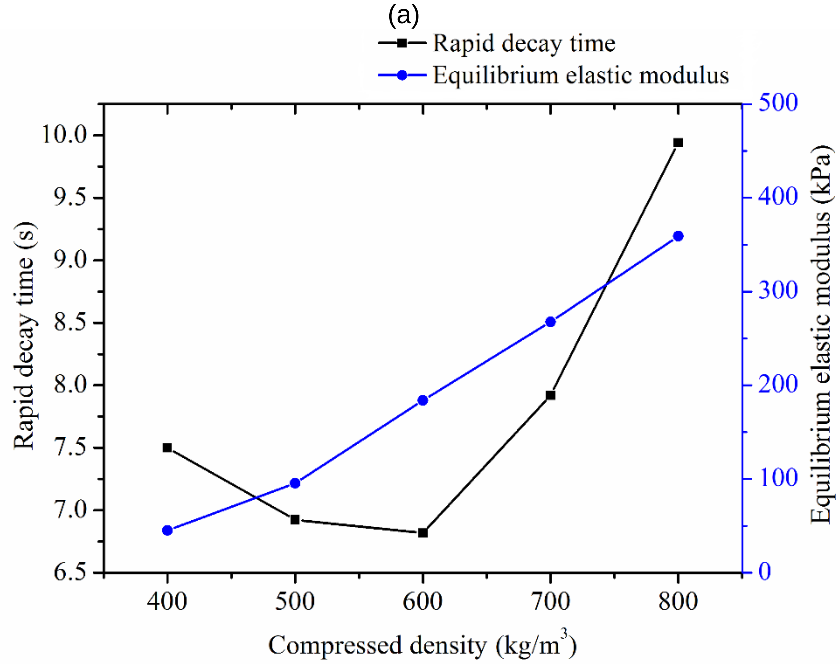
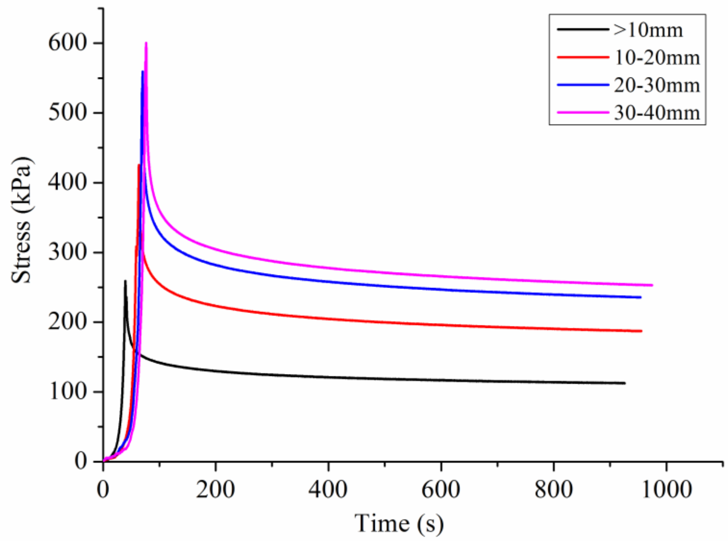


(b)

Fig. 5. Stress-time, T_1, and E_e at different compression densities

Effect of the Length of the Chopped Segment on the Stress Relaxation Characteristics

Increasing the screen size of the hammer mill reduced the density of compressed straw, as reported by Mani *et al*. (2006). Figure 6 shows the relationship among stress-time, T_1, and E_e of elasticity for different chopped lengths. As shown in Fig. 6(a), when the length of the shredding segment increased, a greater force was required for the compression process, resulting in a greater relaxation elastic modulus. When the cutting length was 20 to 40 mm, the force required for the compression process was similar, and the stress relaxation rate change was consistent. This result indicated that as the length of the shredding segment increased, the gap between the materials increased along with the internal friction of the material under the mutual effect of mutual extrusion forces; thus, the stress relaxation process was less effected. As shown in Fig. 6(b), T_1 increased first and then decreased gradually with the increased length of the shredding segment, while E_e showed a slowly increasing trend. When the length of the chopped section of the straw was less than 10 mm, T_1, and E_e all reached their minimums. The above phenomenon indicates that the larger length of the chopped section of the material resulted in a larger gap between the materials and a greater relaxation elastic modulus. As a result, the greater E_e value produced an easier relaxation of the material during relaxation, which worsened the molding effect.



