Experimental Study on Molding Technology for a Mixture of Corn Straw and Cow Manure

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To improve the comprehensive utilization of planting and breeding waste resources, corn straw and cow manure were used as raw materials for exploring the molding process parameters for preparing agricultural fertilizers *via* compression after mixing. The pressure, compression speed, and holding time were the experimental factors, while the block drainage, compression ratio, and dimensional stability were used as evaluation indicators. This study analyzed the influence of various factors on the quality evaluation index of the formed blocks. The results show that the best factor ranges were as follows: a pressure of 15 kN to 24 kN, a compression speed of 200 mm/min to 400 mm/min, and a holding time of 30 s to 60 s. A ternary quadratic regression and rotating-combination test design was used to optimize the combination of forming parameters as well as performing test verification. The formed block yielded the following results: a block drainage of 6.29%, a compression ratio of 3.37, a dimensional stability of 86.5%, a pressure of 23.9 kN, a compression speed of 276 mm/min, and a holding time of 53.1 s. These results can provide a reference for the molding process and equipment development of corn straw and cow manure mixed fertilizer.

Keywords: Straw; Cow manure; Fertilizer; Compression molding; Compression ratio

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INTRODUCTION

The annual crop straw output from China is approximately 1 billion tons. Fertilizer utilization is one of the most important methods for the comprehensive use of straw resources. Currently, the utilization rate is less than 40%, with a large amount of straw being abandoned or burned in the open, causing a serious waste of resources (Wang *et al*. 2017; Shi *et al*. 2018; Huo *et al*. 2019; Zhang *et al*. 2019). In recent years, there have been serious livestock excrement pollution problems throughout the world. The excessive amount of livestock excrement has contributed to pollution both in surface and in ground waters. Many European Union countries have formulated corresponding policies to solve this problem, but the issue has not been fully resolved in China (Pampuro *et al.* 2013; Zhao *et al*. 2014; Tian *et al*. 2018a; Feng *et al*. 2019).

Corn straw and cow manure are important biomass resources that can be characterized as having high organic matter content and a wide variety of sources as well as being easily converted. High-quality agricultural organic fertilizers can directly or indirectly replace chemical fertilizers. This can be done by mixing corn straw with cow manure on the spot or offsite. This effectively solves the problems of reducing the high cost of removing straw from the field, the decline of farmland soil fertility, and the low comprehensive utilization rate of planting and raising waste resources (Moore and Gamroth

1991; Theerarattananoon *et al*. 2011; Samuelsson *et al*. 2012; Xin *et al*. 2017). The scattered distribution of corn straw and cow manure adversely affects the economy and the operability of large-scale resources for utilization. In this scenario, compression molding can effectively solve the problems of large transportation volumes, low bulk densities, and high storage costs. Multiple authors all separately studied the influence of barley, wheat, and other straw particles on the compression force during material forming (Krul *et al*. 2000; Adapa *et al*. 2009; Mitchual *et al*. 2013; Peng *et al*. 2013; Muazu and Stegemann 2015; Yang *et al*. 2016; Gong *et al*. 2019; Pampuro *et al.* 2020). The results showed that when the pressure increases, the density of the particles in the material is greatly increased, which indicated that pressure has a strong influence on the properties of the material formed. Al-Widyan *et al*. (2002) studied the influence of pressure and holding time on the stability and durability of a formed block. O'Dogherty and Wheeler (1984) chose straw and grass as the research objects and obtained the compressive stress range of their mixtures under optimal molding conditions by studying its molding processes. Jackson *et al*. (2016) compressed blind grass, switchgrass, corn straw, and wheat straw and found that the moisture content of the mixture had a significant impact on the durability of the formed particles, content with durability of 92%, 92%, and 96%. Cao *et al*. (2015) performed a compression molding experiment on a mixture of rice straw, corn cob, and cow manure; they studied the influence of pressure and other factors on the quality of the formed block. Gong *et al.* (2019) studied the action and influence of various factors, *e.g.*, compression speed, on the molding process of straw briquettes. Presently, both domestic and foreign scholars have conducted numerous studies on the process conditions of compressing corn straw and cow manure to prepare feed or fuel. However, in-depth research on the compression molding characteristics of corn straw and cow manure mixture is still needed.

