Effect of Vibrational Frequency on Alfalfa Opening Compression Process

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To reveal the action mechanism of vibration frequency in alfalfa opening compression, a self-developed vibration compression test system was used to evaluate the variation of compression force during alfalfa open compression. A faster vibration frequency yielded a smaller compression force required for compressing alfalfa into blocks. Compared with free vibration compression, vibration compression was beneficial to release the internal stress of alfalfa block, reduce the forming pressure, and stabilize the high density. In the range of test vibration frequency, when the frequency was 15 Hz, the residual internal stress release ratio of alfalfa block was the highest, and the stable density of alfalfa block was the largest. Considering the pressure and alfalfa block density comprehensively, the optimized vibration frequency was approximately 15 Hz.

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Keywords: Alfalfa; Compression; Vibration frequency; Density

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INTRODUCTION

Compressing alfalfa into blocks or pellets can not only increase the density of alfalfa, facilitate storage and transportation, but also retain the nutrients in alfalfa and improve its feeding value (Wang *et al*. 2017; Chu and Zhang 2022). Alfalfa is a viscoelastic agricultural fiber material. In the process of compression in an open mold, the compression piston has to overcome the deformation resistance of the material itself, the friction between the materials, the friction between the materials and the mold, and the adhesion between the materials (Tumuluru 2018; De *et al*. 2020). The compression process is as shown in Fig. 1. The mechanical behavior of alfalfa in the compression process will affect the density of products and energy consumption (Yub *et al.* 2018; Lisowski *et al*. 2019).

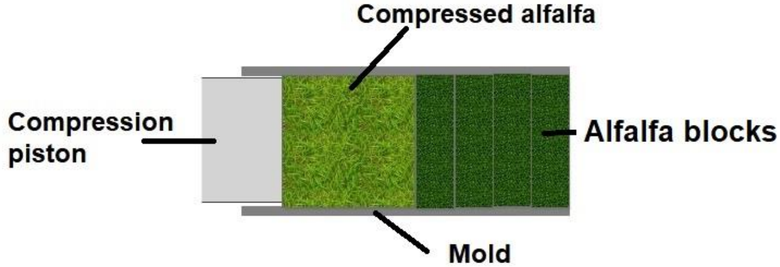


Fig. 1. Schematic diagram of open compression process

In recent years, scholars have extensively studied the stress-strain behavior during the biomass compression process. Tu *et al.* (2014) established the mechanical characteristic model of biomass densification using the finite volume element method and analyzed the variation law of equivalent stress-strain in each stage of densification. Based on the elastic-plastic theory and contact analysis principle, Xin *et al.* (2019) established a three-dimensional simulation model of the compression of straw biomass and revealed the creep law of the compression process. Gu *et al.* (2015) analyzed the force on the die and found that the closer to the die outlet, the smaller the radial and axial force of the material on the die.

Jakub *et al.* (2021) found that the springback of formed products is negatively correlated with the molding pressure through the compression of several biomass. The springback of products will lead to the decline of density. Therefore, the setting of compression parameters should reduce the springback as much as possible.

Due to the friction between the die and the material during compression and the elastic recovery of the material after compression, it is necessary to overcome the deformation rebound and expenditure of useless work during next compression, resulting in high energy consumption and low efficiency of compression (Noorfidza *et al*. 2018; Wang *et al*. 2020).

