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Description of the Instantaneous Stress Drop Behavior of a Cornstraw-Potato Residue Mixture Based on Stress Relaxation Models

Wenbin Guo, Fan Hu, Xuehong De,* Zhibo Hou, Zhipeng Wang, and Xinyang Jiang

Studying the stress relaxation characteristics can provide important process parameters for the granulation and briquetting of biomass materials. In this study, a generalized Maxwell model and fractional model were established to describe and analyze the stress instantaneous drop behavior of a cornstraw-potato residue mixture during the stress relaxation process. Stress relaxation characteristic parameters, *e.g.*, the stress instantaneous drop time, were obtained. Using this information, the influence of the compression speed on the stress instantaneous drop time, stress relaxation time ratio, and other parameters were analyzed. In addition, the regression model of the compression frequency and compression speed was established, which provided a method for determining the appropriate compression frequency of the molding equipment according to the compression speed.

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INTRODUCTION

As the residual waste from agricultural production, cornstraw and other viscoelastic materials are often crushed and compressed into feed pellets or fuel blocks for secondary use (Kaliyan and Morey 2009a; Kaliyan *et al.* 2009b; Rahaman and Salam 2017; Jewiarz *et al.* 2020). Stress relaxation is an important rheological characteristic for the compression process, which greatly affects the compression density, molding effect, and energy consumption of a material during granulation and briquetting. In order to analyze this impact, rheological models of viscoelastic materials have been established to describe their stress relaxation behavior, and the model parameters characterizing the stress relaxation behavior are obtained through nonlinear regression analysis (Peleg 1983; Fang *et al.* 2018; Joyner *et al.* 2021). Common stress relaxation models include the generalized Maxwell model (Mohsenin and Zaske 1976; Kelly 2011; Du *et al.* 2018), the Poynting Thomson Model (Yang 2010; Zhou *et al.* 2013), and the Zener Model (Chen *et al.* 2013; Yin *et al.* 2019). The model parameters generally include the stress relaxation time, modulus of elasticity, and viscosity coefficient. Among them, the stress relaxation time is often used to determine the compression frequency of the molding device, so as to avoid high stress areas and improve the performance of the molding equipment (Wang 2007).

As the compression rate and density of a material gradually increases during processing, a stress instantaneous drop stage appears during the stress relaxation process (Yang 2010). This stage does not last long, but the stress that occurs is large, which can

easily cause large energy consumption and damage to the compression device. Therefore, it is necessary to find a suitable model to describe the stress drop process and obtain the stress dump time, so as to provide a basis for the reasonable selection of parameters , *e.g.*, the compression frequency. Previous studies on the stress instantaneous drop during the stress relaxation are limited. For example, Wang (2007) and Yang (2010) studied the stress relaxation characteristics of forage grass and found that the generalized Maxwell model could not fit the curve at the stress drop phase in the case of few parameters. Thus, it is necessary to establish a more accurate model to describe this stress drop behavior. Since the speed of the stress relaxation is greatly affected by the compression speed, this study takes the stress relaxation characteristics of a cornstraw-potato residue mixture under different compression speeds as the research object (Ma 2015). By establishing a fractional model and a generalized Maxwell model, this study analyzes the stress instantaneous drop during the stress relaxation process and obtains the stress instantaneous drop time. Using this information, the relationship between the compression speed and the compression frequency is established.

EXPERIMENTAL

Materials

The corn stalks used in the test were selected from the whole plant that was naturally dried after harvesting in Hohhot, Inner Mongolia in autumn. The moisture content was (4% ± 0.1%) after being pulverized, and the scraps were sieved to a particle size of less than 3 mm using a punching sieve and then weighed. The potato waste residue was from a starch processing plant in Hohhot, Inner Mongolia, and its moisture content was (65% ± 1%) after pretreatment. In order to prevent material spoilage and reduce water loss, the potato waste residue was stored at a temperature of 2 to 4 °C. The relevant tests were completed within one week. The procedure was to mix cornstraw and potato residue in proportion, and then start the experiment. Referring to the research results of relevant mechanical tests (as found in Guo *et al.* (2022)), the cornstraw particles and potato residue were stirred and mixed at a mass ratio of 1 to 3. The sample of the cornstraw-potato residue mixture was obtained, as shown in Fig. 1.

