EXPERIMENTAL STUDY OF STRESS RELAXATION IN THE PROCESS OF COLD MOLDING WITH STRAW

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In this article, five kinds of straws were used to do compressing molding experiments on stress relaxation by Electric Versatile Material Machine, with specially designed open mode equipment. According to the data from the transition stage of the compression process, regression equations with different straws were built by selective global fitting or piecewise fitting. In addition, the equations were verified by stress logarithm-time curves. A stress relaxation model of the five straws can be summarized by an expression involving the summation of exponential decay terms. This expression provides reference for reducing the specific energy consumption and increasing the pellet density.

Keywords: Straw; Open mode; Compress molding; Transition stage; Stress relaxation

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INTRODUCTION

Studies of the stress relaxation of straw using a closed die system were first carried out by the Russian scholar Osbov approximately fifty years ago (see Zhang 2001). Then, scholars from the USA, UK, Canada, and China began to describe this process using different models drawing upon rheology theory (Hu 2008; Faborode et al. 1986; Mohsenin et al. 1976; Bock et al. 1989). This promoted the development of straw rheology for further advances. There are mainly two kinds of models, one based on closed compressing, which is popular internationally (Federov 1972; Vinogradov et al. 1969; O'Dogherty 1989), and an open compressing model that is popular in China (Du 2005; Yan 2004; Wang 1998;Yang 2000;Wang et al. 1997). These models provide methods for the development of molding theory, although they use different means of compressing and different equations.

There are some limitations in the theoretical analysis and equipment design, when using the conclusions from the existing studies in the development and perfection of compressing molding technology. For example, the closed die model used by the international scholars is not practical for real manufacture. Scholars from China have done a lot of study work using fresh materials for the design and manufacture of bundling machinery. However they have not carried out detailed study on different kinds of straws, so the stress relaxation models with different kinds of straws and their rheological parameters have not been put forward. In particular, studies involving stress relaxation of straw pellets are scarce. Therefore, in this article, five kinds of straws were used to do compressing molding experiments on stress relaxation. Regression equations with different straws were built. This provides a reference for reducing the specific energy consumption and increasing pellet density.

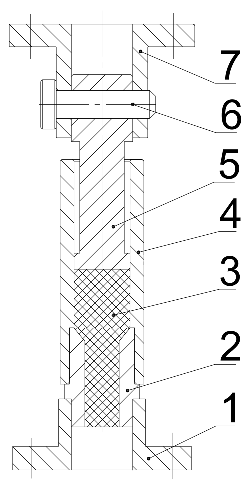
MATERIALS AND EQUIPMENT

Raw Material

Five kinds of materials considered in this work were rice straw, cotton straw, corn stalk, corn cob, and wheat straw, all gathered from the suburbs of Zhengzhou City. The materials were first crushed in a mini crusher. Then they were dried at 105°C for 8 hours and subsequently sealed with plastic bags. When they were cooled, the moisture ratio was adjusted to 16% by adding water into each bag of material to reach a mass of 30g per bag.

Equipment for the Experiment

The equipment used a WDW-50 computer-controlled electrical universal material experimental machine. Its metering range of pressure was 1 to 50 kN, the moving speed of the beam was 2 to 200 mm/min, and the precision of the displacement measurement was ±1%. The open die was designed to fulfill the special needs of the test. It consisted of a sleeve, die, pressure lever, and pin (Hu et al. 2008). An illustration is shown in Fig. 1:



1. bottom 2. die 3. material 4.sleeve 5.pressure lever 6.pin 7. Fixture

Fig. 1. Illustration of open straw pellet molding equipment

As shown in Fig. 1, the inner diameter of the sleeve was 15 mm, the inner diameter of the die was 10 mm, the conicity of the die was 45^{o}, the length-to-diameter ratio was 5.2, and the moving speed of the beam was 40 mm/min. The material was filled into the sleeve after being weighed by an electronic balance. As the raw material was very loose, so the die was pre-pushed, using a stamp stem in the machine, then the computer program was started to control the machine, record the data in different periods, and finally do the computation and regression analysis work.

RESULTS AND DISCUSSION

Compressing Characteristic Curve with Straw

From the experimental results we know that, for different kinds of straws, the changing discipline of their compressing characteristic curve were similar, exhibiting the features shown in Fig. 2 (Bai 2009), although there were differences in detail between different curves.

