

Finite element analysis modeling research on the compression process of cotton fiber assembly

Minjun Xu¹, Xiaochuan Chen¹ , Jun Wang¹  and Yong Li²

Abstract

In order to analyze the compressive stress state of a cotton fiber assembly in the compression process, a new cotton fiber assembly model, the tetrakaidecahedral porous cotton fiber assembly model, is presented based on the idea of three-dimensional open-cell foam material modeling. Based on the model, the compression process of cotton fiber assembly is analyzed using the finite element method. The change in the compressive stress of the cotton fiber assembly in the compression process is successfully described. The measurement method of compressive modulus of the cotton fiber assembly is also studied, and the relation between compressive modulus and relative density of the cotton fiber assembly is determined. Finally, the effect of different moisture regain on compressive stress of the cotton fiber assembly is analyzed, and the reference value of moisture regain in the cotton baling process is given. The results show that the simulation results are consistent with the actual situation. Therefore, the established model of cotton fiber assembly has validity.

Keywords

cotton fiber assembly, compression, finite element method, tetrakaidecahedral model, moisture regain

Cotton is an important material in the textile industry, and is used within fiber assembly. Throughout the picking, storage, and processing of cotton, the cotton fiber assembly needs to be repeatedly compressed and loosened. In the process of compression, the actions of external forces will lead to changes in the properties of the cotton fiber assembly. If the compressive stress is too large, the cotton fibers may form indentations or even crack in contact with each other, which will change their mechanical strength and affect the quality of the cotton.

The mechanical behavior of fiber assemblies under the application and release of pressure has been discussed by scholars for more than half a century. In the process of compression, the internal fiber movements of the fiber assembly are very complex and irregular. The compression behavior of a fiber assembly is composed of the bending, buckling, tensile, torsion, friction, sliding, and compression effects of a large number of fibers. It is also affected by the fiber filling density, fiber arrangement, fiber physical properties, surface properties, and related mechanical properties.¹

Due to the complexity of the compression behavior of the cotton fiber assembly, the finite element method is used to simulate the compression process. Therefore, a reasonable finite element analysis model must be established. However, there are few studies on the model of the cotton fiber assembly, most of which are limited to the mechanical model of a single cotton fiber. Smith and Roberts present a two-dimensional dynamics model of fibers in an accelerating laminar air flow.² This model is composed of a series of spherical elements connected by massless rigid rods. The nonlinear model equation of each fiber includes the effects of inertia, air drag, and flexural rigidity. Yamamoto and Matsuoka

¹Donghua University, Shanghai, China

²Tarim University, Xinjiang, China

Corresponding author:

Xiaochuan Chen, Donghua University 2999#Rinmin North Road, Songjiang DC, Donghua University Shanghai, 201620 China.
Email: xcchen@dhu.edu.cn

consider that the fiber is made up of a series of spheres which are aligned and bonded to their neighbors.³ Each pair of bonded spheres can stretch, bend, and twist. The three parameters of stretching, bending, and twisting constants can express the strength of bonding between the spheres and the flexibility of the fibers. Kong and Platfoot take cotton fiber to be a two-dimensional computational fluid dynamics (CFD) flexible chain model that is connected by dispersed nodes, without considering mass.⁴ By using this model, they simulate and analyze the influence of yarn inside the transportation zone of a spinning machine. Based on the modeling idea of composite laminate, Xiaochuan and Wang⁵ put forward a laminated cotton model, in which cotton fibers are laid at a particular angle on a two-dimensional plane, and then layers of cotton fibers are stacked to form a cotton fiber assembly model. Based on this model, the force of cotton fiber being broken in the ginning process is successfully simulated. However, the above mechanical model of cotton fiber is difficult to apply for the analysis of the compression process. It is necessary to find a new method to establish a model.

Open-cell foam materials have been widely studied and applied because of their unique properties and advantages. Gibson and Ashby, based on a compression deformation study of the unit cell model, put forward the collapse theory of foam materials. They deduce the analytical equation of the relation between the mechanical properties of foam materials and the relative density.⁶ Through a compression test, Yong et al.⁷ find that the compressibility of a cotton fiber assembly is very similar to that of a porous foam material such as porous polyurethane foam and foamed aluminum. The compressibility of a cotton fiber assembly can be analyzed by using the research method used for porous foam materials. Many scholars have studied the mechanical model of open-cell foam materials. Different from closed-cell foam materials, the gas phase in the open-cell foam material is connected. For low-density materials, the single cell body generally has a polyhedral shape, and the connected spatial pillar network structure is formed.⁸ Gent and Thomas propose the elastic pillar network model and the cube structure model, and give prediction results for the elastic modulus.^{9,10} Ko proposes two kinds of five-sided dodecahedron models,¹¹ and obtains different prediction equations for elastic modulus of foam materials. Gibson and Ashby introduce the mechanism of bending deformation through the cubic staggered model.¹² The tetrakaidecahedral model proposed by Kelvin is considered to be the model with the smallest pore surface area per unit volume.¹³ Warren and Kraynik study the tetrakaidecahedral model of open-cell foam materials, and obtain the relation between the volume

modulus of foam materials and the pore microstructure.¹⁴ Zhu et al. use a tetrakaidecahedral structure model to analyze the elastic properties of open-cell foam materials.¹⁵ Based on the idea of open-cell foam material modeling, this paper proposes a new cotton fiber assembly model, which is applied to the analysis of the compression process of the cotton fiber assembly.

In addition, the compressive modulus of the cotton fiber assembly is an indispensable basic material parameter for finite element analysis. However, there are few reports about the compressive modulus of the cotton fiber assembly. Through compression test and data fitting, Yong et al. establish the analytic equation of the relation between compressive stress and the relative density of the cotton fiber assembly.⁷ In order to simplify the problem, Van Wyk assumes that bending is the only important form of fiber movement,¹⁶ thus ignoring the twisting, slipping, and stretching, while ignoring the fiber curl factor, and therefore regard the fiber as a straight rod. Second, he assumes that the fibers are randomly oriented and uniformly stacked, and that there is no friction between fibers. The pressure-volume relation of the fiber assembly in the cyclic process of "compression and release" is deduced. Later scholars, while adopting van Wyk's model, point out the defects in the theory: Most of the compression curve of the fiber assembly does not conform to van Wyk's pressure-volume curve;¹⁷ the theory fails to find the unrecoverable strain and the hysteresis phenomenon in the compression process;¹⁸ and due to the constant value K in the pressure-volume relation of fiber assembly, the difference in compression characteristics between different types of fibers cannot be explained.¹⁹ Therefore, the theory and equation based on some simplified assumptions are still different from the actual compression situation, which needs further modification and improvement.

Establishment of a macroscopic finite element model for the compression process of a cotton fiber assembly

A cotton fiber assembly is a kind of irregular flexible structure, with a large number of internal pores, as shown in Figure 1. The cotton fiber assembly consists of the accumulation of a large number of cotton fibers, forming a roughly irregular ellipsoid. Cotton is formed by a large number of random winding fibers with pores between the inner fibers of the cotton. A cotton fiber assembly is fluffy, soft, and elastic. The arrangement of fibers has almost no law, and the spatial relationship between fibers is very complex.