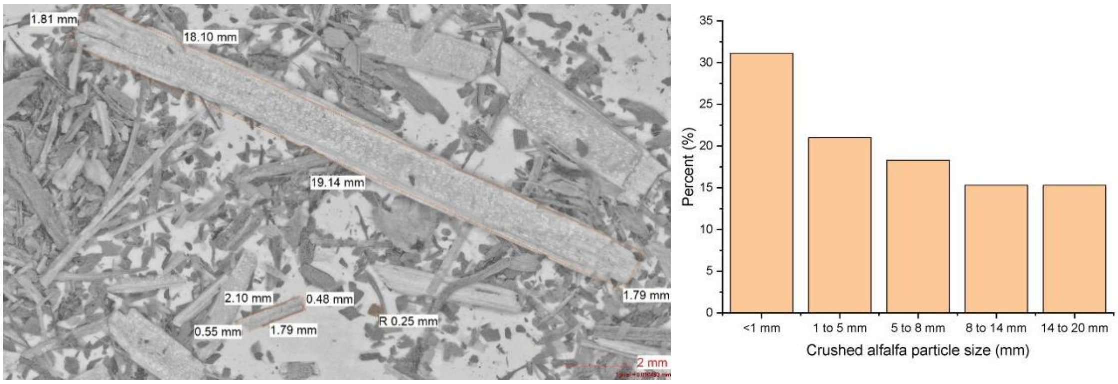
Zhang *et al.* (2011) conducted a closed compression experiment of biomass by ultrasonic vibration (a frequency range of about 2 to 18 megahertz), and the result showed that it helped to reduce the pressure during the biomass compression process. Wu *et al.* (2014) densified caragana into briquettes under the action of vibration force field with a vibration frequency of 10 to 40 Hz and found that the vibration force field can reduce the compression energy and improve the product quality. Lei *et al.* (2022) conducted a closed compression test on alfalfa and found that different vibration frequencies have different compression stress transfer efficiencies. When the vibration frequency was 15 Hz, the stress transmission effect was the best and the stress distribution was more uniform.

Ma *et al.* (2016) and Du *et al.* (2022) showed that vibration can increase the stress relaxation rate and reduce residual stress, thereby improving product quality and reducing compression energy consumption. The above research results on the mechanical behavior of biomass in the process of vibration compression show that the vibration process is beneficial to the transfer of stress and improves product quality.

EXPERIMENTAL

Materials

Alfalfa from the experimental field of Inner Mongolia Agricultural University was used as the experimental material. The harvested alfalfa was dried to a moisture content of approximately 20%, and the alfalfa was crushed with a 550 type crumbling machine (YUYING, Sichuan, China). Then the particle size distribution was observed and measured with a 3800-D high-definition electron microscope (Dongxing Technology, Guangzhou, Shenzhen, China), as shown in Fig. 2.



(a) **(b)**

Fig. 2. Crushed alfalfa: (a-Crushed alfalfa shape and size; b-Crushed alfalfa particle size distribution)

Method

Alfalfa vibration compression test with amplitude of 1 mm and vibration frequency of 10, 15, and 20 Hz was conducted on the self-made biomass densification test system, as shown in Fig. 3.

Fig. 3. The self-made biomass compressive test system

With the force sensor on the upper end of the compression piston, the pressure exerted by the compression piston on the alfalfa particles was tested, as shown in Fig. 4. During the test, 10 g of crushed alfalfa was fed into the system, the hydraulic system and the mechanical vibration device were started, and the hydraulic system drove the compression piston downward at a speed of 5.0 mm/s and compression stroke of 110 mm. After the compressed piston reached the end of the stroke, it kept its shape for 20 s. Then, the piston returned and completed a compression cycle. The above operation cycle was continued 10 times. The data acquisition system collected and stored pressure data. The pressure was analyzed and processed by the Origin (OriginPro, Version 2021, OriginLab Corporation, Northampton, MA, USA) software. This maximum pressure is the average of 10 compressions, the density is the average of the density of three sample blocks.

An electronic scale (manufactured by Lucky Company, with an accuracy of 0.1 g, Shanghai, China) measured the mass of the alfalfa block, and a Vernier caliper measured the diameter and height of the alfalfa block to obtain the density of the alfalfa block.