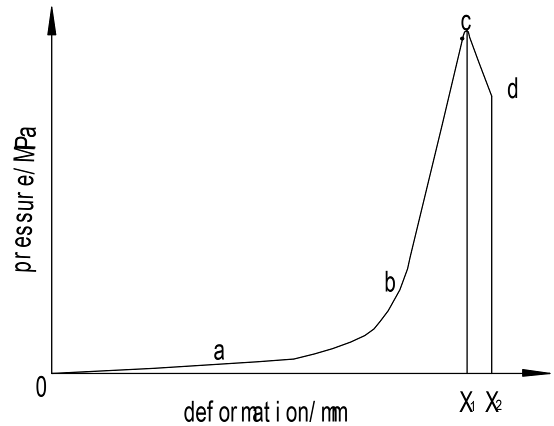


Fig. 2 Compressing characteristic curve with straw

From Fig. 2 it is apparent that the compressing characteristic curves were complex. For the sake of a detailed discussion of the molding process, in this article the compressing curves are divided into four mechanistic stages. These are designated as a loose stage (oa), a transition stage (ab), a compressing stage (bc), and a displacive stage (cd). In stage oa, the pressure is low and local elastic deformation happens. Air and moisture in the loose material are removed. The air gap decreases. In this stage, large deformation can be obtained with small pressure. In stage ab, plastic deformation becomes prominent with the increase of the pressure. As a consequence of the applied pressure, large particles of materials break into small particles, and the particles are re-arranged to fill in the gap between them. In stage bc, the gaps have been eliminated, so plastic deformation occurs. The position and shape of the particles change, or rupture and slippage occurs. The particles are re-arranged. Along the main stress, the particles become thin, and the adjacent particles are closely joined together. Perpendicular to the main stress, the particles are spread, and the particles join together by a gearing mechanism. There is remnant stress, which makes the particles join more closely. In this stage, the pressure is a function of the mechanical resistance. In stage cd, the materials move along with the lever. Sticky deformation occurs in this stage. The deformation is a function not only of pressure, but also the acting time and recovery time. The stress decreases with time, so it's a typical stress relaxation process (Du 2005).

Regression Equation of the Stress Relaxation

Of the four stages described above, elastic deformation occurs mainly in the first two stages, plastic deformation mainly in the third stage, and elastic and elastic-plastic deformation mainly in the last stage. In the last (displacive) stage, the pressure lever moves with the material, which remains stationary in a relative sense. The material shows elastic and elastic-plastic deformation under the same volume, and it's found that the stress decreases with time, which is typical for a stress relaxation process. The data in the displacive stage for the five kinds of straws are given in Table 1 (Hu 2008):

It was found that, for cotton straw and corn straw, the R^2 values from the regression equations were all greater than 0.98. Also, the stress relaxation regression equations all were in the form of $y=Ae^{-Bx}$, where A and B are the factors. These results showed that the overall fitting can well reflect the stress relaxation process for the two kinds of straws. For the fitting results, see Figs. 3 and 4.