In order to simplify the problem and facilitate the calculation, it is necessary to make some assumptions



Figure 1. Cotton fiber assembly in a natural state.

about the problem. The following assumptions are used in the simulation of compression behavior:

1. It is assumed that the cotton fiber assembly is a flexible structure with a large number of holes. From the perspective of material composition, the cotton fiber assembly is regarded as a structure based on the cotton fiber bundles. From the perspective of geometric structure, the large number of holes in the cotton fiber assembly is assumed.
2. It is assumed that the pore shape is regular and evenly distributed. The pore-filling method of three-dimensional porous materials is composed of three-dimensional polyhedrons, and the most common polyhedron models include tetrahedrons, octahedrons, dodecahedrons, and tetrakaidecahedrons.²⁰ The tetrakaidecahedral model is considered to have the highest porosity with the minimum pore surface area per unit volume. In addition, if the tetrakaidecahedral unit cell model is regularly arranged in a body-centered cubic arrangement, it can completely fill the entire three-dimensional space.²¹

Based on the idea of three-dimensional porous material modeling, a new cotton fiber assembly model, namely the tetrakaidecahedral porous cotton fiber assembly model, is presented. The tetrakaidecahedral geometric unicellular model consists of 8 regular hexagons and 6 regular quadrilaterals, and contains 24 vertices and 36 equal-length prisms, as shown in Figure 2(a). With a square as the cross-section shape of the prisms, the unicellular model is arranged regularly in the form of a body-centered cubic arrangement; in order to reduce the subsequent finite element

calculation, only a $2 \times 2 \times 2$ cotton fiber assembly model is established, as shown in Figure 2(b).

For the $2 \times 2 \times 2$ tetrakaidecahedral cotton fiber assembly model, there are 9 tetrakaidecahedral unicellular structures and 240 prisms. The relative density of the tetrakaidecahedral cotton fiber assembly model can be expressed as follows:

$$\frac{\rho}{\rho_0} = \frac{15 \times A}{8\sqrt{2} \times L^2} \quad (1)$$

where ρ is the overall density of the cotton fiber assembly; ρ_0 is the density of the cotton fiber matrix; A is the sectional area of the prism; L is the length of the prism.

Measurement of compressive modulus

The cotton fiber assembly is formed by a large number of cotton fibers that are wound and piled up. In the whole process of processing and using cotton, its mechanical properties are expressed in the form of the aggregate. When the properties of deformation, stress distribution, and compressive stress of cotton fiber assembly are studied by theoretical analysis or numerical simulation, the elastic modulus of the cotton fiber assembly is an indispensable basic parameter. Cotton fiber assembly is loose, and cannot bear pressure under unconfined condition. Therefore, when studying the compressive behavior of a cotton fiber assembly, only the laterally confined elastic modulus is meaningful. The modulus of a material under compression deformation is called the compressive modulus, which is defined as the ratio of stress to corresponding strain when the material is subjected to unidirectional or uniaxial compression. However, there are few related researches on the compressive modulus of cotton fiber assembly. Therefore, in this section, the compressive modulus of the cotton fiber assembly is measured through a compression test, and applied to the finite element analysis.

Test materials and equipment

The test material: No.37 Xinluzhong hand-picked raw cotton, Alar, Xinjiang, China.

The test instruments include a universal testing machine, pressure sensor (FSR400), electronic scale (Shanghai Anting Scientific Instrument Factory, Shanghai, China), and humidity chamber Wenzhou Darong Textile Instrument Co., Ltd., Wenzhou, China). The universal testing machine is produced by Shanghai Zhuoji Instrument Equipment co., LTD (Shanghai Anting Scientific Instrument Factory Shanghai, China). The effective force range is 0–5000 N, and the adjustable range of the test speed is 0–500 mm/min. The effective measuring range of the

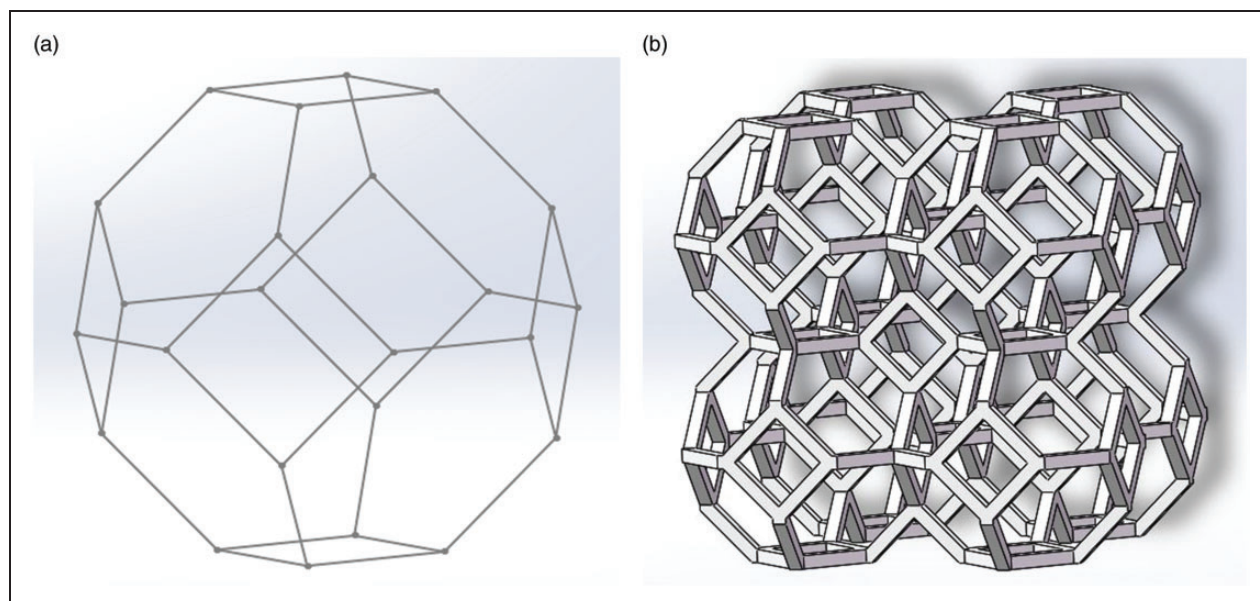


Figure 2. Tetraikaidecahedral model: (a) tetraikaidecahedral geometric unicellular model; (b) tetraikaidecahedral cotton fiber assembly model.

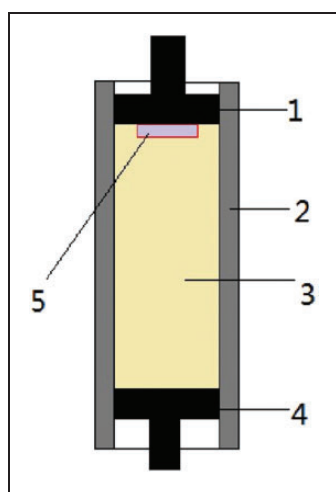


Figure 3. Schematic diagram of the cotton fiber assembly compression test. 1 = dynamic head; 2 = cylinder wall; 3 = sample cotton fiber assembly; 4 = static head; 5 = pressure sensors.

pressure sensor (Interlink Electronics, USA) is 0.01–20 N, and the sensor's sensing area diameter is 5 mm. The schematic diagram of the test is shown in Figure 3.

Test process

This is the uniaxial compression test of a cotton fiber assembly in a laterally confined condition. By measuring the relation between the axial strain and the axial compressive stress and the relation between the axial stress and the relative density of the cotton fiber

assembly, the compressive modulus of the cotton fiber assembly can be calculated further.

A 160 g cotton fiber assembly sample with 6.6% moisture regain is loaded into a cylinder (the height and diameter of the cylinder are 300 mm and 104 mm respectively) and placed on the platform of universal testing machine with a loading speed of 100 mm/min. Room temperature is 14°C and relative humidity is 30%. The pressure data are collected through the upper pressure sensor, and the value of the axial compressive stress of the cotton fiber assembly can be calculated according to equation (2):

$$P = \frac{F}{S} \quad (2)$$

where P is the axial compressive stress of the cotton fiber assembly; F is the pressure collected by the pressure sensor; and S is the contact area between the upper pressure head and the cotton fiber assembly.