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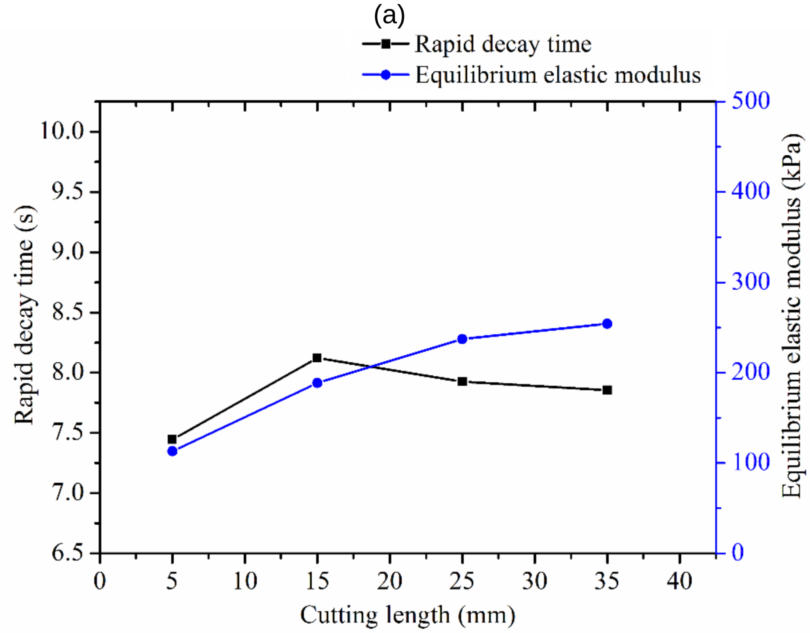
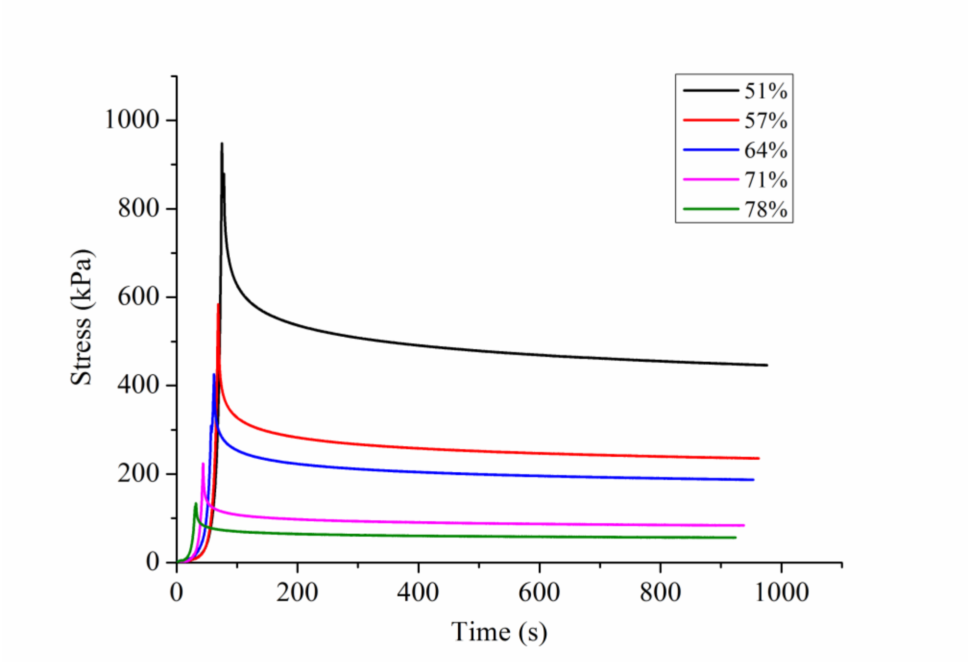


(b)

Fig. 6. Stress-time, T_1, and E_e of different lengths of shredded segments

Effect of Moisture Content on the Stress Relaxation Characteristics

Moisture content increased the density of compacted straw samples. High moisture content led to a remarkable increase of the density of compacts, confirming previous studies (Talebi *et al*. 2011; Guo *et al*. 2016). Figure 7 shows the relationship among stress-time, T_1, and E_e at different moisture contents. As shown in Fig. 7(a), with the increasing moisture content, a smaller compressive force was required when the material was compressed to the same density.