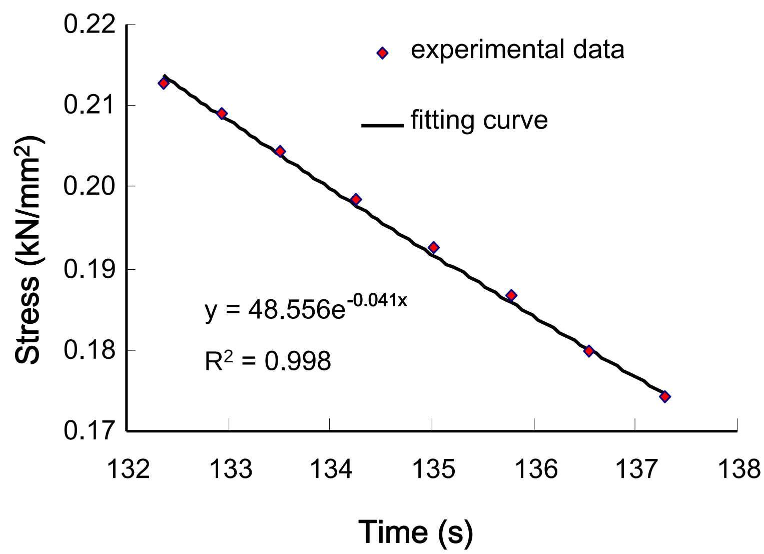


Fig. 3. Overall fitting curve of stress relaxation with cotton straw

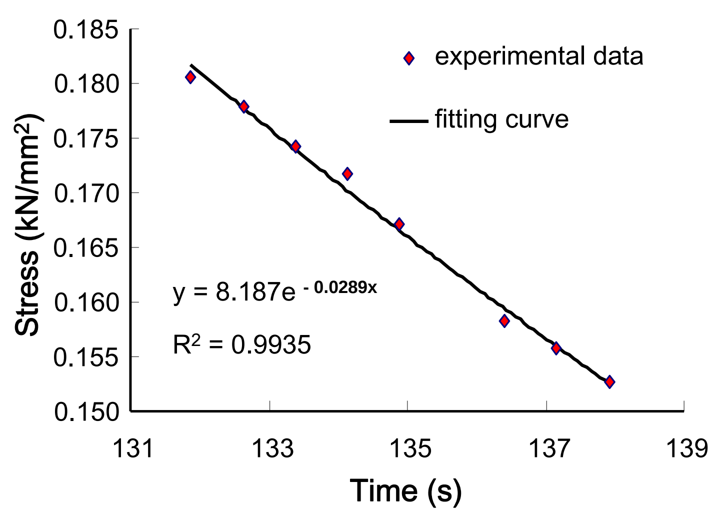


Fig. 4. Overall fitting curve of stress relaxation with corn straw

Table 1 . Parameters in the Displactive Stage with Five Kinds of Straws

Variables / Materials	DEFORMATION/mm	PRESSURE/ kN	TIME/s	STRESS/ kN·mm^{-2}
Rice straw	86.3	41.718	129.5	0.214
	86.8	41.141	130.2	0.212
	87.2	40.042	130.8	0.206
	87.8	39.363	131.7	0.202
	88.3	38.270	132.5	0.197
	88.7	37.167	133.1	0.191
	89.1	35.797	133.6	0.184
	89.2	35.106	133.8	0.181
Cotton straw	88.2	43.988	132.4	0.213
	88.6	43.229	132.9	0.209
	88.6	43.229	132.9	0.209
	89.5	41.025	134.3	0.198
	90.0	39.80	135.0	0.192
	90.5	38.56	135.8	0.186
	91.0	37.149	136.5	0.179
	91.5	36.025	137.3	0.174
Corn straw	87.9	35.256	131.9	0.181
	88.4	34.741	132.6	0.178
	88.9	34.013	133.4	0.174
	89.4	33.538	134.1	0.172
	89.9	32.635	134.9	0.167
	90.9	30.922	136.4	0.158
	91.4	30.435	137.2	0.156
	91.9	29.825	137.9	0.153
Corn cob	87.4	29.490	131.1	0.153
	87.8	28.933	131.7	0.150
	88.0	28.602	131.9	0.148
	88.2	28.386	132.3	0.147
	88.4	28.276	132.6	0.146
	88.7	28.162	133.1	0.146
	88.9	28.095	133.4	0.145
	90.4	27.657	135.5	0.143
Wheat straw	97.8	39.949	146.6	0.198
	97.9	39.874	146.8	0.197
	98.1	39.752	147.2	0.197
	98.4	39.531	147.6	0.195
	98.6	39.000	147.9	0.193
	99.0	38.358	148.5	0.190
	99.4	37.804	149.1	0.187
	99.8	37.215	149.7	0.184

For rice straw, corn cob, and wheat straw, their R^2 values from the regression equations were all less than 0.98. The fitting of the data was not as precise as what is expected, so subsection fitting was adopted. The results from the subsection fitting process are shown in Figs. 5 to 7.