According to the technical specifications of mixed fertilizer comprising of corn straw and cow manure (Li and Dong 2002; Lei *et al*. 2011; Theerarattananoon *et al.* 2011; Tian *et al*. 2018b; NY/T 3442 2019), the mixture must lose less water during the compression process to ensure that the moisture content of the formed block meets the optimal moisture content requirements of fertilizer and is convenient for subsequent storage and transportation. The compressed block must also have a certain degree of stability while ensuring a large compression ratio. Based on the above requirements, this paper will use mixed and stirred corn straw and cow manure in order to study the optimal parameter combination of the two and evaluate compression molding under the cold pressing mode, as well as analyze the influence of pressure, compression speed, and holding time on the loss of water in the formed block. The results are expected to provide theoretical support for exploring the compression molding technology of a straw and cow manure mixture, and the development and improvement of molding equipment.

EXPERIMENTAL

Test Materials and Equipment

According to the Chinese agricultural industry, NY/T standard 3442 (2019) provides technical specifications for the composting of livestock and poultry manure. The technical requirements needed for mixed corn straw and cow manure fertilizer are as follows: a particle size of no greater than 50 mm and an optimal initial moisture content range of 45% to 65% (Tian *et al.* 2018b). The corn straw for the test was collected from the Beishan scientific research base of the Shenyang Agricultural University (Shenyang, China). After harvesting in October 2019, the corn straw was shredded to a geometric width of approximately 2 mm to 5 mm and a geometric length of 10 mm to 20 mm. The average moisture content after natural drying ranged from 13% to 15%. The test cow-manure was obtained from a farm in the Sujiatun District, Shenyang, China. Later, it was passed through a screen to remove impurities. The average moisture content of the cow manure in the natural state was approximately 70% to 72%. The corn straw and cow manure were mixed together in a dry matter to mass ratio of 2 to 3. Deionized water was added before the test to obtain a mixture with an average moisture content of 64% to 66%. The required material quantity was calculated according to the dry matter mass ratio and moisture content of the corn straw and cow manure. The mixture was then evenly stirred, sealed, and stored.

The forming block compression equipment used a WDW-200 microcomputer-controlled, electronic universal testing machine (Jinan Shijin Group Co., Ltd, Shandong, China). The maximum compression force was 200 kN, and the compression speed ranged from 1 mm/min to 500 mm/min. The forming mold was 200 mm long, 200 mm wide, and 480 mm high. The bottom plate can withstand a maximum pressure of 60 kN. The mold primarily consists of a top rod and a compression box. The compression box is hollow with an open upper end and the four walls of the box and the steel plate can be disassembled to facilitate the removal of the formed blocks. The lower part of the compression box contains holes, where the drainage device can be connected to measure the drainage (Wang *et al.* 2020). The schematic diagram of the test equipment is shown in Fig. 1. The moisture content of the mixture was measured *via* a SFY- 60 halogen fast moisture meter (Shenzhen Guanya Electronics Technology Co., Ltd, Guangdong, China), and the quality was measured *via* a YHC - A8 precision electronic scale (Harbin Zhonghui Weighing Apparatus Co., Ltd).