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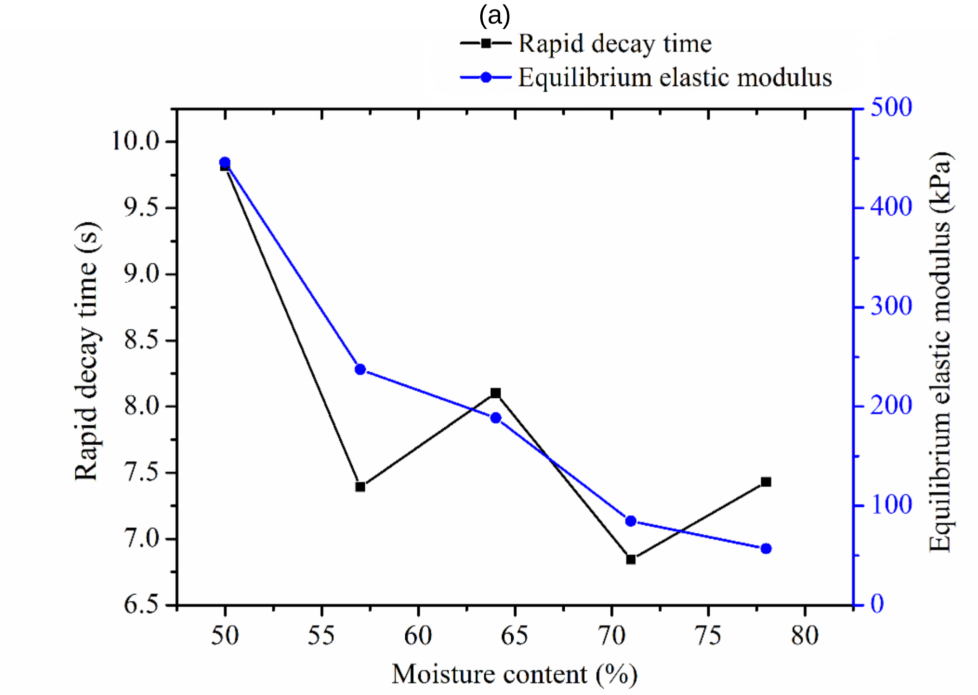


(b)

Fig. 7. Stress-time, T_1, and E_e of different moisture contents

A smaller compression force results in a smaller stress relaxation rate and elastic deformation recovery force, which indicates that moisture content influences the material, stress relaxation rate, and elastic deformation recovery force to some extent. The main reason for this effect is that the straw effectively reduces the distance between molecules under high pressure, which makes it easier to form hydrogen bonds between the hydroxyl groups in the non-crystalline region of hemicellulose and cellulose. Thus, the water absorption capacity of the material is reduced, and the rebound is inhibited. Therefore, a higher moisture content in the material is associated with a smaller elastic deformation recovery force when pressed to the same density.

As shown in Fig. 7(b), with increasing moisture content, the minimum value of T_1 occurred at 71%, and E_e decreased with time. When the same material is compressed to the same density, due to the increased moisture content, water is squeezed out of material. According to liquid film media friction theory and liquid lubrication theory (Huang *et al*. 2011; Chen *et al*. 2013; Li *et al*. 2014), the material is formed between the compression wall and the interior of the material. The liquid film reduces the friction between each other and reduces E_e.

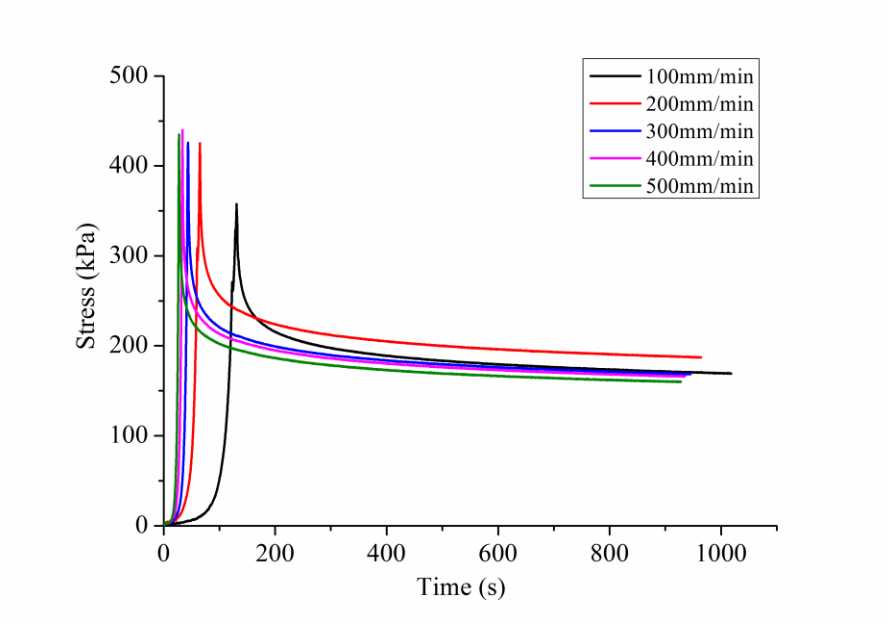
Effect of Compression Speed on the Stress Relaxation Characteristics

The compression speed has a great influence on the straw compression process and molding stability (Fan *et al*. 2008; Hu *et al*. 2013). Figure 8 shows the stress-time at different compression speed and the effect of compression rate on T_1 and E_e. Different compression speed resulted in similar variations in the process of material compression and relaxation (Fig. 8a).