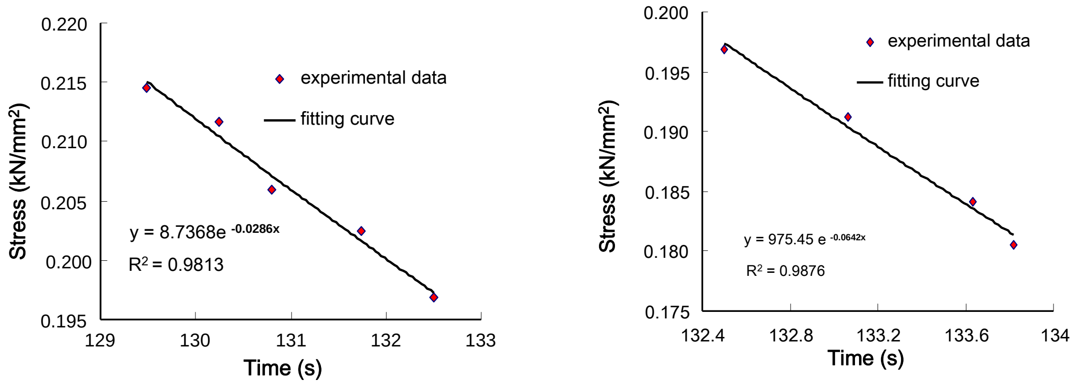


Fig. 5. Subsection fitting curve of stress relaxation with rice straw

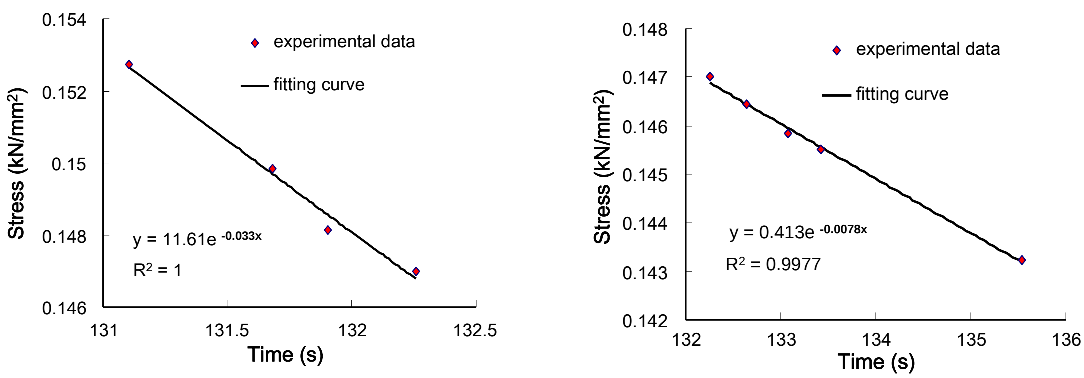


Fig. 6. Subsection fitting curve of stress relaxation with corn cob

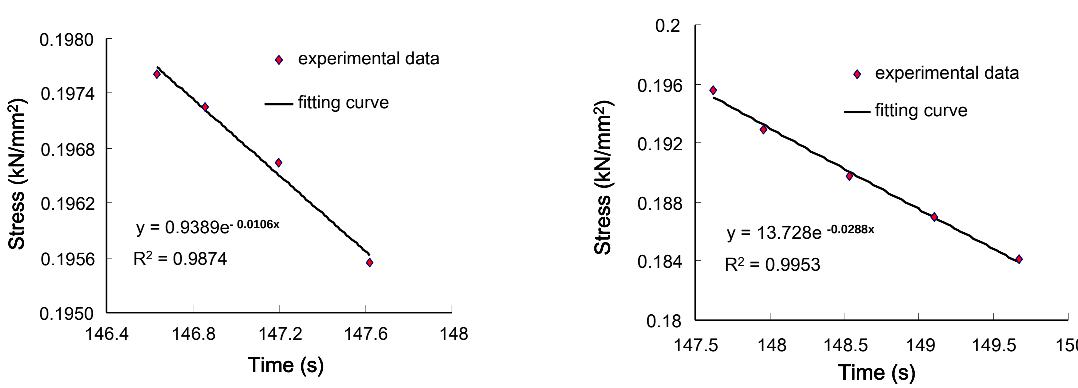


Fig. 7. Subsection fitting curve of stress relaxation with wheat straw

From the figures above, the values of R^2 in the subsection regression equations for the three kinds of straws were all greater than 0.98. These results demonstrate that subsection fitting can well reflect the stress relaxation process in the displacive stage. The process involved two regression terms corresponding to each of the two stages, giving the combined form $y=Ce^{-Dx}+Ee^{-Fx}$, where C, D, E, and F are the coefficients.

The Construction of Stress Relaxation Model

Normally, the material of straw shows elastic and elastic-plastic character at the same time. The two demonstrate respective importance under different experimental conditions. The material mainly shows elastic character when the temperature is low or the compressing speed is especially high. And it mainly shows elastic-plastic character when the temperature is high or the compressing speed is especially low. For the straw pellet molding in this study, the two characters are easy to demonstrate.

Both the international and the Chinese researchers cited in this study have employed ideal mechanical elements (Hooke body, St. Venant body, Newton body, Kulun body) and mechanical models (Maxwell model, Kelvin model, Bugers model, Peleg model) (Yang 2002). For stress relaxation, the Maxwell model has been mainly used. This model has two basic elements, an ideal spring and an ideal dashpot. The former element agrees with Hooke's Law used to simulate elastic deformation. The latter element agrees with Newton's Fluid Law used to simulate elastic-plastic deformation. The two elements can connect in series or in parallel together to make up complex multi-element models. Maxwell models of different forms are shown in Fig. 8.

