Experimental Study on Stress Transfer of Alfalfa during Vibration Compression

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To reveal the mechanistic role of vibration in the compression of alfalfa stalk, the stress transfer of alfalfa compression process under the action of vibration force field was evaluated with a self-developed vibration compression test system. The internal stress in the upper layer of the compressed material was gradually transmitted to the lower layer. The stress transfer rate between the upper and lower material varied with the vibration frequency. Within the experimental vibration frequency range, when the frequency was 15 Hz, the stress transfer rate was the smallest. Compared with ordinary compression, the stress transfer rate and maximum pressure during vibration compression were small, but the relaxation density was high, indicating that vibration is beneficial to alfalfa compression. Comprehensive analysis of stress transfer, maximum pressure and relaxation density, when the vibration with vibration amplitude of 0.5 mm and frequency of 15 Hz was introduced, a denser alfalfa block was obtained with less pressure.

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INTRODUCTION

Alfalfa is a perennial herb, commonly used as livestock feed. Compressing alfalfa into briquettes or pellets can retain the nutrients and improve the palatability of livestock. The compressed alfalfa blocks also have high density and regular shape. This is convenient for storage and transportation and effectively improves the utilization efficiency of alfalfa (Wang *et al*. 2017).

Alfalfa is a viscoelastic material that will exhibit elastic deformation recovery after being compressed, which can result in high energy consumption of compression equipment and poor quality of molded products (Mani *et al*. 2006; Wang 2011; Xia *et al*. 2014; De *et al*. 2020). To solve this problem, scholars have conducted a lot of research into the material properties and compression process (Sheng and Wu 2004; Dong *et al*. 2011; Holm *et al*. 2011; Yan *et al*. 2011; Chen *et al*. 2012; Lee *et al*. 2013). Kaliyan and Morey (2010) conducted compression tests on corncobs with different particle sizes. The results showed that as particle size decreased, the durability of compressed products and the relaxation density increased. Liu *et al.* (2016) studied the effect of moisture content on the yield limit of corn straw molded particles. Li *et al.* (2019) studied the effect of moisture content on relaxation ratio and compression energy consumption. Liu *et al.* (2009) optimized the die cone angle according to force of the die and the density of the molded product. Sun *et al.*

(2015) used numerical analysis and experimental methods to determine the relationship between lignin added in compressed materials and molding pressure. Zhang and Pei (2011) carried out the biomass ultrasonic vibration densification test, which showed that ultrasonic was helpful to reduce the pressure in the process of biomass compression.

The resistance of alfalfa stalk compression mainly comes from the friction between the material and the die wall, the relative movement, and deformation force between the materials. Mani (2005) studied biomass densification process and found that more than 60% of the total energy spent during the extrusion of pellet was to overcome the wall friction. The pelleting energy could be reduced if a new compaction unit may be designed and developed to decrease the frictional energy consumed during the compaction process.

Based on the principles of vibration reducing friction and vibration compaction, the authors' research group introduced the vibration force field into the alfalfa compression process. The experimental results verified that vibration can increase the stress relaxation rate and reduce the residual stress in the briquettes, so as to improve product quality and reduce the compression energy consumption (Wu *et al*. 2014; Ma *et al*. 2016; Xue 2018).

To further reveal the mechanism of vibration on the compression process and optimize the process parameters, an experimental study on stress transfer in compression under the action of vibration force field was carried out on the self-developed compression test system with alfalfa. The effects of vibration frequency on the maximum stress, stress transfer during compression, and relaxation density of alfalfa briquettes were analyzed.

EXPERIMENTAL

Materials

Alfalfa from the experimental field of Inner Mongolia Agricultural University was used for the present study. The harvested alfalfa was dried until the moisture content reached about 20%, as measured by a GMK-3308 moisture content tester (G-WON Company Ltd., Seoul, South Korea). The materials were milled into fibrous form using a 9RS-60 crushing machine (Manufactured in Machinery Plant of Inner Mongolia Agriculture University, Hohhot, China) and then sieved with a standard sieve to make the particle size distribution within 0.9 mm to 4 mm.

Method

A crank connecting rod mechanism is the core of the vibration device. The rotation of the motor is transformed into the up and down reciprocating motion of the vibrating rod through the belt, crank connecting rod, and slider, to realize the vibration compression. Changing the speed of the motor can change the vibration frequency of the vibrating rod, and changing the relevant parameters of the crank connecting rod mechanism can change the amplitude.

