Creep Characteristics of Corn Straw Particles Simulated Based on Burgers Model

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To simulate the creep characteristics of corn straw particles under uniaxial compression, a 6-level 2D model was created using PFC 2D software according to the actual uniaxial creep test, the grain size, and shape of corn straw particles. Five groups of controlled tests were designed by the control variable method to study the influence of Maxwell body parameters E_m, η_m; Kelvin body parameters E_k, η_k; and friction coefficient f on the creep curve of Burgers model. Results revealed that the creep characteristics of corn straw are affected by these 5 parameters. After multiple debugging by trial-and-error method, simulation parameters suitable for describing the creep characteristics of corn straw particles were obtained. The creep curves obtained by simulation under these parameters are consistent with those obtained by physical tests. It was shown that PFC software can not only study the creep characteristics of geotechnical materials, but also study the creep characteristics of agricultural fiber materials, which provides a reference for the subsequent rheological characteristics of biomass materials.

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INTRODUCTION

With the steady development of China's agriculture, grain production has increased each year, and a large amount of straw has also been produced. In recent years, the utilization percentage of straw in China has increased significantly, reaching 64%, but 250 million tons of straw are still burned on the spot or piled up in the field every year to be discarded, which not only wastes valuable biomass resources but also pollutes the environment (Ji 2015; Gong *et al*. 2019; Lv *et al*. 2023). Biomass energy represented by straw has always been an important energy source for human survival, and its consumption ranks No. 4 in the world after coal, oil, and natural gas. It occupies an important position in the energy system of various countries. With the gradual depletion of fossil energy, biomass energy as a renewable energy has attracted increasing attention from governments. However, biomass energy has the disadvantages of large volume, low unit energy density, and inconvenient transportation in the process of utilization. Therefore, to save storage and transportation costs, it is usually necessary to crush it and then perform dense compression treatment (Zhou *et al*. 2016). The crushed straw is different from industrial raw materials such as metals and ores, and its mechanical properties are nonlinear, viscoelastic, and anisotropic. It is granular before compression and lumpy after compression, which is difficult to solve by traditional continuum analysis methods, and its mechanical properties are closer to that of bulk bodies.

The discrete element method (DEM) is an explicit numerical method and a new method for analyzing the mechanics of discontinuous media proposed by Cundall in 1971 based on traditional Newtonian mechanics. The basic idea is to treat the material as a discontinuous medium composed of several particles. The transmission of force and torque between particles are evaluated by giving different models and parameters between particles, fully considering the inhomogeneity, discontinuity, and anisotropy inside the material. By contrast, the finite element method is commonly used to treat the material as a continuum. The material is regarded as if it is composed of continuous gapless particles, without considering the discontinuities of the material. Therefore, discrete elements make up for the shortcomings of the finite element method in dealing with discontinuous materials and restore the mechanical properties of discontinuous materials to the greatest extent from a microscopic perspective (Li *et al*. 2015; Gong *et al*. 2019). Wang and Hu (2018) used the PFC built-in Burgers model to create a three-dimensional model of the recycled asphalt mixture, simulating the uniaxial static creep test of the recycled asphalt mixture. Chen *et al.* (2021) constructed a model of crushed rock through PFC software and studied the creep characteristics of stacked gravel soil through virtual simulation experiments. At present, the discrete element method has been widely used in the rheological characteristics of bulk particles.

There are two major problems in the creep simulation of corn straw particles. First, corn straw is difficult to form a spherical ball after crushing because of its material composition. However, to simplify the model, most scholars often use spherical balls instead of corn straw particles, resulting in inconsistency between the simulation model and the actual sample. Second, because of the many parameters required for creep simulation test, each parameter has its own influence law, resulting in difficulty in calibration, which requires checking many parameters, which affects subsequent research. Therefore, to make the simulation model closer to the actual sample, the corn straw particles are divided into 6 grades according to the particle size and shape. The particle model of corn straw particles was established by PFC 2D software, and the influence of Burgers model parameters on creep curve was obtained by the control variable method, and then the creep model was calibrated by the obtained influence law.

EXPERIMENTAL

Materials and Equipment

The corn straw used in this test were produced from the suburbs of Hohhot City, Inner Mongolia, and were crushed by a crusher after natural air drying, and then bagged with standard screening to 0.25 to 3 mm particle sizes for later use. A sample of straw particles is shown in Fig. 1. A dryer was used to modulate the moisture by 10%. The bulk density of corn straw particles was measured as 96 kg/m^3, and the porosity of particles was 76% evaluated by excluding volume method.