Test data of compressive stress of the cotton fiber assembly

The relative density of the cotton fiber assembly is defined as the ratio of the density of the cotton fiber assembly to the density of the cotton fiber matrix. During the compression process, the relative density can be expressed as in equation (3):

$$\frac{\rho}{\rho_0} = \frac{m}{\rho_0 S(1 - \varepsilon)H} = \frac{1}{1 + e} \quad (3)$$

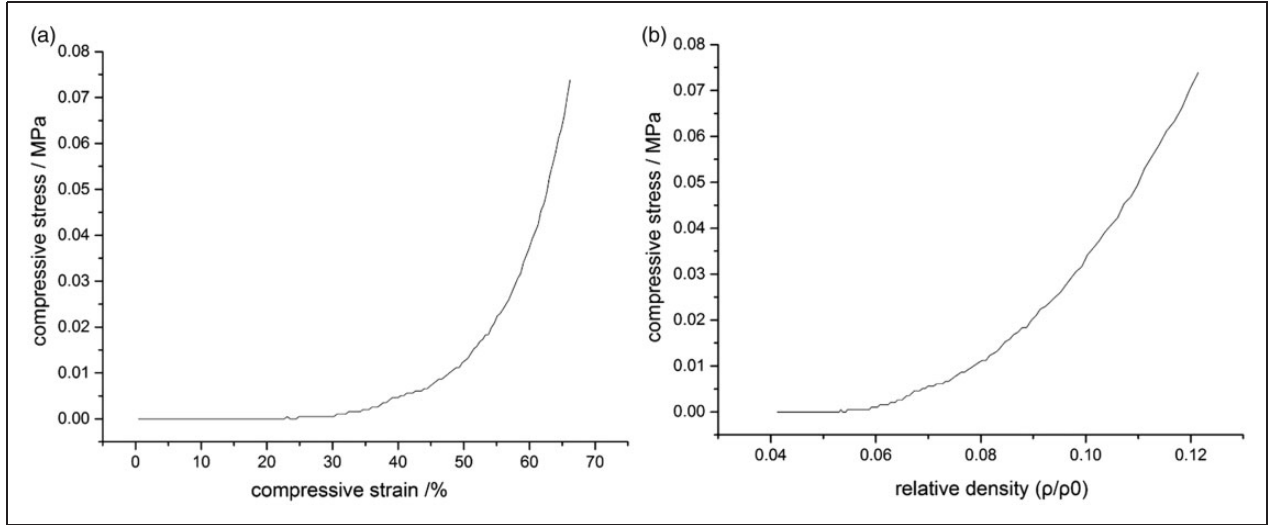


Figure 4. Test data of compressive stress of the cotton fiber assembly when the moisture regain is 6.6%. (a) Curve of compressive stress-strain; (b) curve of compressive stress-relative density.

where ρ is the overall density of the cotton fiber assembly; ρ_0 is the density of the cotton fiber matrix (the relative data show that the average density of the cotton fiber matrix is about 1530 kg/m^3); m is the sample quality of the cotton fiber assembly; S is the base area of the cylinder; ε is the compression strain of the cotton fiber assembly; H is the initial compression height of the cotton fiber assembly sample; and e is the void ratio, which is defined as the ratio of pore volume to the volume of the cotton fiber matrix.

Based on the test data, the compressive stress-strain curve and the compressive stress-relative density curve are shown in Figure 4, where the moisture regain of the cotton fiber assembly is 6.6%.

Figure 4 shows that in the early stage of compression, the compression curve of the cotton fiber assembly is relatively smooth. In this compression stage, the deformation of the cotton fiber assembly is mainly seen in the reduction of the internal pore size and slipping between fibers; the increase of compressive stress is relatively slow. In the later stage of compression, the trend of compressive stress of the cotton fiber assembly grows. In this compression stage, the cotton fiber assembly undergoes elastoplastic deformation and presents significant hardening characteristics; the compressive stress increases rapidly. When the compression strain reaches about 65% and the relative density reaches about 0.12, the compressive stress of the cotton fiber assembly reaches about 0.075 MPa.

Calculation of compressive modulus

The compression test shows that the compressive stress curves of the cotton fiber assembly are very similar to porous foam materials such as porous polyurethane

foam, foamed aluminum, and other foam materials. Therefore, this section attempts to use the theory of compression deformation of foam materials to analyze the relation between compression stress and strain of the cotton fiber assembly; this way, the compressive modulus of the cotton fiber assembly can be refined further. The reliability of the compressive modulus is verified by comparing a finite element simulation with the test data.

Gibson and Ashby⁶ analyzed the compressive deformation characteristics of foam materials and put forward the collapse theory of foam materials as given in equation (4):

$$\frac{\sigma^*}{\sigma_s} = A \left(\frac{\rho^*}{\rho_s} \right)^B \quad (4)$$

where σ^* is the plastic collapse strength of the foam material; ρ^* is the plastic collapse density of the foam material; σ_s is the yield strength of the foam matrix material; ρ_s is the density of the foam matrix material; and A and B are the constants relating to the matrix material. Equation (4) shows that the compressive strength of the foam material has a linear relationship with the power exponent of the relative density of the material. Moreover, based on the geometric model of the porous foam material, the equation for predicting the elastic modulus of the cubic model of a porous foam material was derived as equation (5):

$$\frac{E^*}{E_s} = C \left(\frac{\rho^*}{\rho_s} \right)^2 \quad (5)$$

where E^* is the elastic modulus of the foam material; E_s is the elastic modulus of the foam matrix material; ρ^* is

the plastic collapse density of the foam material; ρ_s is the density of the foam matrix material; and C is the material geometric proportionality constant.

Based on the collapse theory, an analytical equation for the relation between the relative density of the cotton fiber assembly and the compressive stress is established as equation (6):

$$\frac{P}{P_0} = a \left(\frac{\rho}{\rho_0} \right)^b \quad (6)$$

where P is the compressive stress of the cotton fiber assembly; a and b are constants; ρ/ρ_0 is the relative density of the cotton fiber assembly; and P_0 is the collapse strength of the cotton fiber matrix, which is denoted as a constant. Then, equation (6) can be converted into equation (7):

$$P = c \left(\frac{\rho}{\rho_0} \right)^b + d \quad (7)$$

where P is the compressive stress of the cotton fiber assembly; b and c are constants; d is the correction value; and ρ/ρ_0 is the relative density of the cotton fiber assembly. Using different values of b , combined with test data fitting equation (7), the curve of the relation between the compressive stress and the relative density of the cotton fiber assembly is shown in Figure 5, and the corresponding fitting equation is shown in Table 1.

It can be seen from Figure 5 and Table 1 that the coefficient of determination R^2 of different fitting methods is 0.8374, 0.9247, 0.9775, 0.9974, 0.9924, and 0.971, respectively. The fitting results show that $b=4$; namely, the fitting effect of compressive stress and the fourth power of relative density is best, showing a good linear relation, and the fitting equation has a high reference value. Therefore, the fitting equation of the relation between compressive stress and relative density of the cotton fiber assembly can be expressed as equation (8):

$$P = c \left(\frac{\rho}{\rho_0} \right)^4 + d \quad (8)$$

where P is the compressive stress of the cotton fiber assembly; c is a constant; d is a correction value; and ρ/ρ_0 is the relative density of the cotton fiber assembly.

The compressive modulus is defined as the ratio of the stress to the corresponding strain when the material is subjected to unidirectional or uniaxial compression. To simplify the problem, the following assumptions are made in the test.

1. The cotton fiber assembly is simplified as an isotropic continuum from a macroscopic point of view.

2. In the process of uniaxial compression, the cotton fiber assembly only produces axial compression behaviors without lateral deformation.

In this way, if the cotton fiber assembly has a small deformation due to axial compression, in this deformation stage the compressive modulus of the cotton fiber assembly can be approximately expressed as equation (9):

$$E_s = \frac{\Delta P}{\varepsilon_z} \quad (9)$$

where ε_z is the axial deformation amount and ΔP is the change of axial compressive stress of cotton fiber assembly.