The alfalfa compression experiments were carried out when the amplitude was 0.5 mm and the vibration frequencies were 0, 5, 10, 15, and 20 Hz. The internal stress at different positions inside the compressed material was tested, and the effect of the vibration force field on the stress transfer during the compression process of alfalfa was analyzed.

As shown in Fig. 1, two CYYZ11 pressure sensors (Xin Yi Company Ltd., Beijing, China) were placed in the upper and lower positions of the compressed material in the die. 8 g of alfalfa was filled between sensor 1 and the compression piston and between sensor 2 and the vibrating rod, and 25 g alfalfa was compressed each time.

When alfalfa stalk and pressure sensors were put into the die according to the test scheme, the hydraulic system drove the piston down at a speed of 4.8 mm/s, and the mechanical vibration device started to work. When the piston moved to the bottom dead center of the stroke, the vibration compression was kept for 10 s, then the piston went up to complete a compression cycle. Pressure data was collected and recorded to the data acquisition system. The experiment was repeated five times in each group.

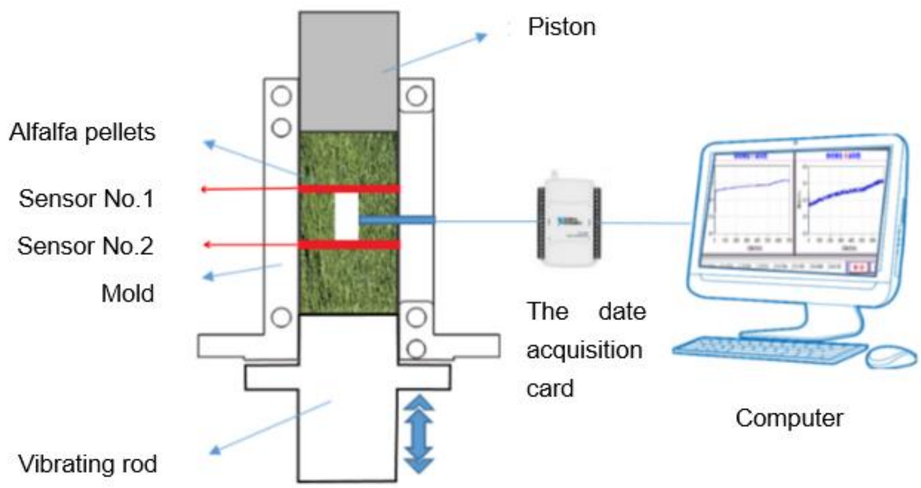

Fig. 1. Sensor layout

RESULTS AND DISCUSSION

Effect of Vibration Frequency on Stress Transmission

The internal stress-time curves of upper and lower layers of alfalfa stalk in the compression process were analyzed using Origin 2017 software (Origin Lab, 2017, Northampton, MA, USA and are shown in Figs. 2 and 3.

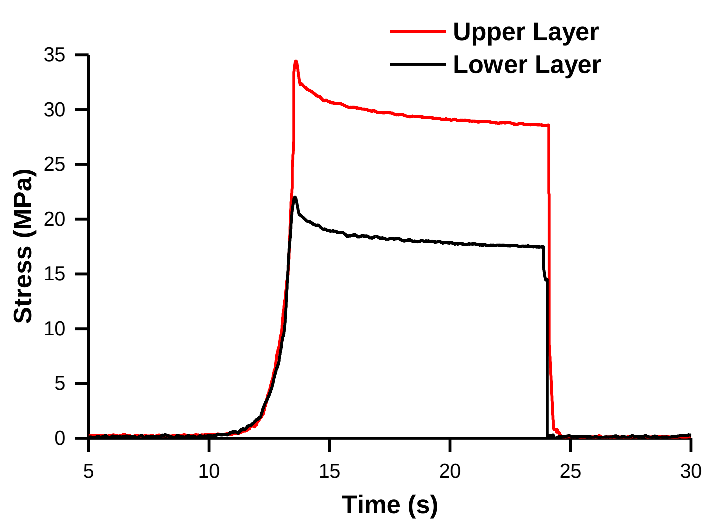

Fig. 2. Stress-time curves during compression without vibration

In the initial stage of compression, the alfalfa stalk in the die was looser, and the gap between materials was larger. The compression piston mainly overcame the gaps between materials and reorganized the materials. Therefore, the internal stress of the materials was very small and tended to zero. With continued compression, the gaps between the materials were eliminated, the material particles came into close contact, and the compressed alfalfa began to deform elastically and plastically. So, the internal stress gradually increased. When the compression piston reached the stop point of the downward stroke, the stress reached its maximum. In the holding stage, the internal stress of the material decreased rapidly at first, and then slowly. The stress in the upper and lower layers had the same changing trend under each compression condition.