Fig. 1. The mixture of cornstalk particle and potato residue

Experimental Method

The test equipment was a microcomputer-controlled electronic universal testing machine equipped with a self-made piston compression device (Fig. 2). The computer program controls the plunger for axial compression and pressure dwell and collects the pressure and displacement during the test. During the test, the cornstraw-potato residue mixture was compressed to a density of 900 kg/mm^3 at different compression speeds (10, 60, 110, 160, and 210 mm/min). The dwell time of pressure was set to 900 s. After the test, the movable base plate was twitched to complete the extrusion of the mixed molding block. The test was repeated 3 times at the same compression speed at room temperature.

To analyze the relationship of the stress relaxation speed and the molding effect with the compression speed, the relaxation time ratio (R_t) and the relaxation ratio (R_r) were used as the test indicators in this study (Faborode and O'Callaghan 1986; O'Dogherty 1989; Ma *et al.* 2016). The R_t value is the ratio of the initial stress to the relaxation time for each stage of the stress relaxation process, which is calculated by Eq. 1,

$$R_t = \sum_{i=1}^{n} \left(\frac{\sigma}{T}\right)_i \tag{1}$$

where R_t is the stress relaxation time ratio (MPa/s), σ is the initial stress (MPa), T is the stress relaxation time (s), and is the stages of stress relaxation.

The R_r value is the ratio of the compression density (ρ) of the material in the stress relaxation test to the relaxed density (ρ_r) of the material block 24 h after demoulding. It can be calculated by Eq. 2,

$$R_r = \frac{\rho}{\rho_r} \tag{2}$$

where R_r is the relaxation ratio, ρ is the compression density (kg/m^3), and ρ_r is the relaxation density (kg/m^3). The smaller the relaxation ratio, the closer the ρ and ρ_r, and the better the molding effect of the material.
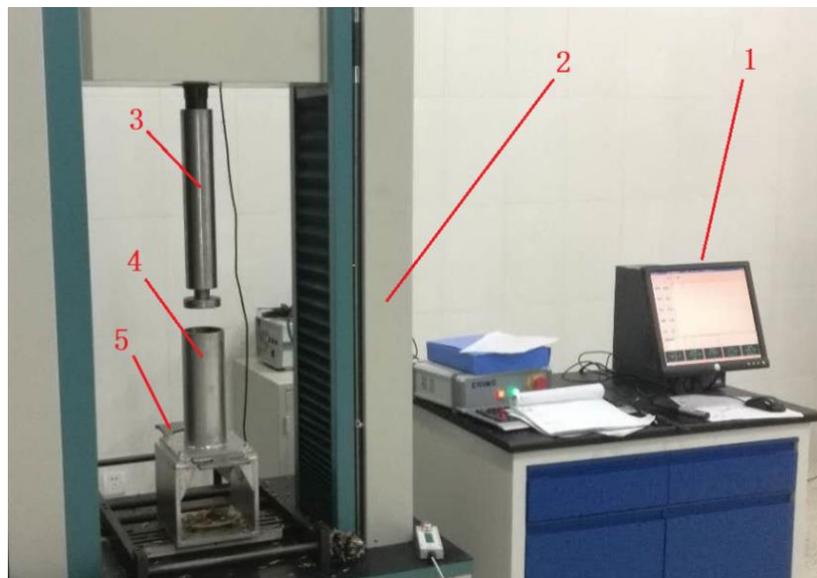
Fig. 2. Electronic universal tester and compression device: 1. Computer; 2. Universal tester; 3. Plunger; 4. Compression device; and 5. Movable base plate