The cotton fiber assembly has both elasticity and plasticity, and its compression deformation curve has no straight segment. With the increase of relative density, the cotton fiber assembly presents significant hardening characteristics, and its stiffness increases sharply. Therefore, the compressive modulus of the cotton fiber assembly is not constant, but varies with relative density. In combination with equations (3) and (8), the derivative of compressive stress to compression strain can be obtained. When the initial relative density is 0.041, the relation between compressive modulus and relative density of the cotton fiber assembly with 6.6% moisture regain can be obtained, as shown in Figure 6 and Table 2.

From Figure 6 and Table 2 it can be seen that the compressive modulus of the cotton fiber assembly increases with the increase of relative density. When the relative density reaches 0.12, the compressive modulus of the cotton fiber assembly reaches about 0.9 MPa.

Finite element simulation

Parameters setting

Parameter setting mainly includes four parts: material parameter definition, model establishment and mesh division, load and constraint condition setting, and analysis type setting.

Material parameters definition. The elastic modulus of the pressing platen is 2.07×10^5 MPa. The compressive modulus of the cotton fiber assembly is variable. When the initial relative density is 0.041 and the moisture regain is 6.6%, the relation between compressive modulus, relative density, and compression strain of the cotton fiber assembly is shown in Figure 6 and Table 2. The Poisson ratio and density is shown in Table 3.

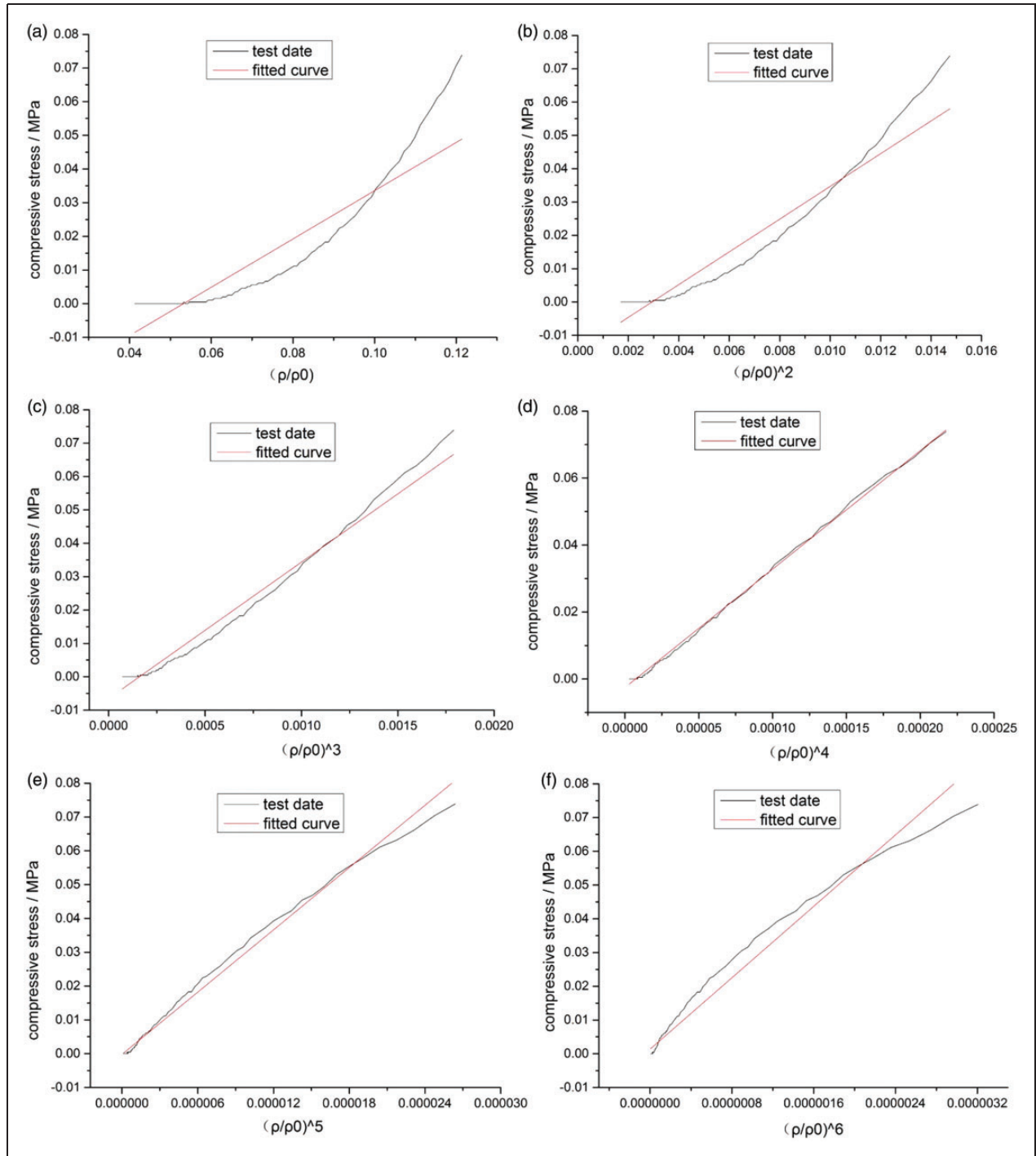


Figure 5. The fitting curves between compressive stress and relative density of the cotton fiber assembly: (a) fitted by linear function; (b) fitted by quadratic function; (c) fitted by cubic function; (d) fitted by quartic function; (e) fitted by fifth-degree function; (f) fitted by sixth-degree function.

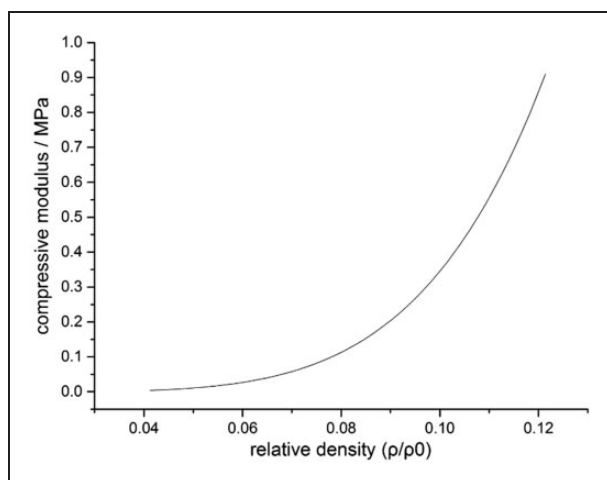
Model establishment and mesh division. The pressing platen model is established at the upper and lower ends of the cotton fiber assembly model. As for the pressing platen model and cotton fiber assembly model, Solid185 three-dimensional solid elements can be used in finite element

software ANSYS for meshing. The divided finite element model is shown in Figure 7.

Load and constraint conditions setting. According to the constraint conditions of the compression test, degrees

Table 1. The fitting equations between compressive stress and relative density of cotton fiber assembly

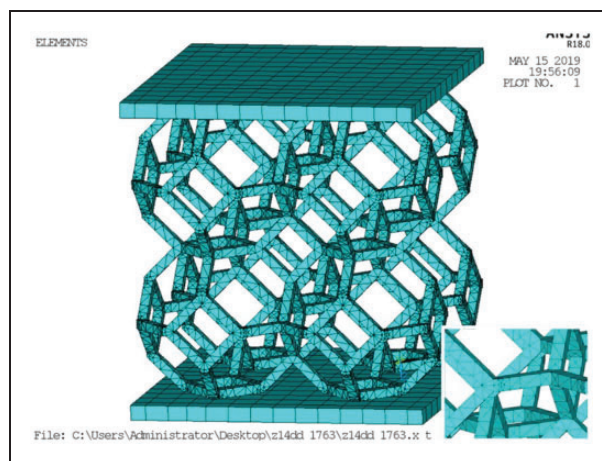
Fitting method	Fitting equation	Coefficient of determination R^2
Fitted by linear function	$P = 0.7168\left(\frac{\rho}{\rho_0}\right) - 0.03814$	0.8374
Fitted by quadratic function	$P = 4.9115\left(\frac{\rho}{\rho_0}\right)^2 - 0.0144$	0.9247
Fitted by cubic function	$P = 40.8768\left(\frac{\rho}{\rho_0}\right)^3 - 0.00653$	0.9775
Fitted by quartic function	$P = 353.838\left(\frac{\rho}{\rho_0}\right)^4 - 0.00258$	0.9974
Fitted by fifth-degree function	$P = 3070.0713\left(\frac{\rho}{\rho_0}\right)^5 - 0.0002238$	0.9924
Fitted by sixth-degree function	$P = 26452.4192\left(\frac{\rho}{\rho_0}\right)^6 + 0.00135$	0.9710