The test equipment was a DDL-200 electronic universal testing machine jointly developed by Changchun Academy of Mechanical Sciences and German DOLI Company. The compression mold is composed of an indenter head, a barrel, a bottom plate, and a base, of which the diameter of the barrel was 15 mm, and the length was 100 mm. The electronic universal testing machine and the mold are shown in Fig. 2.

Fig. 1. A sample of straw particles

Fig. 2. Compression equipment and the mold

Method

In this test, the prepared corn straw particle sample was evenly placed into the mold, parallel to the upper surface of the indenter to the upper end of the mold. Then, it was compressed with the electronic universal testing machine, and the specific test parameters used are shown in Table 1. The experimental data measured by the electronic universal testing machine was saved in .xlsx format. The experiment was performed three times, and the median value was selected as the test results.

Table 1. Test Conditions

Total Test Time (s)	Holding Pressure Time (s)	Load or Unloading Speed (mm/min)	Feed Amount (g)	Pressure (kN)
50	20	400	4.2	17

Results

The experimental data were imported into Origin to generate a creep curve, as shown in Fig. 3. It can be seen from Fig. 3 that the creep curve of corn straw particles can be divided into three stages. The first stage is the loading stage, which is a uniform deformation process, so the deformation of the specimen linearly increases. The second stage is the holding pressure stage. When the pressure reaches the specified value of the test, it enters the holding pressure stage. During that stage the deformation rate is greatly reduced compared with the first stage, and its curve is close to level. The third stage is the creep unloading stage, during which the change trend is more closely in line with the change law of creep test unloading stage.

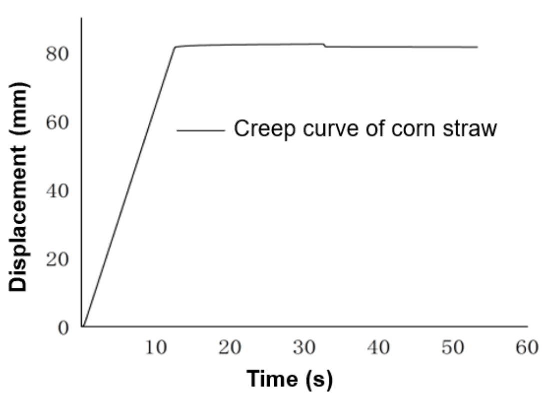

Fig. 3. Creep curve of corn straw

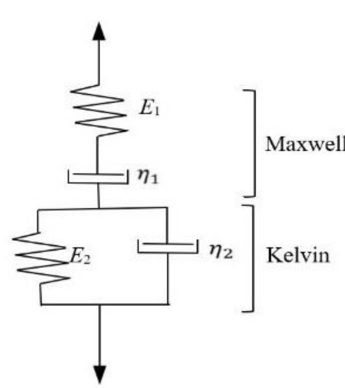

Fig. 4. Macro Burgers model

CONSTRUCTION OF VIRTUAL MODEL FOR CREEP TEST

Macroscopic Burgers Model

To describe the creep characteristics of corn straw particles, various models consisting of springs and damping in series or parallel are usually used to obtain different constitutive equations to describe the corresponding creep characteristics. The Burgers model, as shown in Fig. 4, can well describe the creep characteristics of the holding pressure stage of agricultural fiber materials, such as corn straw, which consists of a Maxwell body and a Kelvin body in series (Ma *et al*. 2017, 2022; Maraldi *et al*. 2018; Xue *et al*. 2021; Wang *et al*. 2022).

The constitutive equation of the macroscopic Burgers model is,

$$\varepsilon(t) = \frac{\sigma_0}{E_1} + \frac{\varepsilon_0}{E_2}(1 - e^{-\frac{t}{\tau}}) + \frac{\sigma_0}{\eta_1}t \tag{1}$$

where $\varepsilon(t)$ is strain (mm), σ_0 is constant stress (N/mm^2), E_1 and E_2 is coefficient of elasticity (N/mm^2), τ is delay time (s), and $\tau = \eta_2/E_2$, η_1 and η_2 are viscosity coefficient (N·s/mm^2), and t is time of action (s).