Constitutive Models

Generalized Maxwell model

Since the cornstraw-potato residue mixture is a viscoelastic material, the Three-element generalized Maxwell model was used to describe its stress relaxation behavior under different compression speeds and obtain parameters such as elastic modulus and stress relaxation time (Guo *et al.* 2022). This model is shown in Eq. 3,

$$E(t) = E_1 e^{-\frac{1}{T_1}t} + E_2 e^{-\frac{1}{T_2}t} + E_e \tag{3}$$

where E_1 and E_2 are the decay moduli (MPa), E_e is the equilibrium modulus (MPa), and T_1 and T_2 are the decay time of stress. When $t = 0$, the initial elastic modulus of stress relaxation can be obtained, as shown in Eq. 4,

$$E_s = E_1 + E_2 + E_e \tag{4}$$

The obtained results will be compared with the results of the fractional model to analyze the effect of the compression speeds on the stress relaxation characteristics of the cornstraw-potato residue mixture.

Fractional model

According to Hooke's Law and Newton's Law, the relationship between stress and strain during elastic and viscous deformation are shown as Eqs. 4 and 5, respectively,

$$\sigma(t) = K \cdot D_t^0 \varepsilon(t) \tag{5}$$

$$\sigma(t) = K \cdot D_t^1 \varepsilon(t) \tag{6}$$

where $\sigma(t)$ in Eqs. 5 and 6 is the zero-order derivative (D_t^0) and the first-order derivative (D_t^1) of the strain $\varepsilon(t)$ with respect to time (t), respectively, and K is the undetermined coefficient. The elastic deformation and viscous flow of the cornstraw-potato residue mixture appear simultaneously in the compression, and there is no obvious yield point, so the fractional order (β) is introduced to establish the fractional model of stress and strain, as shown in Eq. 7,

$$\sigma(t) = K \cdot D_t^\beta \varepsilon(t) \tag{7}$$

where β is the fractional order whose value is between 0 and 1 (Stiassnie 1979; Nonnenmacher and Glockle 1991; Paola *et al.* 2011; Guo *et al.* 2017). According to the definition of a fractional order by the Riemann-Liouville derivative, Eq. 7 can be further rewritten as Eq. 8,

$$\sigma(t) = K \frac{d}{dt} \left[\frac{1}{\Gamma(1-\beta)} \int_0^t (t - \tau)^{-\beta} \varepsilon(\tau) d\tau \right] \tag{8}$$

where Γ is the Gamma function, and τ is a dummy variable. Since the strain is constant during stress relaxation, the strain was replaced by a constant strain. Then, the variation of $\sigma(t)$ over t is shown in Eq. 9,

$$\sigma(t) = \frac{K \varepsilon_0}{\Gamma(1-\beta)} t^{-\beta} \tag{9}$$

After the left of Eq. 8 is transformed into the modulus $E(t)$ at any time, the fractional model of stress relaxation obtained is shown in Eq. 10,

$$E(t) = \frac{K t^{-\beta}}{\Gamma(1-\beta)} \tag{10}$$

According to rheological theory, stress relaxation is the phenomenon of stress attenuations that occurs when a material is instantly compressed to a constant density. However, due to the viscous resistance of the cornstraw-potato residue mixture, the stress generated by instantaneous compression tends to be infinite, which cannot be achieved in practice. Thus, the initial value of t in Eqs. 9 and 10 should be close but not equal to 0 (Koeller *et al.*1984). In order to accurately fit the stress relaxation curve of the cornstraw-potato residue mixture, the t in Eq. 10 is replaced by $t + t_0$ to obtain the modified fractional model, as shown in Eq. 11,

$$E(t) = \frac{K(t+t_0)^{-\beta}}{\Gamma(1-\beta)} \tag{11}$$

where t_0 is the actual start time of stress relaxation, and its magnitude is related to the compression speed during the test.