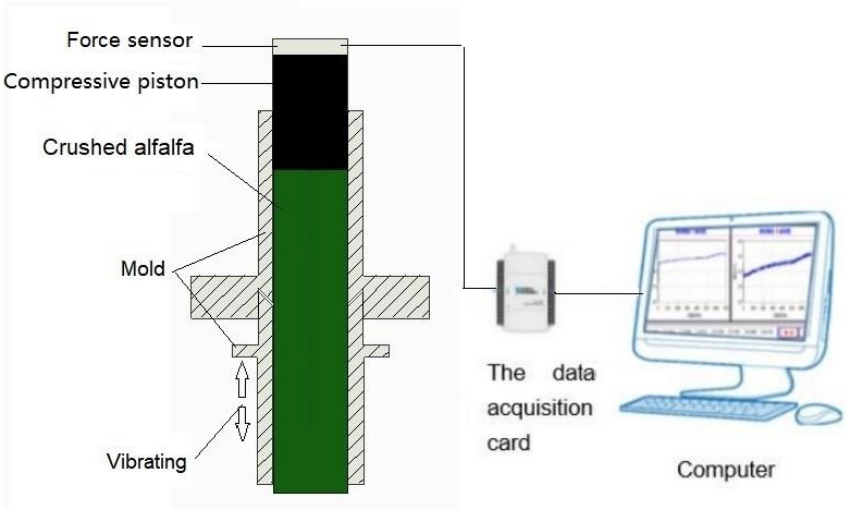


Fig. 4. Test principle schematic

RESULTS AND DISCUSSION

Effect of Vibration Frequency on Stress Transmission

The pressure change graph over time was obtained by Origin 2021, as shown in Fig. 5. According to the change of compression force, the compression process was divided into: compression stage, extrusion stage, and shape retention stage.

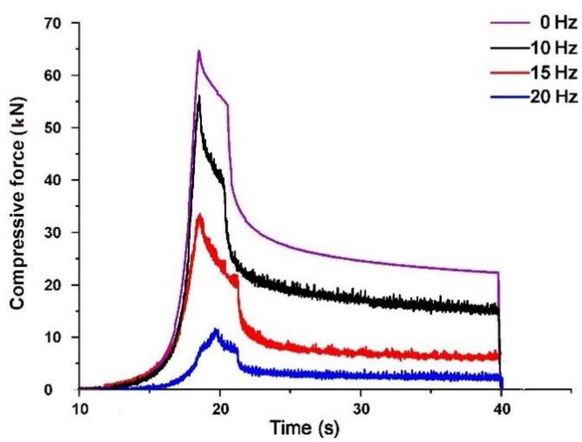


Fig. 5. Compressive force-time during compression under vibration

The compression stage was defined as the peak value of the compression force from 0. At the initial stage of compression, the crushed alfalfa was relatively loose, the gap between particles was large, and the force acting on the compressed material was small. With the increase of downward flow of compressed piston, the particle gap was gradually eliminated, and the contact area between particles increased. The compressed alfalfa began to undergo elastic and plastic deformation, and the pressure acting on the material increased noticeably until the maximum compression force was reached.

After the compression force reached the peak value, it was in the extrusion stage until the compression piston stopped. The friction between the compressed material and the mold wall was one of the main sources of compression resistance for open compression. When the compression force reached the peak, the alfalfa in the mold was compressed to the maximum deformation and started to move downward under the action of the compression piston. At this time, the friction force changed from static friction to dynamic friction.

When the compression piston reached the end point of the downward stroke, it was maintained for a certain period of time, which was the shape preserving stage. When the compression piston stopped, the elastic deformation of the compressed alfalfa in the mold began to recover. Due to the obstruction of the piston, the elastic deformation changed into inelastic deformation, and the elastic restoring force gradually decreased, which was the process of stress relaxation. At this time, the value measured by the pressure sensor was the elastic restoring force of alfalfa.

In the compression stage, with increased vibration frequency, the time when the compression force reached the peak value was later, and the maximum compression force decreased noticeably. The maximum compression force is shown in Table 1. This occurred because vibration can promote the local movement of crushed alfalfa, and speed up the compact arrangement of crushed alfalfa, thereby reducing the "arching effect" (Sun *et al.* 2017; Nada and Hu 2020), which is caused by the accumulation of particulate matter, and the arrangement of material particles tended to be uniform. The arching effect refers to the deformation in the direction of the empty area under the action of self-weight stress and tectonic stress. The concentrated compressive stress will form a regular arch area, and the arch stress shell bears and transmits the upper load and pressure. Vibration accelerated the internal stress release of compressed alfalfa in the mold, and reduced the radial force between the alfalfa block and the mold, thereby reducing the friction and compression force.