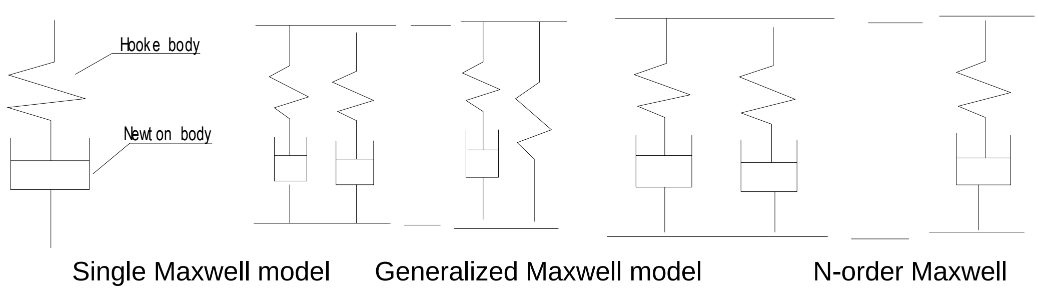


Fig. 8. Chart of Maxwell models

Because straws are typically elastic and elastic-plastic materials, this can be simulated by an ideal spring and dashpot if they are connected with different forms. From the stress relaxation regression equations of the five kinds of straws, they all agree with the Maxwell model.

The rheology equation of a single Maxwell model is:

$$\sigma(t) = Ae^{\frac{t}{T}} \tag{1}$$

In Eq. 1, $\sigma(t)$ is stress, with units of kN/mm^2; A is the maximum stress of a single Maxwell model (with the same units); T is the stress relaxation time for a single Maxwell model; and t is the compressing time in s.

Taking natural logarithms for the two sides of Equation (1), the following equation can be obtained:

$$\ln \sigma(t) = \ln A - \frac{t}{T} \tag{2}$$

Making a chart with stress logarithm as the vertical coordinate and time as the horizontal coordinate, the plot shows a linear relation in the single Maxwell model. In order to check whether the regression equation in the stress relaxation stage was right, we constructed curves between stress logarithm and time. Linear relations were obtained for cotton straw and corn straw. And for rice straw, corn cob and wheat straw, non-linear relations were obtained. So, for different kinds of straws, their stress relaxation regression equations cannot be described by one single Maxwell model. For cotton straw and corn straw which show linear relation, the process can be represented by one single Maxwell model. For rice straw, corn cob, and wheat straw, which showed non-linear relations, the process could be described by two or more Maxwell models, a generalized Maxwell model, or an N-order Maxwell model parallel connected by n Maxwell model. This conclusion fits with the former stress relaxation regression equations with different kinds of straw.

In addition, from the fitting results by different stages of rice straw, corn cob, and wheat straw, their fitting level was quite similar; the related coefficients of determination were greater than 0.98, and there were no remainder terms in the equations. It was demonstrated that the data could be best fit when there was no spring in the three stress relaxation models which can be described by an n-order Maxwell model. So the stress relaxation models for five kinds of straws in this article can be described by the following formula:

$$\sigma(t) = \sum_{i=1}^{n} A_i e^{\frac{-t}{T_i}} \tag{3}$$

In this formula A_i is the maximum stress for the i^{th} Maxwell model, having units of kN/mm^2; T_i is the stress relaxation time for the i^{th} Maxwell element; and n is the number of the Maxwell model (n=1,2).

Moreover, from the stress relaxation regression equations for the five kinds of straws, one can see that the fitting coefficients were suitable for every equation. It was shown that the stress decreased rapidly in the displacive stage. There are mainly two reasons for this. The first is that the predominant factor changed from the friction force term to the kinetic term in this stage in which the pressure was decreasing (Yan 2004). The second is that the stress relaxation for the material occurred, such that recovery from the deformed state decreased after pressure relief. This finding will be helpful for reducing the specific energy consumption of the equipment and increasing the density of the pellet, which are crucial considerations for the molding process.

CONCLUSIONS

1. The process of straw open molding is complex, and it can be divided into four stages, which have been called loose, transitional, compressing, and displacive. Elastic deformation happens mainly in the first two stages, whereas plastic deformation mainly occurs in the third stages, and elastic and elastic-plastic deformation mainly occur in the last stages.
2. In the displacive stage of the straw open molding process, the material shows elastic and elastic-plastic deformation under the same volume. Also, the stress decreases with time, which is typical for a stress relaxation process.
3. The stress relaxation model for five kinds of straws in this article can be described by the following formula: $\sigma(t) = \sum_{i=1}^{n} A_i e^{\frac{-t}{T_i}}$ (n=1,2). The stress relaxation equations for cotton straw and corn straw can be described by a model consisting of a single Maxwell element. The stress relaxation equations for rice straw, corn cob, and wheat straw can be described by two parallel connected Maxwell elements.

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