RESULTS AND DISCUSSION

Curve Analysis

Figure 3 shows the stress-time curves of the cornstraw-potato residue mixture at different compression speeds. It can be seen that before the cornstraw-potato residue mixture was compressed to a constant density of 900 kg/m^3, the higher the compression speed, the faster the stress increased with time in the compression process, and the shorter the time and the larger the stress needed to reach a constant density. When the mixture was compressed to a constant density of 900 kg/m^3 and the pressure started to dwell, the stress reached a peak (σ_0) and began to decrease over time, showing obvious stress relaxation behavior. The decreasing stress trend at different compression speeds tended to be gentle as the time increased.
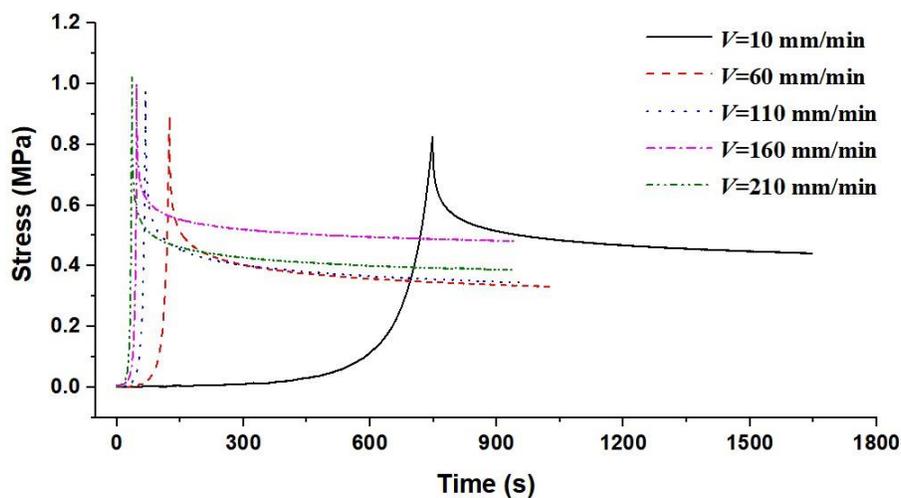
Fig. 3. Stress-time curves of at different compression speeds

Model Evaluation and Analysis

In order to analyze the viscoelastic deformation and the stress dropping rate during the stress relaxation process of the cornstraw-potato residue mixture, the generalized Maxwell model was used for the fitting and regression analyses of the stress relaxation curves under different compression speeds. The results are shown in Table 1. The model fitting coefficient of determination (R^2) was between 0.9832 to 0.9949. The larger the compression speed, the smaller the R^2 and the worse the fitting effect. When the compression speed was 60, 110, 160, and 210 mm/min, R^2 was below 0.99. The model curve did not fit the test curve well at the initial stage of stress decay. Consequently, the fitting effect was poor, and the fitting value could not reach the initial stress σ_0, especially when the compression speed was high.

Table 1. Nonlinear Regression Analysis Results of Stress Relaxation Models

Compression Speed V(mm/min)	Parameters of Generalized Maxwell Model					Parameters of Fractional Model				
	Decay modulus E_1(MPa)	Decay modulus E_2(MPa)	Equilibrium modulus E_e(MPa)	Stress relaxation time T_1(s)	Stress relaxation time T_2(s)	R^2	Fractional orders α	Viscoelastic coefficients K	Start time of stress decay t_0(s)	R^2
10	0.2296	0.1768	0.5902	16.7759	*269.5127*	0.9949	0.0865	1.1240	0.6317	0.9995
60	0.3517	0.2119	0.4540	10.6862	237.5119	0.9892	0.1214	1.1180	0.2081	0.9997
110	0.3897	0.2025	0.4706	8.8440	221.1040	0.9868	0.1143	1.0895	0.0869	0.9974
160	0.3330	0.1663	0.5982	8.1545	204.9260	0.9851	0.0791	1.0593	0.0301	0.9902
210	0.4131	0.1863	0.5342	7.1731	202.0895	0.9832	0.0961	1.0717	0.0267	0.9905