Table 1. Maximum Compressive Force at Different Vibration Frequencies

Vibration Frequency (Hz)	0	10	15	20
Maximum Compressive Stress (kN)	64.8	57.2	33.6	12.3

In the extrusion stage, the alfalfa blocks formed in the mold were gradually extruded, and the friction force changed from static friction to sliding friction. At the same time, the effective contact area between the alfalfa blocks and the mold continued to decrease. Therefore, the compressive force exhibited a decreasing trend as shown in Fig. 5. At first, the compression force decreased rapidly, mainly because the contact state between the mold and the formed alfalfa changed from static friction to sliding friction. After that, the compressive force decreased linearly and smoothly, mainly because the effective contact area between the mold and the alfalfa block decreased at a constant speed, and the internal stress release speed was stable.

Due to the different molding pressure, the compressive force ratio is used to describe the variation trend of the compressive force in the extrusion stage, which is defined as the ratio of compressive force to maximum compressive force when extruding for a certain time. As shown in Fig. 6, from the peak of the compression force to when the compression piston stopped, a higher frequency resulted in a higher proportion of the reduction in the compression force. Compared with the free-vibration (0 Hz) force field and the vibration force field (10, 15, and 20 Hz), the reduction ratio of the compressive force was different, mainly because the vibration accelerated the release speed of the internal stress, resulting in a rapid decrease in the friction force. In the vibration frequency range of 10 to 20 Hz, because the vibration frequency was higher, the decline rate of compression force became faster, indicating that a higher vibration frequency resulted in a faster release speed of the internal stress of the alfalfa block.