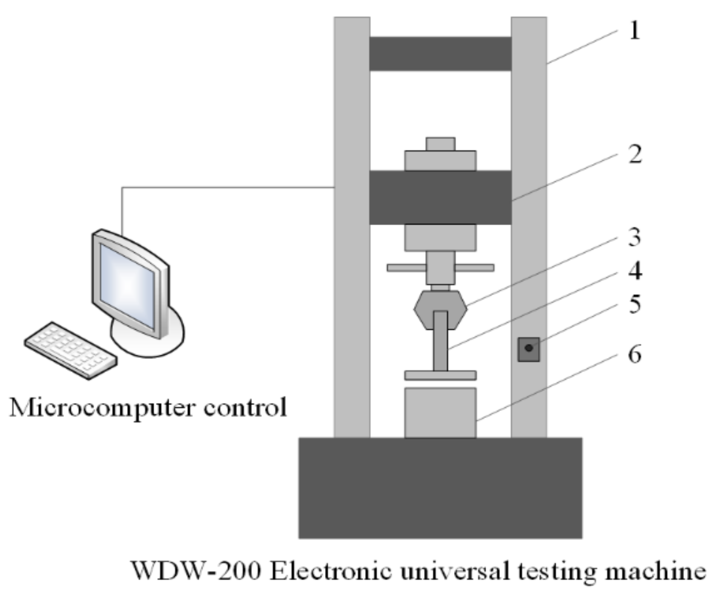


Fig. 1. Schematic diagram of the compression test equipment. Labels: 1. Frame 2. Beam 3. Chuck 4. Ejector pin 5. Test equipment switch 6. Compression box

Statistics

The statistical package of Excel 2016 software was employed to analyze the experimental data. The variance of the test data was analyzed for each factor to determine the significance of the factors, establish the regression model of each index and the factor and regression graph, and conduct the significance test and the lack of fit test.

Test Index

Drainage

The amount of drainage (Li *et al*. 2011) can reflect the change in the moisture content of the material before and after compression molding. The calculation formula is shown in Eq. 1. A SFY- 60 moisture meter was used to measure the moisture content of the mixture before and after the compression process. The optimum initial moisture content range for the mixed fertilizer was 45% to 65%, but since the mixed material had an initial moisture content of 64% to 66%, the water loss should be minimized during the compression process. The drainage of the material after undergoing compression molding was made less than 20% to meet the test requirements, as calculated by Eq. 1,

$$D = P_o - P_k \quad (1)$$

where D is the drainage (%) of the formed block, P_o is the moisture content of the material before compression (%), and P_k is the water content of the formed block after compression (%).

Compression ratio

The compression ratio (Liu *et al*. 2018) refers to the ratio of the volume of the material before and after undergoing compression molding, and the calculation formula is shown in Eq. 2. First, the bulk density and mass of the mixture before compression are measured to calculate its volume, then the size of the formed block is measured to calculate the volume. The larger the compression ratio, the better the compression effect, as calculated in Eq. 2,

$$\mathrm{CR} = \frac{V_o}{V_n} \quad (2)$$

where CR is the compression ratio of the formed block, V_o is the volume of the material before compression (m^3), and V_n is the volume of the formed block after the material is compressed (m^3).

Dimensional stability

Dimensional stability (Chen *et al*. 2016) is used as an evaluation indicator of the molding effect, which can reflect the stability of the formed block after 72 h of relaxation. The calculation formula is shown in Eq. 3. The size of the compressed block, as well as its size after 72 h of relaxation, are measured, which are used to calculate the volume of the block. The greater the dimensional stability, the better the molding effect, as calculated by Eq. 3,

$$\mathrm{DS} = \left(1 - \frac{V_t - V_n}{V_n}\right) \times 100\% \quad (3)$$

where DS is the dimensional stability (%) of the formed block, V_n is the volume of the formed block (m^3), and V_t is the volume (m^3) of the formed block after being allowed to stand for 72 h.

Test factor level determination

A single factor test was utilized to analyze the influence of the pressure, compression speed, and pressure-holding time on the quality evaluation index of the mixture molding process. In addition, this analysis was used to determine: 1.) the range of influencing factors on the compression molding process for a mixture of corn straw and cow manure; and 2.) the optimal molding process, according to the preliminary tests and literature reviews. The influencing factors were as follows: pressure values (9 levels), 6, 9, 12, 15, 18, 21, 24, 27, and 30 kN; compression speeds (9 levels) 100, 150, 200, 250, 300, 350, 400, 450, and 500 mm/min; and pressure-holding time (9 levels), 10, 20, 30, 40, 50, 60, 70, 80, and 90 s. The experiment was repeated three times for each factor level. Excel 2016 and Origin 2018 software were used to analyze the variance of the experimental data and to draw the trend chart. In addition, it was used to establish the regression model of each index and factor as well as conduct a significance test and a lack of fit test.

Test design

Using the pressure, compression speed, and holding time as the experimental factors, a ternary quadratic regression orthogonal rotation combination design was adopted. The experimental data was processed with Design Expert 8.0 and Excel 2016 software in order to determine the range of levels for each factor, according to the results of the single factor test, and code its value range (Table 1).