Microscopic Burgers Model

In PFC 2D, the various mechanical properties of materials are represented by assigning various contact models between particles or between particles and walls. Common models include sliding model, contact model, and contact bonding model, but none of these three models can be used to describe the creep characteristics of corn straw particles. Therefore, the Burgers model built into PFC 2D software was chosen to describe the creep behavior of corn straw particles. The microscopic Burgers model built in the PFC software is shown in Fig. 5. The microscopic Burgers model is slightly different from the macroscopic Burgers model. The microscopic Burgers model consists of a tangential and a normal Burgers model, and a friction block element is connected in series on the tangential Burgers model (Behzad *et al.* 2018; Em-Udom and Pisutha-Arnond 2018; Liu 2022; Ma *et al*. 2022).

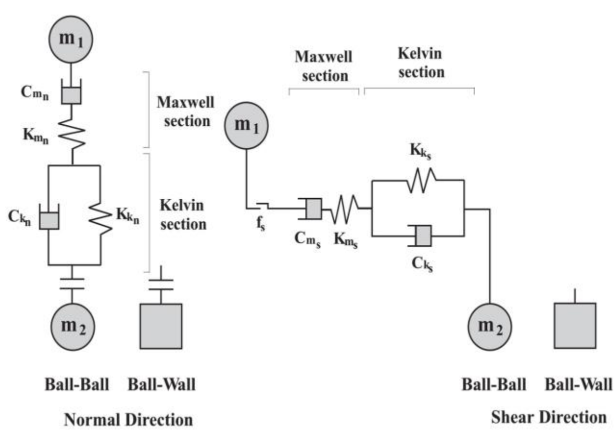

Fig. 5. Microscopic Burgers model

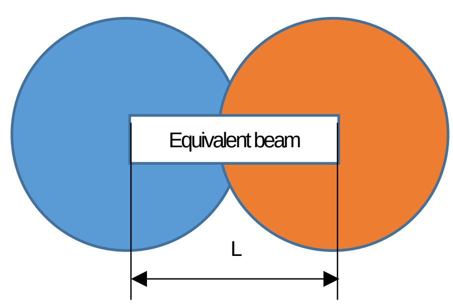

Fig. 6. Equivalent beam at the contact point

From Fig. 5, it can be seen that the microscopic Burgers model consists of 9 parameters: C_{mn}, K_{mn}, C_{kn}, K_{kn}, C_{ms}, K_{ms}, K_{ks}, C_{ks}, and f. The help file of PFC software and the research of Tian *et al*. (2008) show that the contact behavior between two particles in the Burgers model can be replaced by an equivalent beam as shown in Fig. 6, and based on this assumption, the relationship between microscopic parameters and macro parameters can be derived. These parameters are defined as Eqs. 2 through 9 and are as follows,

$$K_{kn} = \frac{E_2 A}{L} = E_2 L \tag{2}$$

$$C_{kn} = \frac{\eta_2 A}{L} = \eta_2 L \tag{3}$$

$$K_{kn} = \frac{E_1 A}{L} = E_1 L \tag{4}$$

$$C_{kn} = \frac{\eta_1 A}{L} = \eta_1 L \tag{5}$$

$$K_{ks} = \frac{K_{kn}}{2(1+v)} = \frac{E_2 L}{2(1+v)} \tag{6}$$

$$C_{ks} = \frac{C_{kn}}{2(1+v)} = \frac{\eta_2 L}{2(1+v)} \tag{7}$$

$$K_{ms} = \frac{K_{mn}}{2(1+v)} = \frac{E_1 L}{2(1+v)} \tag{8}$$

$$C_{ms} = \frac{C_{mn}}{2(1+v)} = \frac{\eta_1 L}{2(1+v)} \tag{9}$$

where A is the cross-sectional area connecting the two particle equivalent beams (mm^2), L is the length of the beam connecting the two particles, that is, the sum of the two particle radii (mm), and v is the Poisson's ratio.

In the actual model, due to the complexity and randomness of the model, only the reference values of the parameters of the microscopic Burgers model can be obtained. Because the error is large and cannot be used directly, it is necessary to calibrate the obtained reference value until the fitting curve of the creep test is basically fitted to the actual test curve.

Building Model

The creep characteristics of materials are closely related to the quality and water content of materials, the shape and diameter of particles, and the stress magnitude and other basic mechanical properties of materials. However, agricultural fiber materials, such as corn straw are difficult to present regular spherical shape after crushing because of their composition and structure, most of which are presented in long strips, short cobs, blocks, and balls, and the particle diameter distribution is not uniform.