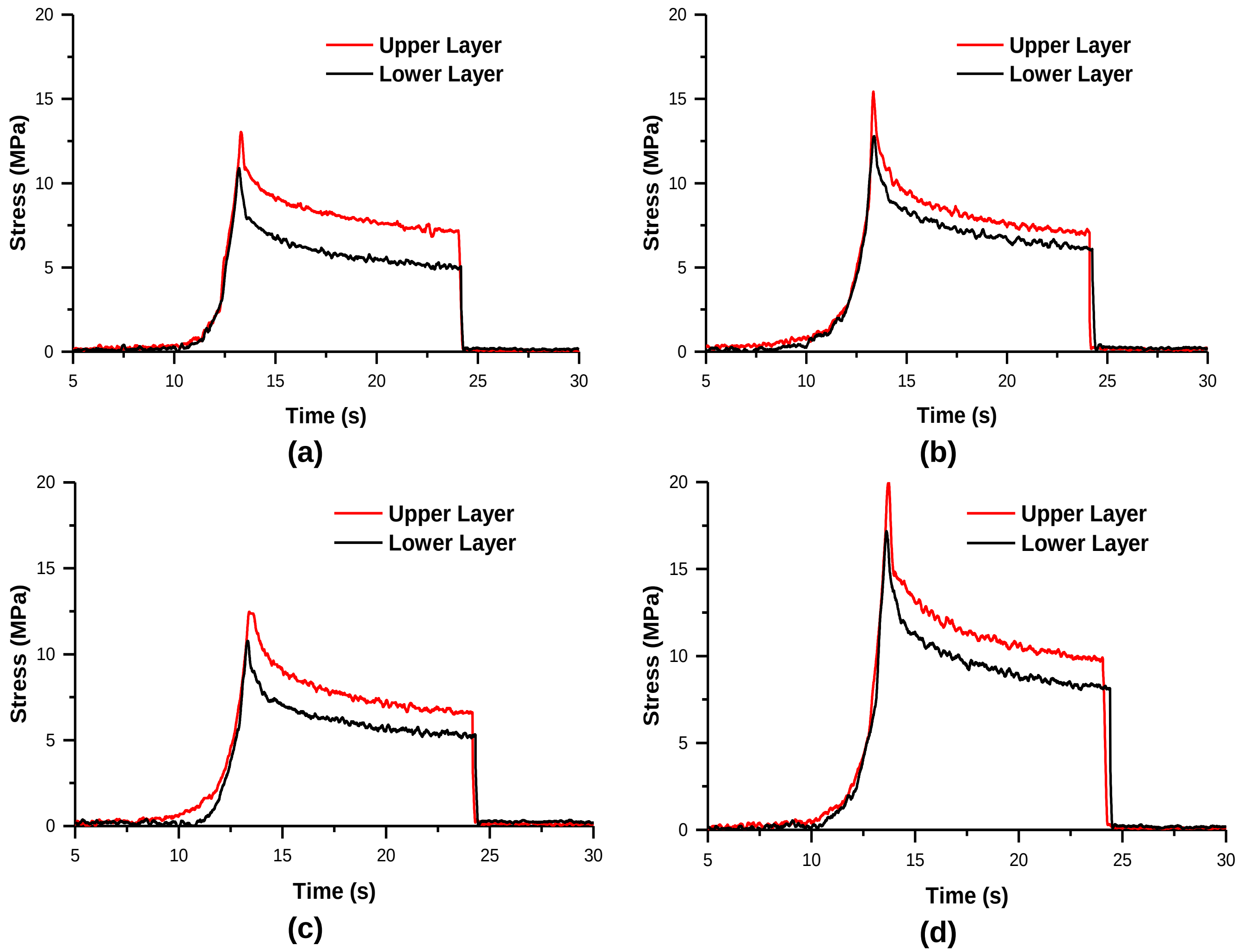

Fig. 3. Stress-time curves during compression under vibration: (a-5 Hz; b-10 Hz; c-15 Hz; d-20 Hz)

The internal stress in the upper layer was greater than that in the lower layer, which showed that the internal stress between materials decreased from the upper to the lower. The stress analysis of the upper material was carried out to explain this result. The stress analysis in the axial direction of the die is shown in the Fig. 4.