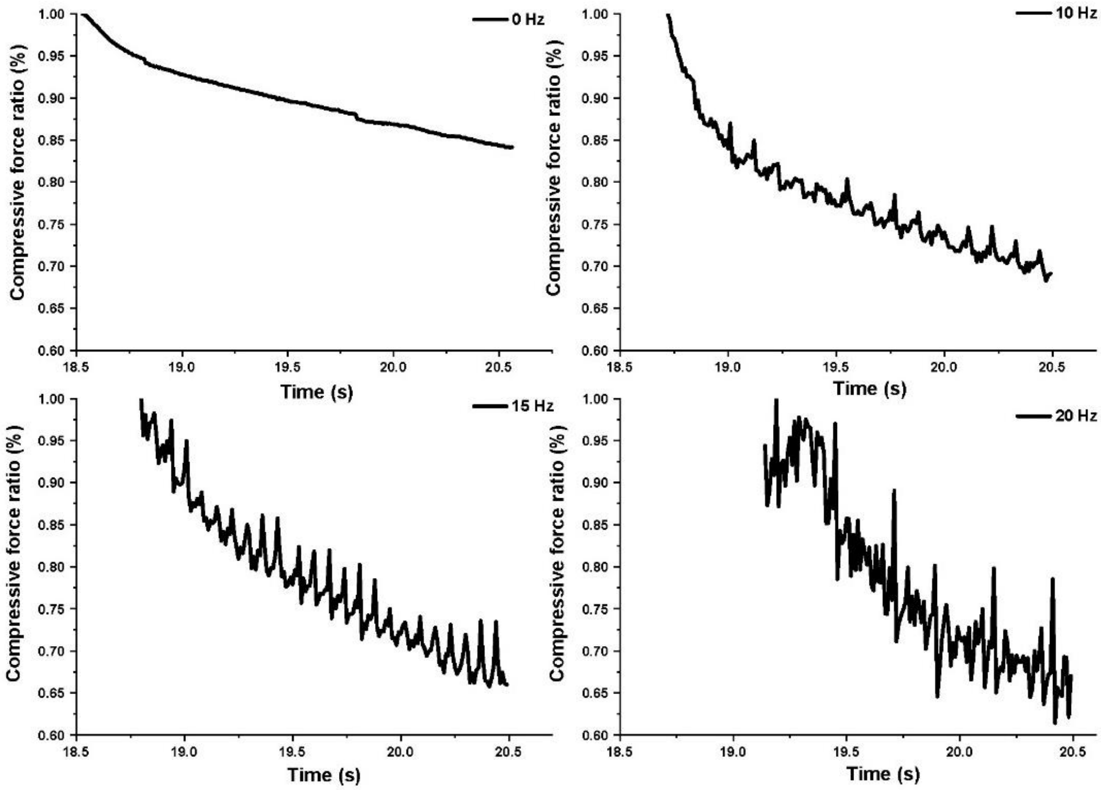


Fig. 6. Compression force ratio in extrusion stage

The shape retention stage is mainly the stress relaxation process of the formed alfalfa. The Maxwell model composed of springs and dampers in series is the basic model for simulating stress relaxation of agricultural materials (Qi 2019). Figure 7 depicts the experimental data and fitting curve of the compressive force changing with time in the shape retention stage under different vibration frequencies. The Origin 2021 data fitting tool performed a regression analysis and curve fitting on the compressive force-time relationship in the stress relaxation process of alfalfa straw, and the mathematical expression of the compressive force-time relationship was obtained, which was a second-order generalized Maxwell model. In the formula, y (MPa) is the elastic rebound force of the alfalfa block; A, B, t_1, and t_2 are the fitting coefficients; t is the relaxation time (s); y_0 is the residual elastic force in a certain period of time. A higher vibration frequency resulted in a smaller residual elastic force in the alfalfa block, as well as providing a more stable alfalfa block.