Therefore, to better simulate the creep experiment of corn straw, it is necessary to classify the crushed corn straw particles, divide them into several particles of different sizes, and calculate their respective proportions. It has been found that the shape of particles in each particle size range is clearly different. In 2 to 3 mm, it is mainly long strips, short rods, and blocks. In the range of 1 to 2 mm, it is mainly short rods and blocks. In the particle size range of 0.25 to 1 mm, because the particles are too small and close to spherical, they are classified as sphere. According to the particle size and shape of the particles, the corn straw particles can be divided into 6 grades, and the proportion of each grade is shown in Table 2.

Table 2. Grades of Corn Straw Particles

Particle Length (mm)	0.25 to 1	1 to 2		2 to 3		
Particle shape	Sphere	Short Rods	Blocks	Long Strips	Short Rods	Blocks
Mass ratio (%)	30	13	18	15	13	11

Referring to the particle size and shape of corn straw particles, the clump command of PFC software is used to generate irregular clusters of corn straw particles. The corn straw particles of various shapes and the corresponding models are shown in Figs. 7 to 9.

Fig. 7. Long strips of corn straw particles and simulation model

Fig. 8. Short rods of corn straw particles and simulation model

Fig. 9. Blocks of corn straw particles and simulation model

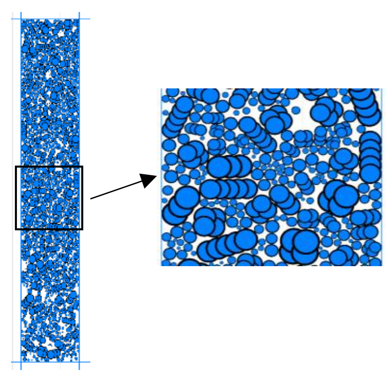

Fig. 10. Simulation test model

When generating particles, the particle densities of all species are treated as the same, *i.e.*, the particle mass ratio shown in Table 2 is equivalent to the volume fraction, and the particle sizes within each grade are randomly distributed. Using PFC 2D software, the simulation model shown in Fig. 10 is generated at the scale specified in Table 2 for each grade.

CALIBRATION OF BURGERS MODEL PARAMETERS

The macro mechanical parameters of the Burgers model cannot be used directly in the PFC software. Although the macro and microscopic parameter conversion formulas described earlier in this paper can be used to obtain microscopic parameters, there is a significant error, such that the values can only be used as a reference value for calibration. Therefore, to make the created simulation model consistent with the macro mechanical characteristics of the test specimen, the influence of the microscopic Burgers model parameters on the creep curve of the holding pressure stage is studied by the control variable method, and the microscopic mechanical parameters in the numerical model are gradually adjusted through the trial-and-error method, so that the calibrated numerical model achieves the same macro mechanical performance as the specimen.

Rheological Tests and Parameter Setting of The Burgers Model

To determine the influence of Burgers model parameters on the creep curve of the holding pressure stage, the data were first imported into the Matlab software to generate the creep curve of the specimen, as shown in Fig. 11. The constitutive equation of macroscopic Burgers was used to fit the data in the holding pressure stage to obtain the corresponding 4 macro parameters.

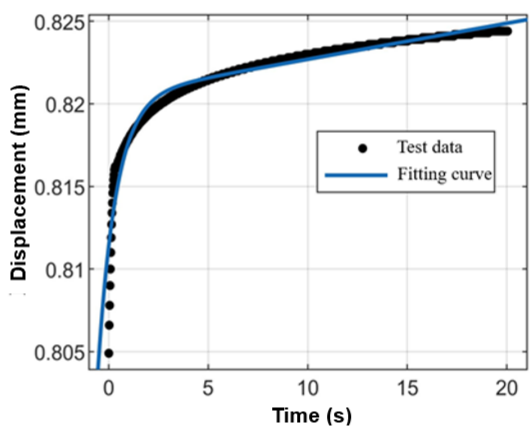

Fig. 11. Creep curve fitting plot

Using the conversion formulas discussed earlier in this paper, the macro parameters obtained by fitting were converted into microscopic Burgers model parameters. Taking the converted parameters as the reference value, the influence of the parameters of the microscopic Burgers model on the creep curve was analyzed by the control variable method. The normal parameters in the model were set to $2(1+v)$ times of the tangential parameters. According to the research, the Poisson's ratio ν of corn straw particles is 0.3 (Zhang *et al.* 2019). So, to simplify the analysis, the number of parameters was reduced to 5, namely: E_m, η_m, E_k, η_k, f.