According to Newton's law, there is the following force balance formula,

$$F_p = F_1 + F_f + F_d \tag{1}$$

where F_p is the pressure of the compression piston on the material, F_f is the friction between the upper material and the die wall, F_d is the total deformation force of the upper material, F_1 is the stress exerted by the lower material on the upper material, and this stress is the force transmitted from the piston force to the lower material through the upper material.

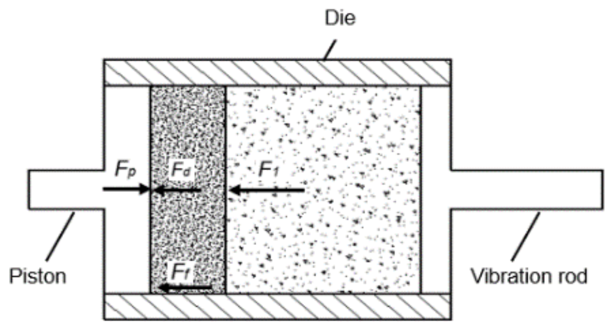

Fig. 4. Schematic diagram of stress analysis

During the compression process, the upper alfalfa stalk was compressed by the piston to produce elastic deformation and plastic deformation and then transmit the stress downward. The deformation of alfalfa stalk consumed part of the compressive force, and the friction between the material and the die wall also consumed part of the pressure, resulting in a decreasing trend of the internal stress in the material layer from top to bottom.

When the vibration frequency was varied, the internal stress was different when the material was compressed to the same density, and the difference between the two layers was different, indicating that the vibration frequency had a significant effect on the stress transmission.

The stress transfer rate is defined to calculate the transfer of stress in the compressed material. Stress transfer rate refers to the relative difference between the upper and lower layers of alfalfa stalk when the stress is transmitted from top to bottom during compression. The formula can be expressed as follows,

$$\eta = \frac{\sigma_{upper} - \sigma_{lower}}{\sigma_{\mathrm{upper}}} \times 100\% \tag{2}$$

where η denotes the stress transfer rate between the two layers of alfalfa stalk; σ_{upper} denotes the maximum stress on the upper layer of alfalfa; and σ_{lower} denotes the maximum stress on the lower layer of alfalfa. The greater stress transfer rate η, the less stress transfer from the upper material to the lower material, and the more energy is consumed by elastic and plastic deformation of alfalfa stalk. This is not conducive to the compression of alfalfa, and the resulting product quality tends to be poor. The specific values of stress transfer rate under various working conditions are shown in Table 1.

Table 1. Stress Transfer Rate under Various Test Conditions

Amplitude (mm)	Frequency (Hz)	σ_{upper}-σ_{lower} (MPa)	Transitive Relation (%)
0	0	12.43	36.08
0.5	5	2.14	16.42
	10	2.64	17.11
	15	1.7	13.63
	20	2.8	14.02

In the compression under vibration force field, the stress difference between the upper and lower layers of alfalfa stalk was significantly less than that in the non-vibration compression. The vibration was conducive to the stress transfer, thus reducing compression energy consumption. In the process of compression, superimposed vibration acts as a pulse force on the material, which makes the elastic deformation and plastic deformation of the material more sufficient, and the material adheres more closely, which is beneficial to the transmission of stress.

The stress transfer rate was different with different vibration frequencies. When the amplitude was 0.5 mm and the frequency was 15 Hz, the stress difference and the stress transfer rate, η, of the upper and lower layers were the smallest, so the compaction effect was better.

The Effect of Vibration Frequency on Maximum Pressure

Table 2 shows the maximum compression force without and with vibration compression. Compression force refers to the force exerted by the compression piston on the all alfalfa stalk in the die. The compression force mainly came from the friction between the material, the friction between the material and the inner wall of the die, the deformation resistance of the material, and the reaction at the bottom of the die.