Table 1. Table of Factors and Levels

Levels	Pressure (X_1) (kN)	Compression Speed (X_2) (mm·min^{-1})	Holding Time (X_3) (s)
Upper asterisk arm (+1.682)	24	400	60
Upper level (+1)	22.2	359.5	54
Zero level (0)	19.5	300	45
Lower level (-1)	16.8	240.4	36
Lower asterisk arm (-1.682)	15	200	30

RESULTS AND DISCUSSION

Effects of the Test Factors

Effect of pressure

The experiment was carried out according to the experimental plan, with the compression speed set to 100 mm/min and the holding time set to 60 s. The results of the variance analysis for the effect the pressure had on the drainage of the formed block showed that the F_A (123.08) was greater than the $F_{0.01}[8,18]$ (3.71), which indicated that the pressure had an extremely significant effect on the drainage of the formed block. A regression model of the drainage was established, and a regression curve was drawn, as shown in Fig. 2. The amount of drainage increased with an increase in pressure. When the pressure was 30 kN, the amount of drainage of the formed block reached its highest value (8%). However, all drainage values were less than 10%, which met the test requirements. The regression equation is shown in Eq. 4,

$$\widehat{D} = 0.0016p^2 + 0.4166p - 2.8302 \quad (4)$$

where D refers to the factor " drainage " and p refers to the factor "pressure".

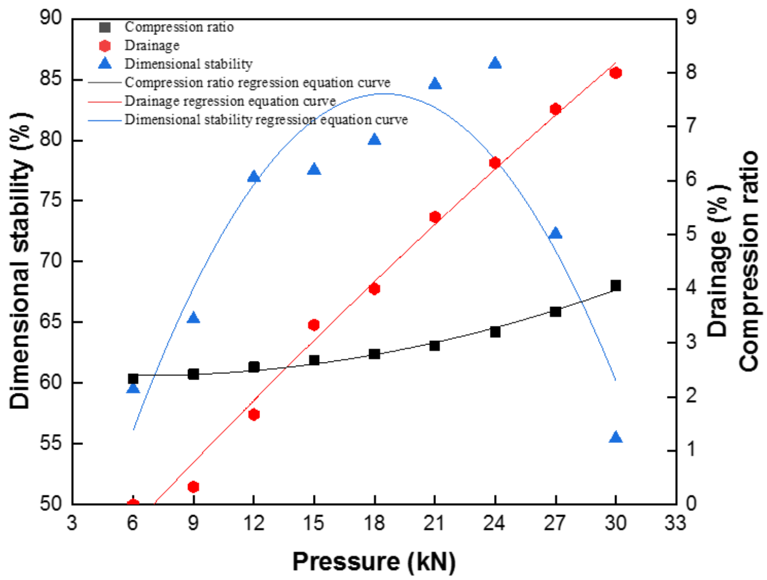


Fig. 2. Influence of the pressure, compression ratio, and dimension stability of the formed blocks. Dimensional stability regression equation curve or left, drainage and compression ratio regression equation curve belongs to right Y-axis

The results of the variance analysis for the effect the pressure had on the compression ratio of the formed block showed that the F_A (557.56) was greater than the $F_{0.01}[8,18]$ (3.71), which indicated that the pressure had an extremely significant effect on the compression ratio of the formed block. A regression model of the compression ratio was established, and a regression curve was drawn, as shown in Fig. 2. The compression ratio of the formed block increases with an increase in pressure and when the pressure is 30 kN, the maximum compression ratio of the formed block is 4.06. The regression equation is shown in Eq. 5,

$$\widehat{CR} = 0.0028p^2 + 0.0347p + 2.4969 \tag{5}$$

where *CR* refers to the factor " compression ratio ", and *p* refers to the factor "pressure".