**Figure 6.** Curves between compressive modulus and relative density of the cotton fiber assembly when the moisture regain is 6.6%**Table 2.** Compressive modulus of cotton fiber assembly when the moisture regain is 6.6%

Compressive strain (%)	Relative density	Compressive modulus (MPa)
5	0.043	0.0052
10	0.046	0.0069
15	0.048	0.0091
20	0.051	0.0122
25	0.055	0.0168
30	0.059	0.0242
35	0.063	0.0349
40	0.068	0.0516
45	0.074	0.0789
50	0.082	0.1311
55	0.091	0.2198
60	0.103	0.3912
65	0.117	0.7503
66	0.121	0.9105

Table 3. The Poisson ratio and density of pressing platen and cotton fiber^{5,22}

	Poisson ratio	Density (kg/m ³)
Pressing platen	0.29	7850
Cotton fiber	0.4	1530

**Figure 7.** Finite element model of cotton fiber assembly and pressing platen.

of freedom in the horizontal direction of the upper press platen are restricted; degrees of freedom in all directions of the lower platen are restricted; degrees of freedom in the horizontal direction of the cotton fiber assembly are restricted. The contact between the pressing platen and cotton fiber assembly model is established. An axial displacement of 65% compression is applied to the upper platen at approximately 39 mm. The platen loading speed is set to 100 mm/min.

Analysis type settings. Analysis type is set to static analysis, and the type of equation solver is specified as the sparse direct equation solver (SPARSE) to solve the problem.

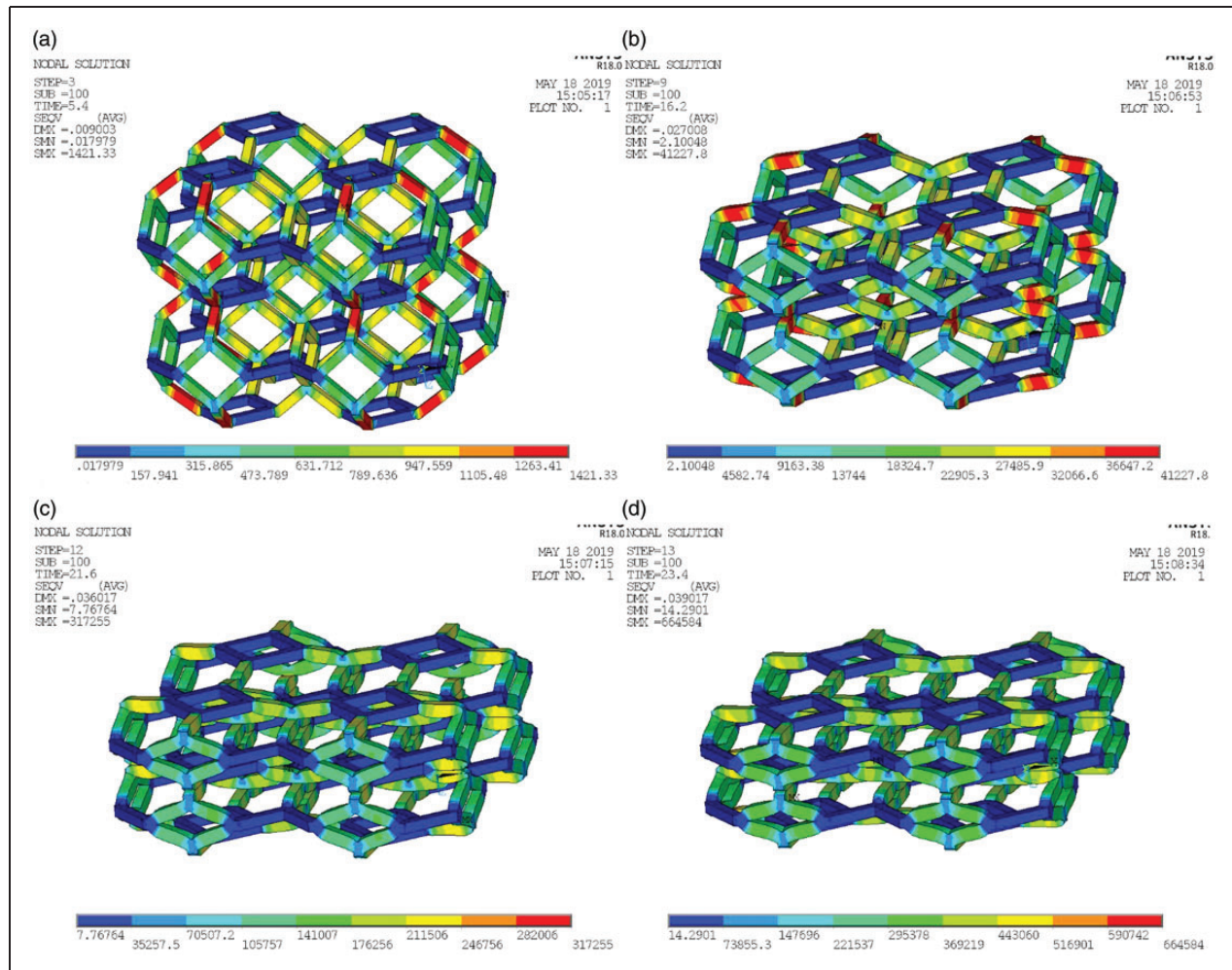


Figure 8. The stress nephogram: (a) 15% compression; (b) 45% compression; (c) 60% compression; (d) 65% compression.

Finite element analysis results and comparison with test data

The solution is a nonlinear process. Through the ANSYS general post-processor “POST1,” the results of the action of the platen and the cotton fiber assembly can be obtained. Figure 8 shows the stress nephogram of the cotton fiber assembly when compression is 15%, 45%, 60%, and 65%. Figure 9 and Table 4 show the simulation results and test results of the relation between the compressive stress, the compressive amount, and the relative density of the cotton fiber assembly.

It can be seen from Figure 8 that the cotton fiber assembly has a large deformation under compression. The stress of the cotton fiber assembly shows an increasing trend with increasing compression. In the stress nephogram, the support part (red region) of the model prism has a large stress, while the horizontal part (blue region) has a small stress, which is affected by the geometric shape of the model. In the compression

process, the deformation of the model is dominated by the bending deformation of the support part of the prism, and the bending moment of this part of the model is large. However, in the actual compression process of the cotton fiber assembly, there is a slip behavior in the cotton fiber, and the deformation of the cotton fiber assembly is not dominated by the bending deformation of some fibers. Therefore, the model does not well explain the deformation behavior of internal fibers, but only the macroscopic mechanical properties of the cotton fiber assembly. This is a limitation of the macroscopic model.