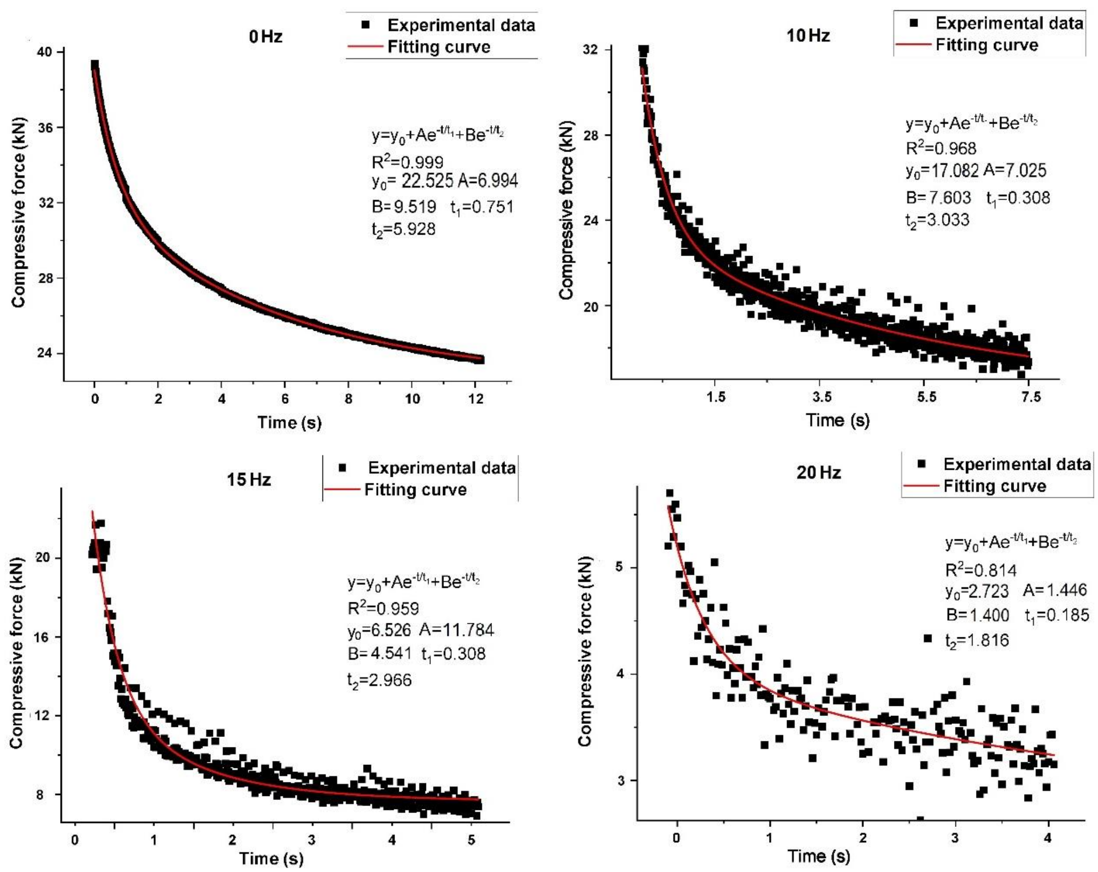


Fig. 7. Experimental data and fitted curves of compressive force-time

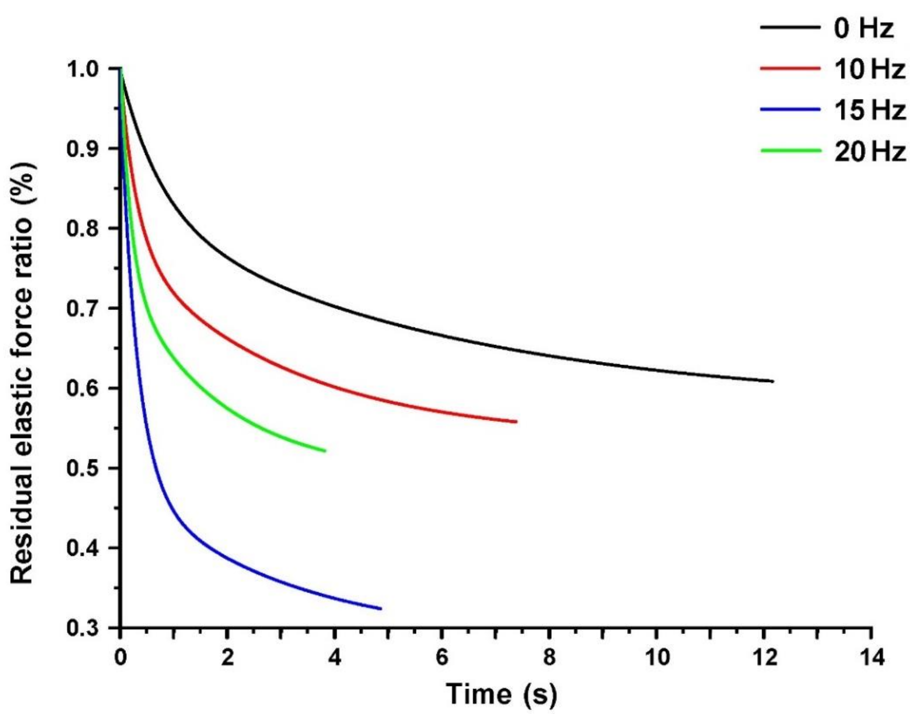


Fig. 8. The variation of the residual elastic force ratio with time under different vibration frequencies

Because of the influence of test conditions, the initial elastic force was different, and the ratio of residual elastic force was used to measure the recovery speed of elastic deformation. Residual elastic deformation force ratio refers to the ratio of the residual elastic force in the forming block to the initial elastic deformation restoring force after stress relaxation for a certain period of time. Figure 8 shows the variation of the residual elastic force ratio with time under different vibration frequencies. Compared with the vibration-free compression, the vibration reduced the residual elastic force in a high proportion and fast within a certain period of time. In the vibration frequency range of 10 to 20 Hz, when compressed at the vibration frequency of 15 Hz, the residual elastic force decreased the most, and the decline rate was the fastest. Therefore, vibration compression of alfalfa was conducive to the release of internal stress of materials, accelerating the speed of stress relaxation and improving product quality.

Effect of Vibration Frequency on Density Transmission

Figure 9 illustrates the change process of alfalfa block density with time under different vibration frequencies.