The results of the variance analysis for the effect the pressure had on the dimensional stability of the formed block showed that the F_A (38.50) was greater than the $F_{0.01}[8,18]$ (3.71), which indicated that the pressure had a significant influence on the dimensional stability of the formed block. A regression model of the dimensional stability was established, and a regression curve was drawn (Fig. 2). When the pressure ranged from 6 to 24 kN, the dimensional stability of the formed block increased as the pressure increased; when the pressure ranged from 24 to 30 kN, the dimensional stability of the formed block decreased as the pressure increased. When the pressure was 24 kN, the maximum dimensional stability of the formed block was 86.3%. The regression equation is shown in Eq. 6,

$$\widehat{DS} = 0.178p^2 + 6.5772p + 23.065 \tag{6}$$

where *DS* refers to the factor " dimensional stability ", *p* refers to the factor "pressure".

To summarize, the total compression of the formed block was relatively large and it had high dimensional stability, under the premises that the drainage amount meets the test requirements and that the pressure applied during block formation was within the range of 15 kN to 24 kN.

Effect of the compression speed

The experiment was performed according to the experimental plan, with the pressure set to 23 kN and the holding time set to 60 s. The results of the variance analysis of the effect the compression speed had on the drainage of the formed block showed that the $F_{0.05}$[8,18] (2.58) was less than the F_A (3.65), which was less than the $F_{0.01}$[8,18] (3.71), which indicated that the compression speed had an extremely significant effect on the drainage of the formed block. A regression model of the drainage was established, and a regression curve was drawn, as shown in Fig. 3. The amount of drainage increased with an increase in compression speed. When the compression speed was 450 mm/min or 500 mm/min, the highest rate of water loss of the formed block was 7.67%; which is less than 10% and therefore meets the test requirements. The regression equation is shown in Eq. 7,

$$\widehat{D} = 5 \times 10^{-6} cs^2 + 0.0069cs + 5.5825 \quad (7)$$

where *D* refers to the factor " drainage ", and *cs* refers to "compression speed ".

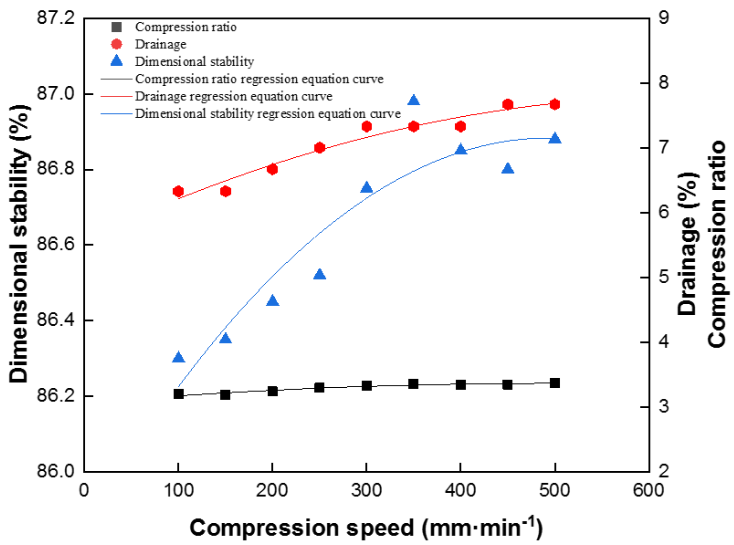


Fig. 3. Influence of the compression speed on the drainage, compression ratio, and dimension stability of the formed blocks. Dimensional stability regression equation curve or left, drainage and compression ratio regression equation curve belongs to right Y-axis.

The results of the variance analysis of the effect the compression speed had on the compression ratio of the formed block showed that the $F_{0.05}$[8,18] (2.58) was less than the F_A (2.97), which was less than the $F_{0.01}$[8,18] (3.71), which indicated that the pressure had an extremely significant effect on the compression ratio of the formed block. A regression model of the compression ratio was established, and a regression curve was drawn, as shown in Fig. 3. When the compression speed ranged from 100 to 150 mm/min, the compression ratio of the formed block decreased as the compression speed increased; when the compression speed ranged from 150 to 350 mm/min, the compression ratio of the formed block increased as the compression speed increased. When the compression speed ranged from 350 to 450 mm/min, the compression ratio of the formed block decreased as the compression speed increased; when the compression speed ranged from 400 to 500 mm/min, the compression ratio of the formed block increased as the compression speed increased. When the compression speed was 500 mm/min, the maximum compression ratio of the formed block was 3.37. The regression equation is shown in Eq. 8,

$$\widehat{CR} = 1 \times 10^{-6}cs^2 + 0.0012cs + 3.0649 \quad (8)$$

where *CR* refers to the factor "compression ratio" and *cs* refers to "compression speed".