It can be seen from Figure 9 and Table 4 that with increased compression and relative density, the compressive stress of the cotton fiber assembly increases continuously. However, when the relative density is less than 0.055, there is a large fluctuation in the relative error between the finite element analysis result and the test data. The fluctuation is mainly caused by the accuracy of the pressure sensors in the test. The minimum stress that the pressure sensor can measure is

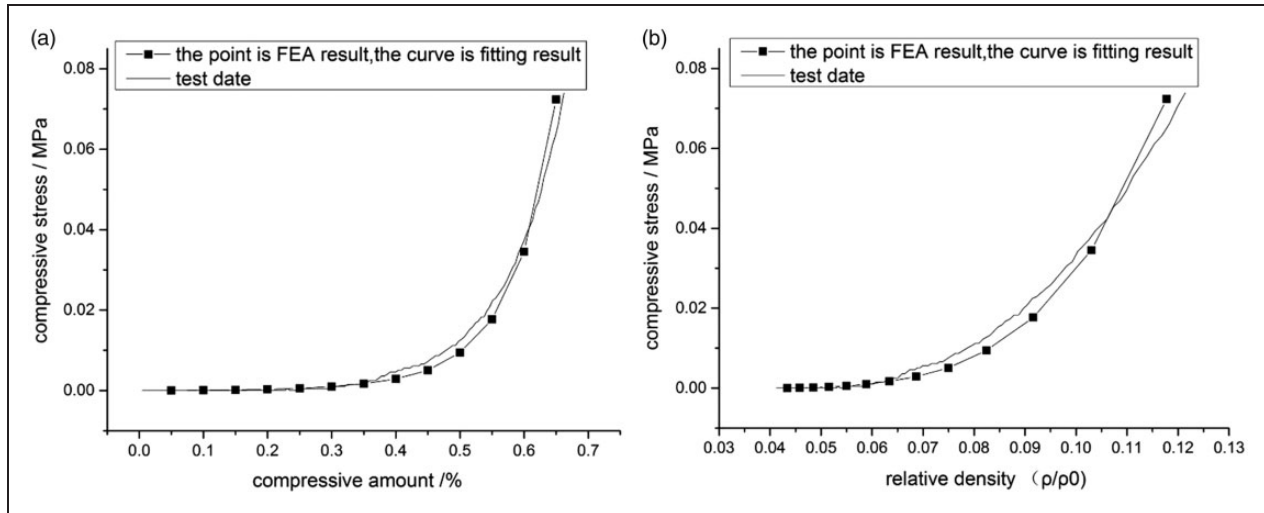


Figure 9. Compressive stress curves: (a) the relation between compressive stress and compressive amount; (b) the relation between compressive stress and relative density.

Table 4. Relation between compressive stress, compressive amount, and relative density of the cotton fiber assembly when the moisture regain is 6.6%

Compressive amount (%)	Relative density	Finite element analysis value of compressive stress (MPa)	Test value of compressive stress (MPa)	Relative error (%)
20	0.052	0.00031	0.00000	100
25	0.055	0.00055	0.00051	7.3
30	0.059	0.00098	0.00051	48.1
35	0.063	0.00168	0.00204	17.6
40	0.068	0.00289	0.00459	37.0
45	0.074	0.00505	0.00713	29.1
50	0.082	0.00947	0.01274	25.7
55	0.091	0.01766	0.02242	21.2
60	0.103	0.03453	0.03720	7.2
65	0.117	0.07234	0.06318	14.5

0.00051 MPa. Therefore, when the compressive stress is less than 0.00051 MPa, the measured value of the pressure sensor is zero and the relative error is 100%. When the compressive stress increases to 0.00051 MPa, the measured value suddenly changes from zero to 0.00051 MPa, and the relative error changes to 7.3%. This shows that when the compressive stress reaches the measurable range of the pressure sensor, the finite element analysis result is similar to the test result.

As the compression process continues, the relative error still fluctuates. But, in general, with increased compression and relative density, the relative error decreases continuously, from 48% to about 14%.

There are two main factors contributing to this fluctuation: the first is the model factor and the second is the test factor. For the model, in the early stage of the compression process, the pore of the model is larger and the model can be more easily compressed, so the compressive stress will be relatively small. For the test, in the early stage of the compression process, the compressive stress is very small, at basically one or two orders of magnitude smaller than that in the later stage. Therefore, the measured value in the early stage is more susceptible to interference by external conditions, resulting in larger errors. Combining these two factors, the relative error in the early stage of the compression process is larger than that in the later stage.

In the actual compression process of the cotton fiber assembly, the cotton fiber assembly needs to be compressed to a higher relative density and to reduce the volume as much as possible to facilitate storage and transportation. According to China's National Standard GB 6975-2013 for cotton baling, the overall density of the cotton fiber assembly when the cotton is finally packed into a cotton bale is above 315 kg/m^3 , that is, the relative density of the cotton fiber assembly is above 0.2.²³ Therefore, for the actual compression process, the stress condition of the cotton fiber assembly at high relative density is worthy of attention. The stress condition at very low relative density has no great practical research significance. When the cotton fiber assembly is compressed to a relative density greater than 0.1, the relative error between the finite element analysis result and the test result is less than 15%. Therefore, the macroscopic model can well simulate the compressive stress of the cotton fiber assembly as a whole.

Analysis of the impact of moisture regain on the compression process of the cotton fiber assembly

The moisture absorption of cotton fibers is a relatively complex physical and chemical phenomenon. On the one hand, the hydrophilic groups of cotton fibers and the surface pores and crevices have the ability to absorb water molecules. On the other hand, external air pressure, temperature, relative humidity, and so on will affect the moisture absorption performance of cotton fibers. The moisture absorption affects the physical and chemical properties of cotton fiber, and further affects the quality of cotton fiber during processing. The moisture content of the cotton fiber assembly is expressed by moisture regain, which is defined as the ratio of moisture weight to dry weight in the fiber, as shown in equation (10):

$$w = \frac{G - G_0}{G_0} \quad (10)$$

where G is the wet weight of the sample and G_0 is the dry weight.

Measurement of compressive modulus of the cotton fiber assembly at different moisture regain

We analyze the influence of different moisture regain of the cotton fiber assembly on compression behavior. The moisture regains are 4.2%, 6.6%, 8.8%, 10.7%, 14.1%, and 20.4%. The method for controlling the moisture regain of samples in the test is as follows: An appropriate amount of raw cotton is placed in the oven, dried to a constant weight, and then part of the dried raw cotton is weighed and recorded as dry weight, which is placed in the temperature and humidity chamber to humidify the sample; the weight of the sample after humidification is obtained and recorded as wet weight, and the moisture regain of the sample is calculated according to equation (10).

We conduct compression tests of cotton fiber assembly samples with different moisture regains, then the obtained test data are used to fit equation (8) is fitted. The relationship curve between the compressive stress and the relative density of the cotton fiber assembly at different moisture regain is shown in Figure 10, and the corresponding fitting equation is shown in Table 5. The coefficient of determination is 0.9960, 0.9974, 0.9612, 0.9942, 0.9915, and 0.9775, respectively. The fitting effect is good.

Combined with equation (3), the relation between the compressive modulus and the relative density of the cotton fiber assembly at different moisture regains can be obtained, as shown in Figure 11.

Finite element simulation of the compression process of the cotton fiber assembly at different moisture regains

Combined with the compressive modulus measured above, setting the loading speed of 100 mm/min and initial relative density of 0.041 of the cotton fiber assembly, we repeat the finite element simulation process. When the relative density of the cotton fiber assembly is 0.103 and 0.117, the relation between compressive stress and moisture regain is shown in Figure 12, Table 6, and Table 7.

It can be seen from Figure 12 that the moisture regain of the cotton fiber assembly has a great influence on the compressive stress. If the moisture regain of the cotton fiber assembly is too low or too high, the compressive stress will increase. Therefore, controlling the moisture regain to an appropriate value can reduce the compressive stress of the cotton fiber assembly. While the moisture regain is about 8.8–10.7%, the compressive stress is relatively small. The simulation result curve is similar to the test data curve.

It can be seen from Table 6 that when the relative density is 0.103, the minimum compressive stress of the cotton fiber assembly is about 0.02 MPa at different moisture regains, and the maximum value is about 0.05 MPa. The minimum value of the relative error between simulation results and test data is 3.8%, and the maximum value is 15.3%. It can be seen from Table 7 that when the relative density is 0.117, the minimum compressive stress of the cotton fiber assembly is about 0.04 MPa at different moisture regains, and the maximum value is about 0.1 MPa. The minimum value of relative error between simulation results and test data is 2.5%, and the maximum value is 12.7%.