It can be seen from the mechanical analogy of the generalized Maxwell model (Fig. 4a) that when the material was instantly compressed to a constant strain (constant density) in an ideal state, the resistance forces σ_1, σ_2, and σ_e were all from elastic deformation and could be obtained by the elastic modulus and constant strain. In practice, however, a viscoelastic material cannot be instantaneously compressed to a constant strain. For this reason, the instantaneous loading can only be replaced by loading at a certain speed, which results in the nonlinear viscoelastic deformation of the stress-time curve at the loading stage (Fig. 3). This means that when the viscoelastic material is compressed to a larger density at a certain speed, there will be some irrecoverable viscous deformation. According to Yang (2010), this viscous deformation behavior can be explained by adding a parallel damper element to the Zener Model, *i.e.*, the Yang Model (as shown in Fig. 4b). The viscous deformation resistance (σ_3) of the material during compression was partly from the damper element, and its magnitude was determined by the product of the viscous coefficient and the strain rate (Zhou 1994). Therefore, for materials with the same viscoelastic characteristics, the greater the compression speed, the greater the σ_3, and the greater the initial stress (σ_0) ($\sigma_0 = \sigma_1 + \sigma_2 + \sigma_3$) when the material reached constant density. Nevertheless, in the dwell stage, the plunger stopped moving, the viscous deformation resistance σ_3 disappeared, and (σ_0) instantaneously dropped (Yang *et al.* 2010). In this case, the larger the compression speed, the faster the stress σ_0 declined at the beginning of the dwell stage (Fig. 3). Due to the abovementioned stress instantaneous drop stage in the stress relaxation process, the fitting accuracy of the generalized Maxwell model to the stress relaxation curve of the cornstraw-potato residue mixture was low. However, if the fitting accuracy was improved by increasing the number of elements in the generalized Maxwell

model. This will not only complicate the model, but also it will increase the obtained parameters, making it difficult to analyze the stress relaxation characteristics of the cornstraw-potato residue mixture.

(a) Generalized Maxwell Model   **(b)** Yang Model
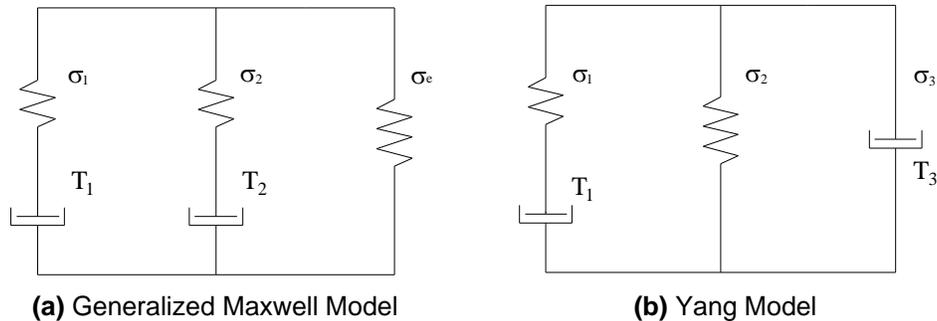
Fig. 4. The mechanical analogy of the stress relaxation models