The results of the variance analysis of the effect the compression speed had on the dimensional stability of the formed block showed that the F_A (0.04) was less than the $F_{0.05}$[8,18] (2.58). This indicated that the compression speed had no significant effect on the dimensional stability of the formed block because a high compression speed was unfavorable for corn straw bonding with cow manure, thus resulting in larger volume expansion of the formed block after compression, as well as lower stability. A regression model of the dimensional stability was established, and a regression curve was drawn, as shown in Fig. 3. When the compression speed was 350 mm/min, the dimensional stability of the formed block reached 86.98%. The regression equation is shown in Eq. 9,

$$\widehat{DS} = 4 \times 10^{-6}cs^2 + 0.0042cs + 85.849 \quad (9)$$

where *DS* refers to the factor "dimensional stability" and *cs* refers to "compression speed".

Assuming that the drainage amount meets the test requirements and that the compression speed was within a range of 200 mm/min to 400 mm/min, the total compression of the formed block was relatively large, and it also had high dimensional stability.

Effect of the holding time

The experiment was carried out according to the experimental plan, with the pressure set to 23 kN and the compression speed set to 100mm/min. The results of the variance analysis of the effect the holding time had on the drainage of the formed block showed that the $F_{0.05}$[8,18] (2.58) was less than the F_A (3.25), which was less than the $F_{0.01}$[8,18] (3.71), which indicated that the holding time had a significant effect on the drainage of the formed block. A regression model of the drainage was established, and a regression curve was drawn (Fig. 4).

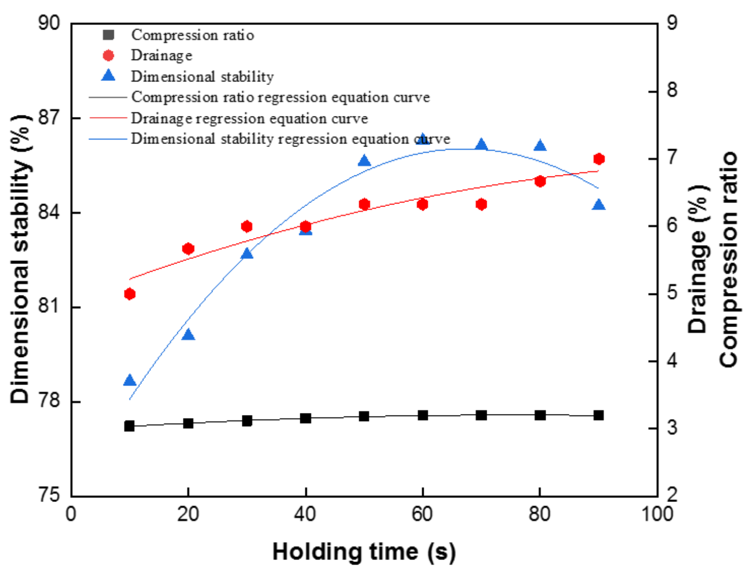


Fig. 4. Influence of the holding time on the drainage, compression ratio and dimension stability of the formed blocks. Dimensional stability regression equation curve or left, drainage and compression ratio regression equation curve belongs to right Y-axis

The amount of drainage of the formed block increases with an increase in the pressure holding time and when the pressure holding time was 90 s, the drainage of the formed block reached the highest value of 7%, which is less than 10% and therefore meets the test requirements. The regression equation is shown in Eq. 10,

$$\widehat{D} = 0.0001ht^2 + 0.0337ht + 4.8968 \tag{10}$$

where D refers to the factor " drainage ", ht refers to the factor "holding time".