After the cotton fiber assembly is compressed and baled, the contact points between cotton fibers are prone to indentation, and the cotton fiber cell wall is even deformed under high pressure. This deformation behavior has an impact on the breaking strength, weavability, and yarn quality of cotton fibers. At the same time, the stability of the cotton bale is poor under the action of high stress. Therefore, it is advantageous to reduce the compressive stress of the cotton bale as much as possible.

The moisture content of a cotton fiber has an influence on its properties. If the moisture content of a cotton fiber is too high, it is prone to production of mildew and discoloration, reduced grade of cotton, and it is more likely that impurities will be produced in the process of cotton ginning, increasing the difficulty of spinning. If the moisture content of cotton fiber is too low, the strength of the fiber is reduced and it is easy to form short fibers in the process of cotton ginning, meaning reduced strength of the

yarn. At present, the conventional moisture regain of cotton fiber stipulated by China's national standard is 8.5%.²⁴

The finite element analysis result shows that when the moisture regain is 8.8–10.7%, the compressive stress is low in the compression process. However, a moisture regain of 10.7% is high, which may affect the grade performance of the cotton fiber. Therefore, for the

compression baling process, it is appropriate to control the moisture regain to be about 8.8% in practice. At present, the conventional moisture regain of cotton fiber is 8.5% in practice. The conventional value is selected for convenience, according to the moisture absorption capacity of the fiber. The regulation of conventional moisture regain is usually based on the actual situation, rather than the compression process.

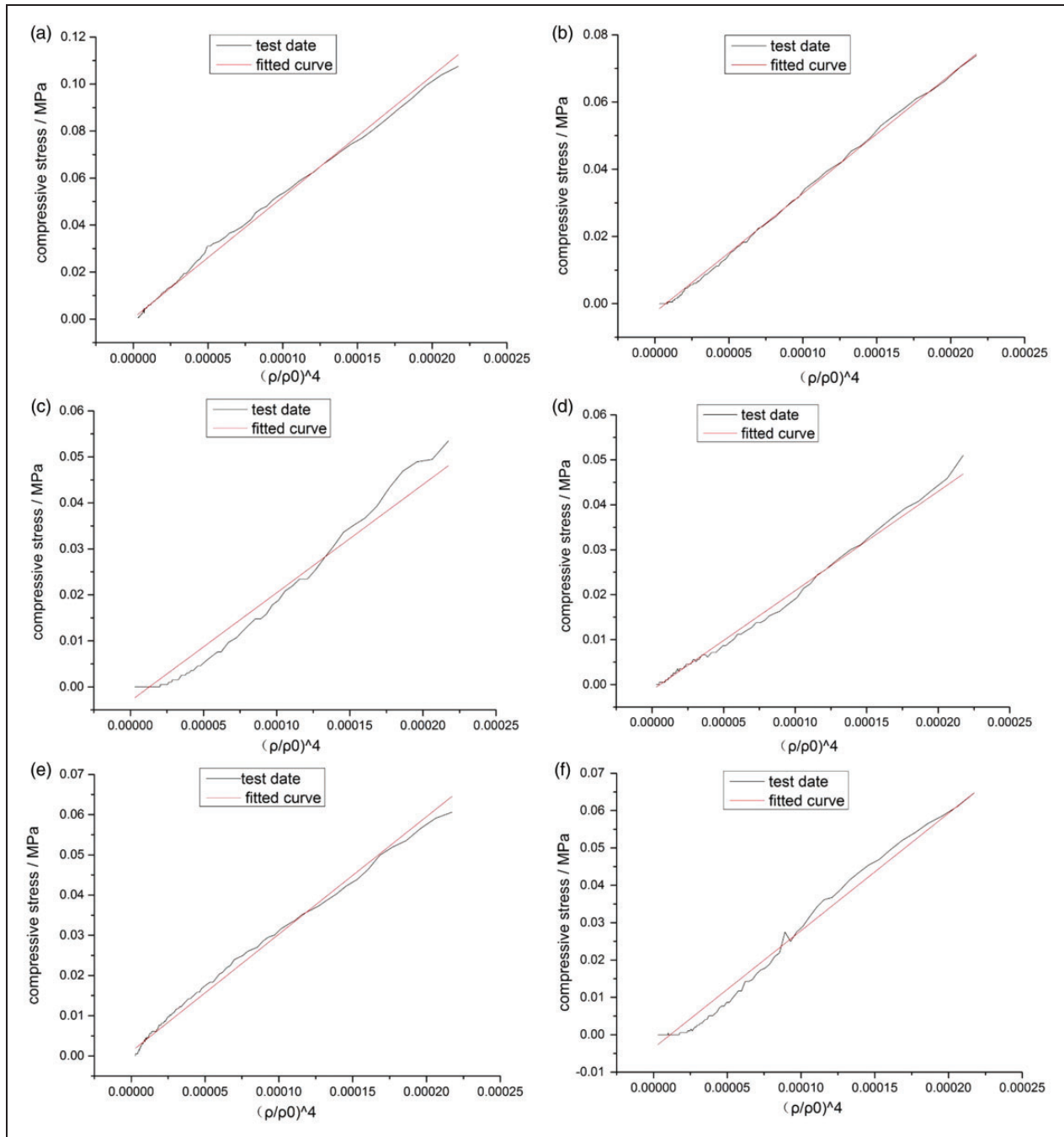
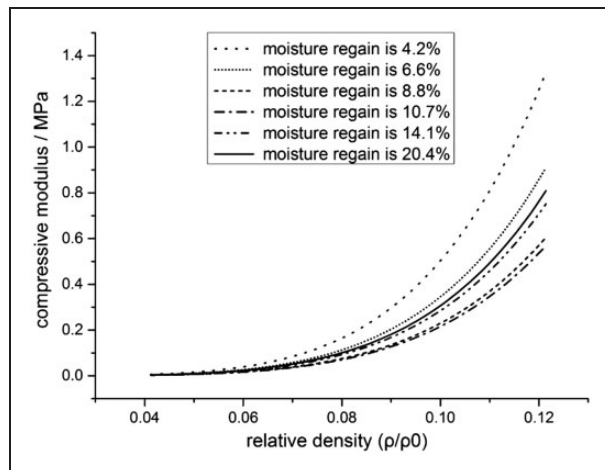


Figure 10. The fitting curves between compressive stress and relative density of the cotton fiber assembly: (a) 4.2% moisture regain; (b) 6.6% moisture regain; (c) 8.8% moisture regain; (d) 10.7% moisture regain; (e) 14.1% moisture regain; (f) 20.4% moisture regain.

Table 5. The fitting equations between compressive stress and relative density of the cotton fiber assembly at different moisture regain

Moisture regain (%)	Fitting equation	Coefficient of determination R^2
4.2	$P = 515.469 \left(\frac{\rho}{\rho_0} \right)^4 + 0.000403$	0.9960
6.6	$P = 353.838 \left(\frac{\rho}{\rho_0} \right)^4 + 0.00258$	0.9974
8.8	$P = 235.178 \left(\frac{\rho}{\rho_0} \right)^4 + 0.00305$	0.9612
10.7	$P = 221.05 \left(\frac{\rho}{\rho_0} \right)^4 + 0.00123$	0.9942
14.1	$P = 292.002 \left(\frac{\rho}{\rho_0} \right)^4 + 0.00205$	0.9915
20.4	$P = 314.289 \left(\frac{\rho}{\rho_0} \right)^4 + 0.00358$	0.9775

**Figure 11.** Curves of compressive modulus and relative density of the cotton fiber assembly at different moisture regains.