When the alfalfa stalk was compressed to the same deformation, the maximum compression force under the action of vibration force field was smaller than that without vibration. The results showed that vibration force field can reduce the frictional force between materials and the friction between materials and die wall and the deformation resistance. The maximum pressure was the smallest while the alfalfa stalk was compressed under the vibration with the amplitude of 0.5 mm and frequency of 15 Hz.

Table 2. Maximum Pressure under Various Test Conditions

Amplitude (mm)	Frequency (Hz)	Maximum Stress (MPa)
0	0	34.45
0.5	5	13.03
	10	15.43
	15	12.47
	20	19.97

The Effect of Vibration Frequency on Relaxation Density

The test was carried out with the relaxation density of alfalfa briquettes to verify the effect of stress transfer on the quality of briquettes. Due to the recovery of elastic deformation, the density of alfalfa briquette will gradually decrease after being out of the die, and the density tends to be stable after a period of time. At this time, the density is the relaxation density. In this experiment, the density of briquettes after being released from the die for 24 h was taken as the relaxed density.

The alfalfa briquettes were a solid cylinder, and the relaxation density was calculated by estimating the volume of the briquettes. The method is as follows: After the alfalfa briquettes were allowed to relax for 24 h, the diameter d (mm) and height h (mm) of the alfalfa briquettes were measured with a caliper, and then the mass m (g) of the briquettes was weighed with an electronic counting scale. The relaxation density ρ (g/cm^3) of alfalfa briquettes could be expressed as follows.

$$\rho = \frac{4000m}{\pi d^2 h} \text{ (g/cm}^3\text{)} \quad (3)$$

The changing trend of alfalfa briquettes density under various test conditions is shown in Fig. 5. Compared with the alfalfa briquettes without vibration compression, the relaxation density of the alfalfa briquettes compressed by vibration was larger.

In the process of compressing alfalfa stalk, the stress in each layer of material was different. The upper material was compacted under greater pressure, and the lower layer material was relatively loose under less stress. If the stress transfer effect is good, then the density of the alfalfa briquette is uniform, and the ability to maintain its shape after being ejected from the die is strong. The above test results indicate that the vibration force field was conducive to stress transmission, and the result was that vibration can improve the density of alfalfa briquettes.

The relaxation density increased with the increase of vibration frequency. A large density can be obtained when the vibration frequency was 20 Hz, but the pressure required was also increased. Combining the relaxation density and maximum pressure, the better compression performance could be obtained when the vibration frequency was 15 Hz.

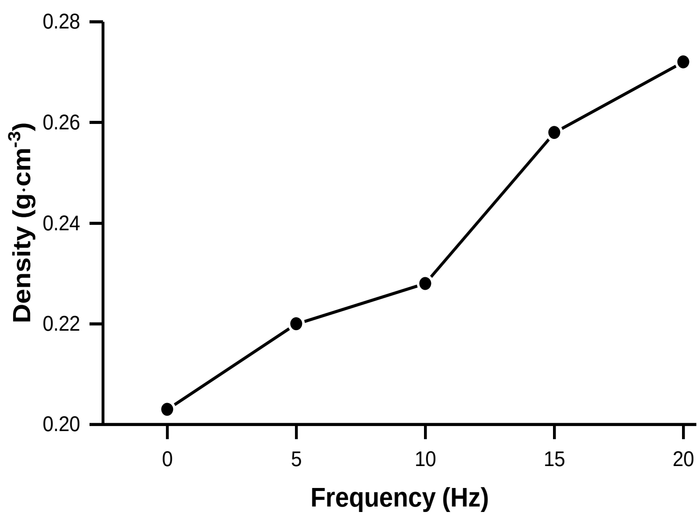

Fig. 5. Curve for relaxation density

CONCLUSIONS

1. The experimental study of stress transfer showed that the internal stress of the upper layer in the compressed alfalfa stalk was greater than that of the lower layer, indicating that the internal stress decreased from the upper layer to the lower layer.
2. The stress transfer rate of the upper and lower layers during vibration compression was less than that without vibration compression. That is, the stress of each layer in the material was more uniform during vibration compression, so the density of alfalfa briquette was higher than that without vibration compression.
3. The vibration frequency had a significant effect on the maximum pressure and the stress transfer rate in the compressed alfalfa. Based on the analysis of relaxation density, maximum pressure and stress transfer rate, the vibration force field with a vibration

amplitude of 0.5 mm and frequency of 15 Hz was superimposed, dense alfalfa briquettes were obtained with less pressure, and the stress transfer effect was the best.

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