With increased compression speed, the time required for the materials to reach the equivalent compression density was shorter, and when the compression speed was greater than 100 mm/min, the compressive force required for the compression process remained the same. In the relaxation process, the stress relaxation rate and deformation recovery force of the material fluctuated greatly. When the same initial density was compressed at different compression speeds, the form of deformation during compression of the sweet sorghum straw changed.

The ratio of viscoelastic deformation, plastic deformation, and inertial deformation occurred, and the resistance of compressed sweet sorghum straw was mainly derived from the deformation resistance of straw. The compression force required for various deformations was different, which caused the materials to behave differently. Therefore, the compressibility causes a large fluctuation in the stress relaxation rate and the deformation restoring force.

As shown in Fig. 8(b), with the continuous increase of the compression speed, T_1 occurred at a speed of 200 mm/min, and then T_1 first increased and then decreased with increasing compression speed. However, the overall tendency of change was relatively slow. E_e remained mostly unchanged with the increased compression speed, but the change tendency was not obvious, which indicates that the compression speed had little effect on E_e. With the scope of the test, when the compression speed was 200 mm/min, the stress relaxation time of the sweet sorghum relaxation process was the shortest.



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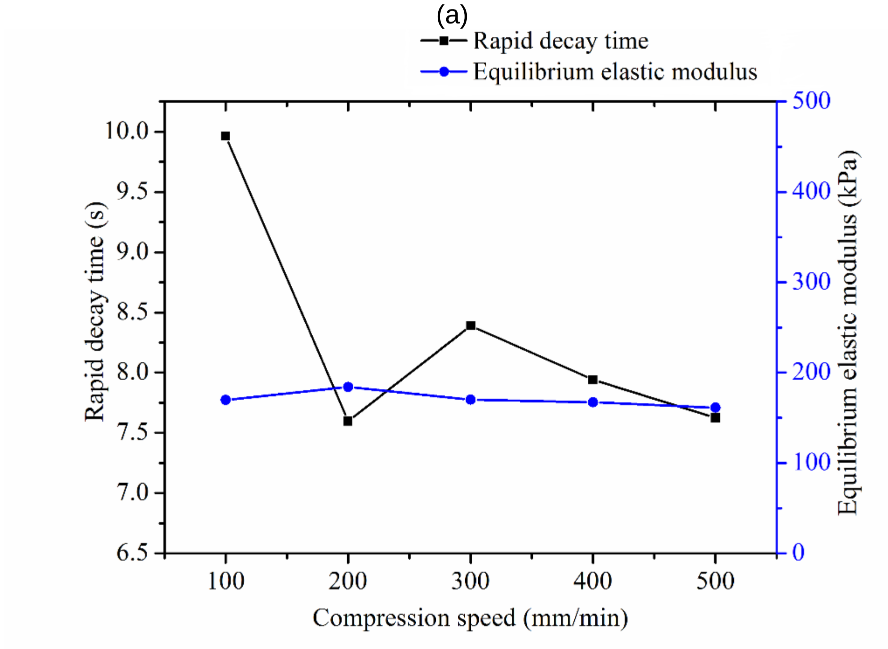

(b)

Fig. 8. Stress-time, T_1 and E_e at different compression speed

CONCLUSIONS

1. The stress relaxation model of sweet sorghum straw can be described by a three-element generalized Maxwell model. The relevant parameters of the stress relaxation model at different levels of the moisture content, the compression density, the length of the chopping section, and the compression speed were obtained. The fitting coefficient of determination was greater than 0.99.
2. After analyzing the influence of the compression density on the rapid decay time of stress and the equilibrium elastic modulus, the results showed that as the compression

density increased, both the rapid decay time and the equilibrium elastic modulus increase nonlinearly.

3. After analyzing the influence of the length of the chopped segment on the rapid decay time of stress and the equilibrium elastic modulus, the result showed that with the increase of the length of the chopped segment, the stress rapidly decayed first and then increased. Between 10 to 20 mm, the stress decay time was the minimum. The equilibrium elastic modulus increased nonlinearly with the length of the chopped segment.
4. After analyzing the influence of moisture content on the rapid decay time of stress and the equilibrium elastic modulus, the results showed that with the increase of moisture content, the most rapid decay time of the stress appeared when the moisture content was 57% and 71% respectively. When the moisture content increased, the equilibrium elastic modulus decreased nonlinearly.
5. After analyzing the influence of the compression speed on the rapid decay time of stress and the equilibrium elastic modulus, the results showed that the stress decay time was the smallest at the compression speed of 200 mm/min. With the increase of the compression speed, the equilibrium elastic modulus remained unchanged.

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