According to the stress relaxation characteristics of the cornstraw-potato residue mixture, the fractional model (as shown in Eq. 11) and the generalized Maxwell model were used to fit and analyze its stress relaxation curve (Fig. 5). Compared with the generalized Maxwell model, the fractional model can more accurately describe the entire stress relaxation process of the cornstraw-potato residue mixture, including the instantaneous drop stage of stress relaxation. In addition, as shown in Table 1, the fitting determination coefficient (R^2) of the fractional model under different compression speeds was greater than 0.99, which was considerably better than the fitting results of the generalized Maxwell model. This was because the fractional model could accurately describe the viscoelastic deformation process during stress relaxation through the fractional order (Guo *et al.* 2017). In the obtained model parameters, t_0 was the time when the stress began to instantaneously drop. The greater the compression speed (the closer it was to instantaneous compression), the smaller the t_0 and the closer t_0 was to 0, and the faster the stress relaxation response occurred after compression.
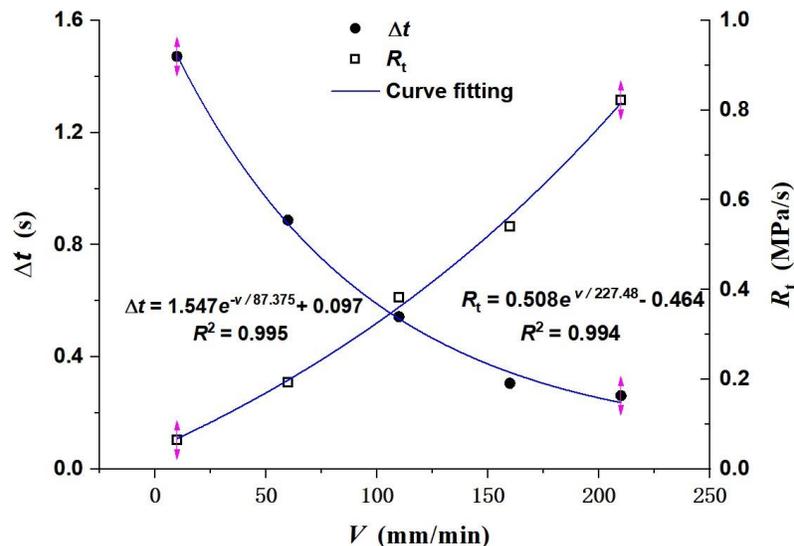
Fig. 5. The stress relaxation curve fitted by different models

To compare the curve fitting results of the fractional model and the generalized Maxwell model, the stress relaxation process of the cornstraw-potato residue mixture was divided into the stress instantaneous drop stage and the stress decay stage, as shown in Fig. 6. The initial elastic modulus E_s, as calculated by Eq. 12,

$$E_s = \frac{\sigma_s}{\varepsilon_0} \tag{12}$$

where σ_s is the initial stress at the stress decay stage (MPa) and ε_0 is the constant strain was obtained by fitting the stress relaxation curve with the generalized Maxwell model and was brought into Eq. 13, so the start time (t_s) of the stress decay stage could be obtained. Based on t_s, the time (Δt) for stress instantaneous drop can be obtained, as shown in Eq.14:

$$t_s = \left[\frac{K}{E_s \cdot \Gamma(1-\beta)} \right]^{\frac{1}{\beta}} \tag{13}$$

With the obtained Δt, T_1, and T_2, the stress relaxation time ratio (R_t) can be calculated from Eq. 1,

$$\Delta t = t_s - t_0 \tag{14}$$
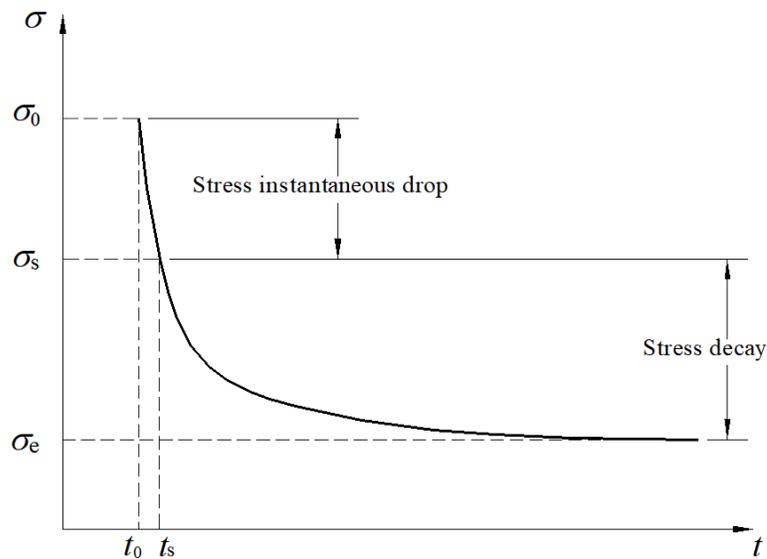
Fig. 6. Stages of the stress relaxation