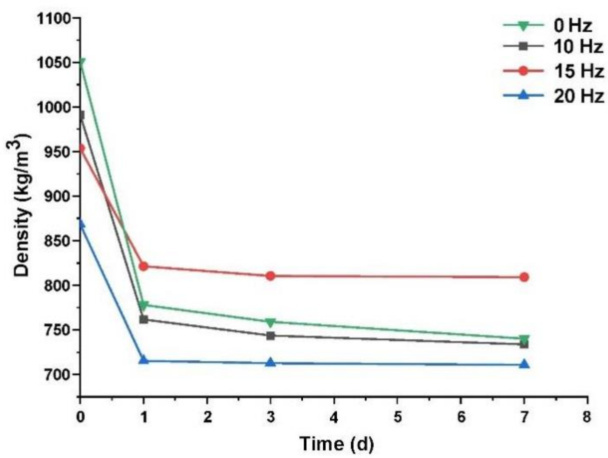


Fig. 9. Density-change curves over time

A lower vibration frequency resulted in a higher density of the alfalfa block extruded in the mold. With increased storage time, the density of the alfalfa block decreased. When the alfalfa block was placed in the natural environment for 7 days, the density of alfalfa blocks when the vibration frequency was 15 Hz was highest, followed by 10 Hz, and 20 Hz was the lowest.

The density change rate was defined to measure the stability of the alfalfa block. Density change rate refers to the difference in density change of alfalfa blocks after being placed for a certain period of time. This is shown in Eq. 1,

$$\delta = \frac{\rho_0 - \rho_1}{\rho_0} \times 100\% \quad (1)$$

where δ is the density change rate, ρ_0 is the extrusion density (kg/m^3) of alfalfa blocks, and ρ_1 is the density (kg/m^3) of the alfalfa block after a certain period of time. A smaller density change rate resulted in more stable density of the alfalfa block. The density change rates of the alfalfa blocks at different times are shown in Table 2. According to the density change rate, a higher vibration frequency results in a shorter time required for the alfalfa block to reach a stable density, indicating that the vibration frequency was positively correlated with the stress release of the alfalfa block. Taking the relaxation density for 7 days as the target, the stable density of alfalfa block was the highest and the change rate of density was smallest when the vibration frequency was 15 Hz.

Table 2. Density Change Rate at Different Times of Placement

Period	Density Change Rate (%)			
	0 Hz	10 Hz	15 Hz	20 Hz
0 to 1 d	26.0	23.2	13.9	17.6
0 to 3 d	27.8	25.0	15.0	17.9
0 to 7 d	29.6	26.1	15.1	18.0

Figure 10 shows photos of the product when the alfalfa blocks were relaxed for 7 days. It was found that the alfalfa blocks obtained under the vibration frequency of 0 and 10 Hz had obvious cracks, and the alfalfa blocks obtained under the vibration frequency of 15 and 20 Hz had almost no cracks on the surface, indicating that the vibration improved the surface quality of the alfalfa product.