For these five parameters, a total of five controlled trials were designed, as shown in Table 3. Only 1 parameter was changed in each group of control experiments, and the other parameters remained unchanged, so the influence of 5 Burgers model parameters on the creep characteristics of the simulation model was studied separately (Yang *et al.* 2015; Tian and Sun 2019; Ji *et al.* 2021).

Table 3. Parameter Values of the Control Tests

Groups	Test Parameters				
	Maxwell Body		Kelvin Body		f
	E_m ($N \cdot m^{-1}$)	η_m ($N \cdot s \cdot m^{-1}$)	E_k ($N \cdot m^{-1}$)	η_K ($N \cdot s \cdot m^{-1}$)	
1	1×10^7	6×10^9	3×10^7	6×10^7	0.5
	3.5×10^7				
	6×10^7				
2	3.5×10^7	1×10^9	3×10^7	6×10^7	0.5
		6×10^9			
		1.1×10^{10}			
3	3.5×10^7	6×10^9	1×10^7	6×10^7	0.5
			3×10^7		
			5×10^7		
4	3.5×10^7	6×10^9	3×10^7	1×10^7	0.5
				6×10^7	
				1×10^8	
5	3.5×10^7	6×10^9	3×10^7	6×10^7	0.2
					0.5
					0.8

Influence of Burgers Model Parameters on Rheological Characteristics

The influence of E_m on the creep curve of the holding pressure stage

Group 1 of controlled tests mainly studied the influence of the elastic coefficient E_m in Maxwell body on the creep curve of the holding pressure stage. When E_m takes different values, the creep curve of the holding pressure stage is obtained as shown in Fig. 12.

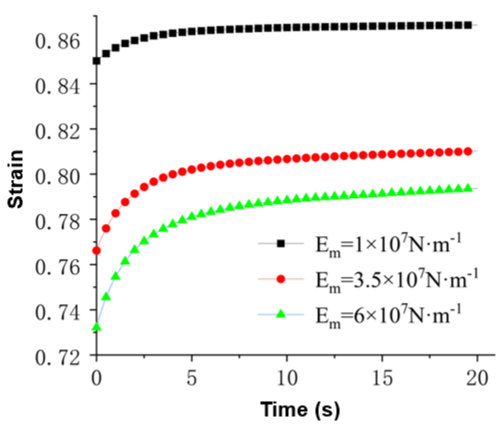

Fig. 12. Effect on elasticity coefficient E_m of Maxwell body

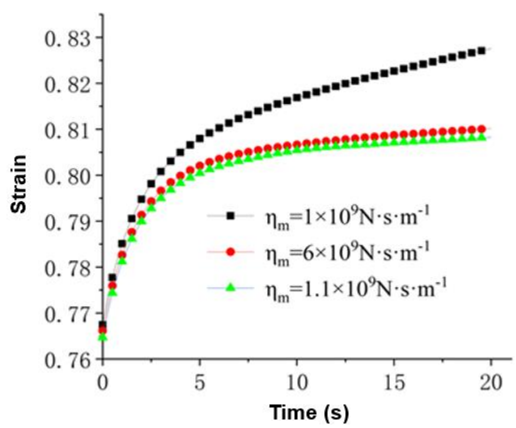

Fig. 13. Effect on viscosity coefficient η_m of Maxwell body

According to the variation law of the creep curve in the figure, E_m mainly affects the instantaneous strain variable, initial creep variable, and initial creep rate of the Burgers model. When entering the holding pressure stage, the instantaneous strain variable of the model decreases with the increase of E_m, and the decrease gradually slows down. In the initial creep stage, the starting creep and the initial creep rate increase with the increase of E_m. There is a clear transition between the initial creep phase and the stable creep phase.

In the stable creep stage, the stable creep rate does not change significantly with the increase of E_m.

The influence of η_m on the creep curve of the holding pressure stage

Group 2 of controlled tests mainly studied the effect of Maxwell body viscosity coefficient η_m. When η_m is taken at different values, the creep curve of the holding pressure stage is obtained, as shown in Fig. 13.