Effects of the Compression Speeds on the Stress Relaxation Parameters

To investigate the correlations of the parameters β, K, t_0, and Δt (obtained at different compression speeds) with the stress relaxation speed and molding effect of the mixed material, correlation analysis was carried out on the following parameters: the relaxation time ratio (R_t), the relaxation ratio (R_r), and the generalized Maxwell model parameters (E_1, E_2, E_e, T_1, and T_2). The results are presented in Table 2. The compression speed V was significantly correlated with K, Δt, T_1, T_2, R_t, and R_r (significance level p-value less than or equal to 0.05). The compression speed was significantly negatively correlated with the Δt and T_2, and significantly positively correlated with R_t (p-value less than or equal to 0.01). This indicated that the higher the compression speed, the faster the stress dropped during dwell, which in turn affected the relaxation ratio after dwell. Nonlinear regression analysis was performed on the Δt and R_t, which were significantly

affected by the compression speed, and the determination coefficient (R^2) was greater than 0.99 (Fig. 7). It can be seen that with the increase of V, the Δt and R_t decreased and increased exponentially, respectively, showing an obvious nonlinear variation law.

The Δt was significantly correlated with the t_0, K, T_1, T_2, R_t, and R_r. Specifically, Δt had a significant positive correlation with t_0, T_1, and T_2, which indicated that the earlier the stress started to plunge, the faster the stress plunged, and that the duration of the stress instantaneous drop directly impacted the stress decay time. In addition, the significant correlation between the Δt and the K, R_t, and R_r also demonstrated that in the case of a large compression rate, the stress instantaneous drop during stress relaxation was fast (Δt was small) and the relaxation time ratio was large. This indicated that the mixture particles were not well compacted, resulting in a large relaxation after demoulding and a poor molding effect. As for the fractional model parameters, K was significantly correlated with V, Δt, and T_2, which partly reflected the impact of the compression speeds on the stress relaxation speed. Moreover, the change of the compression speed also impacted the degree of viscoelastic deformation of the mixture, and a smaller α indicated better elasticity of the material during the stress relaxation. Therefore, α was significantly negatively correlated with E_e. On the contrary, a larger α indicated better viscosity, thus α had a very significant positive correlation with E_2.

Table 2. Correlation Analysis of Model Parameters and Compression Speed

	α	K	t_0	Δt	E_1	E_2	E_e	T_1	T_2	R_t	R_r
V	-0.203 (0.74)	-0.915* (0.03)	-0.864 (0.06)	-0.948** (0.01)	0.776 (0.12)	-0.227 (0.71)	0.077 (0.90)	-0.898* (0.04)	-0.957** (0.01)	0.991** (<0.01)	0.917* (0.03)
α	1	0.420 (0.48)	-0.167 (0.79)	0.035 (0.96)	0.455 (0.44)	0.997** (<0.01)	-0.991** (<0.01)	-0.156 (0.80)	0.063 (0.92)	-0.221 (0.72)	0.096 (0.88)
K	—	1	0.816 (0.09)	0.916* (0.03)	-0.576 (0.31)	0.463 (0.43)	-0.296 (0.63)	0.821 (0.09)	0.921* (0.03)	-0.871 (0.06)	-0.860 (0.06)
t_0	—	—	1	0.974** (<0.01)	-0.896* (0.04)	-0.121 (0.85)	0.293 (0.63)	0.995** (<0.01)	0.967** (<0.01)	-0.800 (0.10)	-0.985** (<0.01)
Δt	—	—	—	1	-0.845 (0.07)	0.077 (0.90)	0.097 (0.88)	0.981** (<0.01)	0.999** (<0.01)	-0.899* (0.04)	-0.989** (<0.01)

Note: Asterisks(**)and(*)indicate that the correlation is significant at the 0.01 level and 0.05 level (*p*-values shown in parentheses).