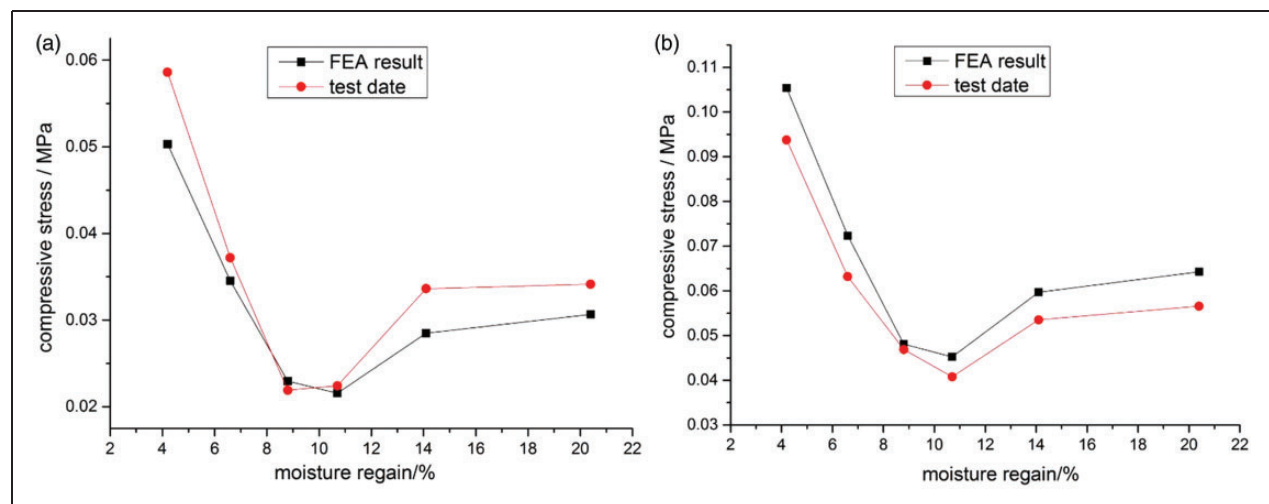
In comparison, the moisture regain of the simulation analysis is very close to the conventional moisture regain. Therefore, the analysis result is in accordance with the existing experience.

Table 6. The relationship between compressive stress and moisture regain when relative density is 0.103

Moisture regain (%)	Finite element analysis value of compressive stress (MPa)	Test value of compressive stress (MPa)	Relative error (%)
4.2	0.0503	0.0586	14.2
6.6	0.0345	0.0372	7.2
8.8	0.0229	0.0219	4.5
10.7	0.0216	0.0224	3.8
14.1	0.0285	0.0336	15.3
20.4	0.0307	0.0341	10.2

Table 7. The relationship between compressive stress and moisture regain when relative density is 0.117

Moisture regain (%)	Finite element analysis value of compressive stress (MPa)	Test value of compressive stress (MPa)	Relative error (%)
4.2	0.1054	0.0938	11.0
6.6	0.0723	0.0632	12.7
8.8	0.0481	0.0469	2.5
10.7	0.0452	0.0408	9.8
14.1	0.0597	0.0535	10.4
20.4	0.0643	0.0566	12.0

**Figure 12.** Curves of the relation between compressive stress and moisture regain: (a) the relative density is 0.103; (b) the relative density is 0.117.

Conclusion

From the above analysis, the following conclusions can be drawn:

1. A tetrakaidecahedral porous cotton fiber assembly model is presented. Based on the model, the compressive stress condition of the cotton fiber assembly is successfully simulated by the finite element method. The analysis result is consistent with the test data, which verifies the validity of the model.
2. The impact of different moisture regain on the compression process is analyzed. The analysis result shows that the compressive stress is the least when the moisture regain is 8.8%. Small compressive stress is beneficial to the compression process and the stability of cotton bales. The result provides a certain reference value for the cotton baling process.
3. In this paper, the compression property of the cotton fiber assembly is analyzed from a macroscopic perspective, and some simplifying assumptions are made. Therefore, it is inevitable that there are certain limitations, mainly reflected in the way the model does not well explain the deformation behavior of internal fibers, but only explains the macroscopic mechanical properties of the cotton fiber assembly. However, the deformation behavior of the internal fibers has an effect on the macroscopic mechanical properties, which is worthy of further research.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research is supported by National Natural Science Foundation of China (Project number: 11762020), the University Research Project of Xinjiang Uygur Autonomous Region (Project number: XJEDU2017S009), the Science and Technology Project of Quality and Technical Supervision Bureau in Xinjiang Uygur Autonomous Region (Project number: 201632, 201806).

References

1. Qian L and Weidong Y. Research and prospect of compressional behavior of fiber assembly. *J Donghua University* 2005; 31(3): 127–132.

2. Smith AC and Roberts WW. Straightening of crimped and hooked fibers in converging transport ducts: computational modeling. *Text Res J* 1994; 64(6): 335–344.
3. Yamamoto S and Matsuoka T. A method for dynamic simulation of rigid and flexible fibers in slow field. *J Chem Phys* 1993; 98(1): 644–650.
4. Kong LX and Platfoot RA. Two-dimensional simulation of air flow in the transfer channel of open-end rotor spinning machines. *Text Res J* 1996; 66(10): 641–650.
5. Xiaochuan C and Wang D. Finite element analysis of cotton ginning state based on ANSYS. *Text Res J* 2019; 89(11): 2142–2153.
6. Gibson LG and Ashby MF. *Cellular solids structure and properties*. Cambridge: Cambridge University Press, 1997.
7. Yong L, Hong Z, Youqiang Z, et al. Research on compressive force transmission properties and densities: mechanical properties model of cotton fiber assembly. *Text Res J* 2016; 37(11): 19–25.
8. Zixing L and Shanglu S. Theoretical studies on mechanical models of low density foam. *Mech Eng* 2005; 27(5): 13–20.
9. Gent AN and Thomas AG. The deformation of foamed elastic materials. *J Appl Polym Sci* 1959; 1: 107–113.
10. Gent AN and Thomas AG. Mechanics of foamed elastic materials. *Rubber Chem Technol* 1963; 36: 597–610.
11. Ko WL. Deformations of foamed elastomers. *J Cell Plast* 1965; 1: 45–50.
12. Gibson LJ and Ashby MF. The mechanics of three-dimensional cellular materials. *Proc Roy Soc Lond* 1982; A382: 43–59.
13. Gibson LJ and Ashby MF. *Cellular solids: structure and properties*. Beijing: Tsinghua University Press, 2003.
14. Warren WE and Kraynik AM. Linear elastic behavior of low-density Kelvin foam with open cells. *J Appl Mech* 1997; 64: 787–794.
15. Zhu HX, Mills NJ and Knott JF. Analysis of the elastic properties of open-cell foams with tetrakaidecahedral cells. *J Mech Phys Solids* 1997; 45(3): 319–343.
16. Van Wyk CM. Notes on the compressibility of wool. *Trans J Text Inst* 1946; 37(12): 285–292.
17. Komori T and Itoh M. A modified theory of fiber contact in general fiber assemblies. *Text Res J* 1994; 64(9): 519–528.
18. Komori T, Itoh M and Takaku A. A model analysis of the compressibility of fiber assemblies [J]. *Text Res J* 1992; 62(10): 567–574.
19. Komori T and Makishima K. Numbers of fiber-to-fiber contacts in general fiber assemblies. *Text Res J* 1977; 47(1): 13–17.
20. Sawei Q, Xinna Z, Qingxian H, et al. Research progress on simulation modeling of metal foams. *Rare Metal Mat Eng* 2015; 44(11): 2670–2676.
21. Shanglu S and Zixing L. Finite element analysis for the elastic modulus of open-cell foams based on a tetrakaidecahedron model. *J Mech Strength* 2006; 28(1): 108–112.
22. Hong X and Xiaohong S. *Cotton inspection and processing*. Beijing: China Textile Press, 2006.
23. GB 6975-2013 (2013) Cotton baling.
24. GB/T 9994-2018 (2018) Conventional moisture regains of textile materials.