According to the change law of the creep curve in the figure, η_m mainly affects the stable creep rate of the Burgers model, and when entering the holding pressure stage, the instantaneous strain variable does not change significantly with the increase of η_m. In the initial creep stage, the initial creep and the initial creep rate do not change significantly with the increase of η_m. There is a significant transition between the initial creep stage and the stable creep stage, and after entering the stable creep stage, the stable creep rate decreases with the increase of η_m. The variation range is large between $1 \times 10^9 \sim 6 \times 10^9$ $N{\cdot}s{\cdot}m^{-1}$, and the variation between $6 \times 10^9 \sim 1.1 \times 10^{10}$ $N{\cdot}s{\cdot}m^{-1}$ is small.

The influence of E_k on the creep curve of the holding pressure stage

Group 3 controlled test focused on the effect of Kelvin body elasticity coefficient E_k. When E_k is taken at different values, the creep curve of the holding pressure phase is obtained as shown in Fig. 14.

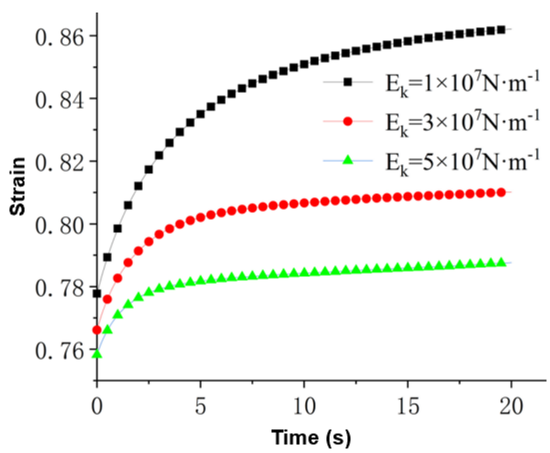

Fig. 14. Effect on elasticity coefficient E_k of Kelvin body

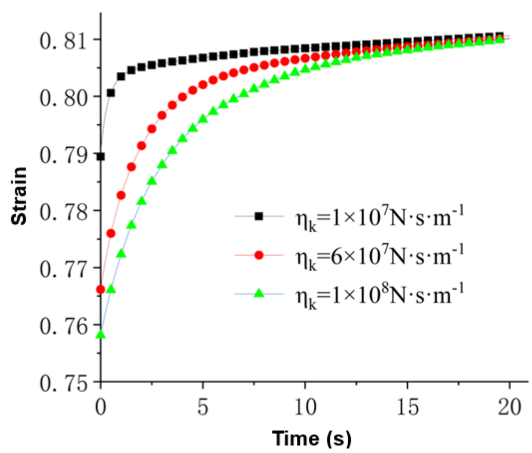

Fig. 15. Effect on viscosity coefficient η_k of Kelvin body

From the figure, it can be seen that η_k mainly affects the instantaneous strain variable, initial creep variable, and initial creep rate of the Burgers model. When entering the holding pressure state, the instantaneous strain variable rate decreases with the increase of η_k, and the reduction trend gradually slows down. In the initial creep stage, the initial creep increases with the increase of η_k, and the initial creep rate decreases with the increase of η_k. There is a significant transition between the initial creep phase and the stable creep phase, and after entering the stable creep phase, the stable creep rate of the three curves do not change significantly and the total strain variable of the virtual specimen is almost the same.

The influence of f on the creep curve of the holding pressure stage

Group 5 controlled test focused on the effect of friction factor *f*. When different values are taken for *f*, the creep curve of the holding pressure stage is obtained as shown in Fig. 16.