To sum up, the compression speed (V) had an effect on the stress relaxation of the cornstraw-potato residue mixture. The larger the V, the shorter the stress instantaneous drop time and the stress decay time, and the faster the stress relaxation. Although the stress instantaneous drop time was short (Δt = 0.262 s to 1.472 s), the stress during which was the largest throughout the whole stress relaxation process, thereby exerting a negative impact on the molding energy consumption and the performance of the molding equipment during actual production. Therefore, when designing biomass molding equipment, *e.g.*, granulators and briquetting machines, the compression time interval at different compression speeds can be determined by referring to the abovementioned calculation method of the stress instantaneous drop time (Δt), so as to avoid the highest stress ranges, reduce the energy consumption and equipment damage caused by large compressive stress,

accurately control the compression frequency during the processing of biomass products, and improve the molding quality. Taking the cornstraw-potato residue mixture as an example, the relationship between the compression frequency (F) and the compression speed (V) was established by referring to the regression model, as shown in Fig. 7 and by Eq. 15,

$$F_c = \frac{60}{\Delta t} = \frac{60}{1.547e^{-V/87.375}+0.097} \qquad (15)$$

where F_c is the maximum compression frequency (number of compressions/min), Δt is the compression time interval, *i.e.* the stress instantaneous drop time (s), and V is the compression speed (mm/min).
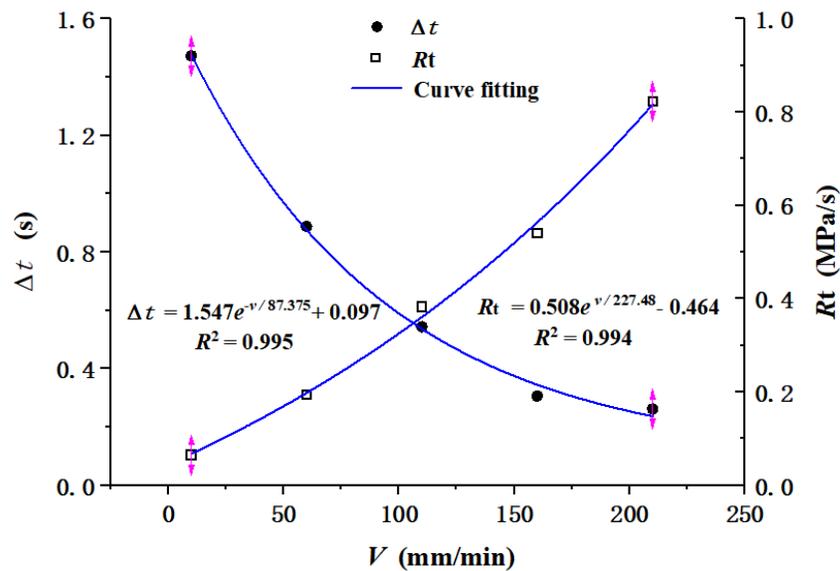
Fig. 7. Nonlinear regression analysis

     In actual production, the maximum compression frequency can be calculated according to the compression speed.

CONCLUSIONS

1. A fractional model was established to describe the stress instantaneous drop behavior during the stress relaxation process of a cornstraw-potato residue mixture and fit the stress relaxation curve. The determination coefficient (R^2) was greater than 0.99. It was found that the stress relaxation process of the cornstraw-potato residue mixture could be divided into the stress instantaneous drop stage and the stress decay stage. The characteristic parameters affecting the stress relaxation speed, *e.g.*, the stress instantaneous drop time (Δt) and the stress relaxation time ratio (R_t), were calculated. Furthermore, the reasons for the instantaneous stress drop during the cornstraw-potato residue mixture were analyzed.

2. The correlations between the compression speed (V) and the parameters of the stress relaxation model were obtained. A nonlinear regression analysis was carried out on the

Δt and R_t, which were significantly correlated with the compression speed (V). Additionally, the change rule that Δt exponentially decreased with the increase of V was determined, and a regression model was established (R^2 equals 0.995). On this basis, the relationship between the compression frequency (F) and the compression speed (V) was calculated. The result can provide a basis for determining the appropriate compression frequency when designing the molding equipment.

ACKNOWLEDGMENTS

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