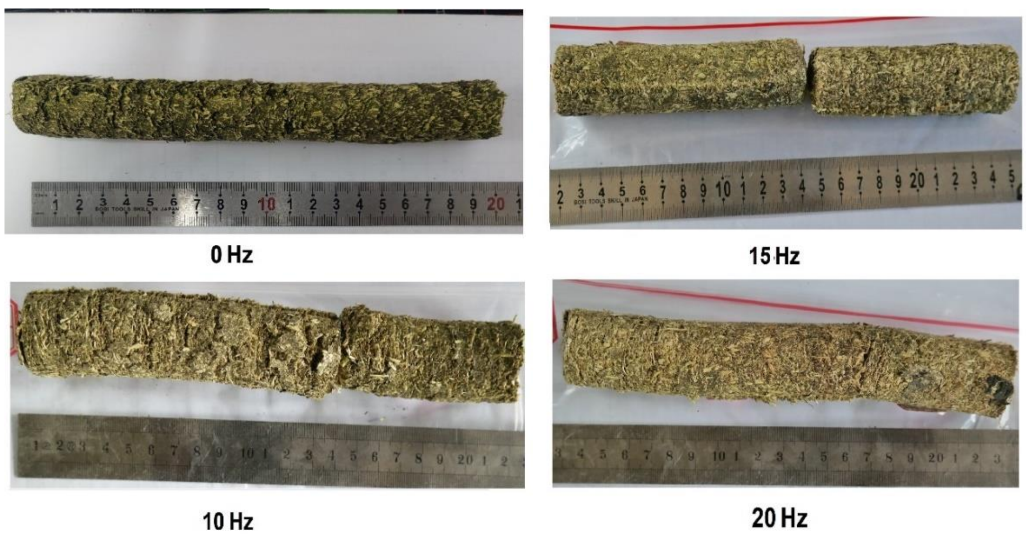


Fig. 10. Forming alfalfa block

Effect of Vibration Frequency on Production Efficiency

Combining the compression force and product, it can be seen that high pressure does not mean that high-density products can be produced. Figure 11 shows the maximum forming pressure and block density required to compress alfalfa at various vibration frequencies. It can be seen from the figure that the vibration not only reduced the pressure, but also increased the density of the product. In the frequency range of 0 to 15 Hz, the compressive force was negatively correlated with the vibration frequency, and the density of alfalfa blocks was positively correlated with the vibration frequency. In the 15 to 20 Hz range, the compressive force and the density were negatively correlated with the vibration frequency, but the alfalfa block density decreased at higher speed. Considering the pressure and the density, the optimized vibration frequency was approximately 15 Hz.

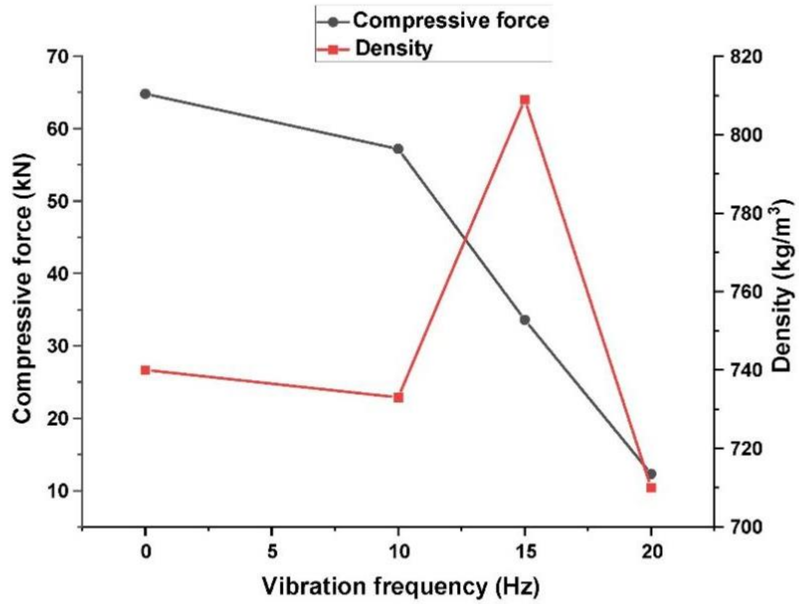


Fig. 11. Effect of vibration frequency on compressive force and forming density

CONCLUSIONS

1. Vibration can reduce compressive forces during alfalfa compression. Vibration frequency was negatively correlated with maximum compressive force.
2. The vibration was conducive to the release of the internal stress of the alfalfa block. In the shape retention stage, a second-order generalized Maxwell model was established to effectively fit the release law of the residual elastic force. The release ratio of the residual elastic force was the highest and the release speed was the fastest at 15 Hz of vibration frequency.
3. The vibration was beneficial to the stability of the alfalfa block. When the vibration frequency was 15 Hz, the stable density of the alfalfa block was the highest, the density change rate was the lowest, and there was no obvious crack on its surface.
4. Considering the pressure and molding density comprehensively, the optimized vibration frequency was about 15 Hz.

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