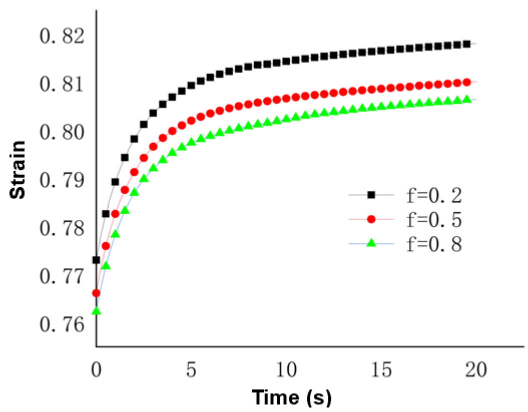

Fig. 16. Effect on friction factor *f* of Kelvin body

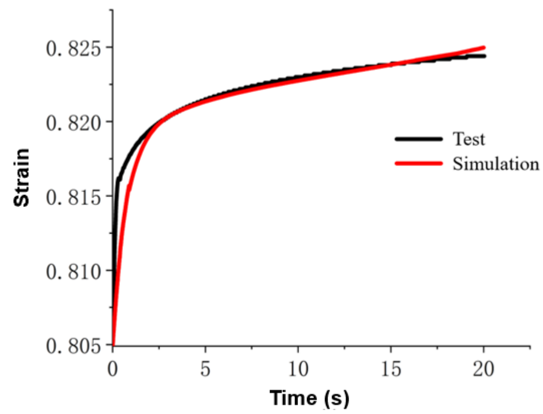

Fig. 17. Comparison of simulation test curve and physical test curve

According to the figure, *f* mainly affects the instantaneous strain variable of the Burgers model. When entering the holding pressure state, the instantaneous strain variable decreases with the increase of *f*. In the initial creep stage, the initial creep and the initial creep rate do not change significantly with the increase of *f*. There is a significant transition between the initial creep stage and the stable creep stage, and after entering the stable creep stage, the stable creep rate does not change significantly with the increase of *f*.

Through analyzing the above 5 groups of control tests, the influence of each parameter of the Burgers model on the rheological characteristics of the specimen in the holding pressure stage can be obtained, as shown in Table 4 in detail.

Table 4. Influence of Burgers Model Parameters on Creep Characteristics

Rheological C	Maxwell Body		Kelvin Body		Friction Factor *f*
	Elastic Coefficient E_m	Viscosity Coefficient η_m	Elastic Coefficient E_k	Viscosity Coefficient η_k	
Instantaneous strain variable	-		-	-	-
Initial creep	+		-	+	
Initial creep rate	+		-	-	
Stable creep rate		-			
"+" Means positive correlation, and "-" means negative correlation					

Parameter Calibration

The trial-and-error method was used to debug the simulation parameters several times, and a set of parameters as shown in Table 5 was obtained, and the error value was within the allowable range.

Table 5. Simulation Parameters

Action Direction	Maxwell Body		Kelvin Body		Friction Factor f
	Elastic Coefficient E_m ($N \cdot m^{-1}$)	Viscosity Coefficient η_m ($N \cdot s \cdot m^{-1}$)	Elastic Coefficient E_k ($N \cdot m^{-1}$)	Viscosity Coefficient η_K ($N \cdot s \cdot m^{-1}$)	
Normal	2.147×10^7	5×10^9	3.6×10^7	2.6×10^7	0.5
Tangential	8.258×10^6	1.923×10^9	1.385×10^7	1×10^7	

Figure 17 shows the test value curve and simulation value curve of corn straw creep test. It can be seen from the figure that the error of the two is slightly larger in the initial creep stage, and the maximum error value is less than 2%. The reasons for this are as follows: First, in the early stage of the initial creep stage, due to the loading speed and weight of the compression device, it takes multiple servos to stabilize the pressure, and the simulation model can stabilize the model pressure almost instantly; Second, the particle size uniformity, particle shape, and porosity of the model are different from the actual sample. However, in the stable creep stage, because the porosity and pressure are basically stable, the error between the two is minimal and the values almost coincide.

CONCLUSIONS

To study the creep characteristics of corn straw particles in the holding pressure stage, the Burgers model built in PFC software was used to simulate the creep experiment in uniaxial compression. The influence of the parameters E_m, η_m, E_k, η_k, and f on the creep curve of corn straw particles in the holding pressure stage was analyzed by the control variable method, and then the parameter values were gradually adjusted until they were basically consistent with the physical test data by trial-and-error method. The following conclusions were obtained.

1. The influence of Burgers model parameters on the creep curve of corn straw holding pressure stage can be found by analyzing the control variable method: The creep characteristics of corn straw are affected by the 5 parameters of E_m, η_m, E_k, η_k, and f of the Burgers model. The instantaneous strain variable was negatively correlated with E_m, E_k, η_k, and f. The starting creep is negatively correlated with E_k and positively correlated with E_m and η_k. The initial creep rate is negatively correlated with η_k and E_k, and positively correlated with E_m. The stable creep rate is negatively correlated with η_m. Its influence law can be used to calibrate Burgers model parameters.
2. A set of parameter values are obtained after multiple debugging by trial-and-error method. The simulation test according to these parameters is close to the creep test curve obtained by the physical test, and the maximum error value is less than 2%, which meets the error requirements. It was shown that PFC software can not only be used to simulate creep experiments of geotechnical materials, but also for creep simulation experiments of agricultural fiber materials, which provides a reference for subsequent rheological characteristics of biomass materials.

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