The results of the variance analysis of the effect the holding time had on the compression ratio of the formed block showed that the F_A (19.01) was greater than the $F_{0.01}$[8,18] (3.71), which indicated that the pressure holding time had a significant impact on the compression ratio of the formed block. A regression model of the compression ratio was established, and a regression curve was drawn, as shown in Fig. 4. The compression ratio of the formed block increased with an increase in the holding time. When the holding time was 60, 70, 80, or 90 s, the formed block yielded the highest compression ratio (3.20). The regression equation is shown in Eq. 11,

$$\widehat{CR} = -4 \times 10^{-5}ht^2 + 0.0059ht + 2.9819 \tag{11}$$

where CR refers to the factor "compression ratio, and ht refers to the factor "holding time".

The results of the variance analysis of the effect the pressure holding time had on the dimensional stability of the formed block showed that the F_A (11.65) was greater than $F_{0.01}$[8,18] (3.71), which indicated that the pressure holding time had a significant influence on the dimensional stability of the formed block. A regression model of the dimensional stability was established, and a regression curve was drawn, as shown in Fig. 4. When the holding time ranged from 10 to 60 s, the dimensional stability of the formed block increased as the holding time increased. When the holding time ranged from 60 s to 90 s, the dimensional stability of the formed block decreased as the holding time increased; when the holding time was 60 s, the dimensional stability of the formed block was 86.3%. The regression equation is shown in Eq. 12,

$$\widehat{DS} = -0.0024ht^2 + 0.3267ht + 75.06 \tag{12}$$

where DS refers to the factor "dimensional stability" and ht refers to "holding time".

Considering that the longer the holding time, the greater the energy consumption and the lower the compression efficiency (when applied to the test range), assuming that the drainage amount meets the test requirements, the holding time should range from 30 s to 60 s.

Molding Process Parameter Optimization Test

The test was carried out as per the design scheme, and the results are shown in Table 2. A compressed block is shown in Fig. 5. Regression models were established for the drainage, compression ratio, and dimensional stability of the formed blocks, and analysis of variance was also performed (Table 3). The analysis of variance was performed based on the regression model of the drainage amount of the formed block, and the lack of fit (F) = 311.32 was greater than the $F_{0.01}$ [9,8] (5.91) (p-value was less than 0.0001). Thus, the regression model was extremely significant. The multiple correlation coefficient (R^2) = 0.9972, the F (6.14) was less than the $F_{0.05}$[5,3] (9.01), and the Pr (0.0786) was greater than 0.05, which indicated that the objective function strongly correlated with each factor, and that the regression-equation fitting effect was good. Factors X_1, X_2, and X_3 had a significant effect on the drainage of the formed block, with the order of their influence as follows: the pressure (X_1) was greater than the compression speed (X_2), which was greater than the holding time (X_3). Excluding the insignificant items in the model, X_2X_3, X_1^2, X_2^2, and X_3^2, the regression equation for the drainage of the formed block is shown in Eq. 13,

$$\hat{Y}_1 = 6.06 + 0.56X_1 - 0.0002X_2 + 0.1005X_3 + 0.0004X_1X_2 + 0.0034X_1X_3 \quad (13)$$

where X_1,X_2,X_3 refers to the factors pressure, compression speed, and holding time, respectively.

Table 2. Experimental Design and Results of the Drainage, Compression Ratio, and Dimension Stability of the Formed Blocks

Test No.	Pressure (X_1) (kN)	Compression Speed (X_2) (mm·min^{-1})	Holding Time (X_3) (s)	Drainage (Y_1) (%)	Compression Ratio (Y_2)	Dimension Stability (Y_3) (%)
1	-1	-1	-1	4.07	2.75	79.95
2	1	-1	-1	5.67	3.05	85.18
3	-1	1	-1	4.10	2.82	80.02
4	1	1	-1	6.07	3.12	85.26
5	-1	-1	1	4.30	2.88	81.06
6	1	-1	1	5.70	3.15	85.60
7	-1	1	1	4.33	2.89	81.10
8	1	1	1	5.89	3.26	85.57
9	- 1.682	0	0	3.53	2.73	78.62
10	+ 1.682	0	0	6.50	3.35	86.35
11	0	- 1.682	0	5.17	2.90	83.15
12	0	+ 1.682	0	5.25	2.98	83.30
13	0	0	- 1.682	5.20	2.88	83.56
14	0	0	+ 1.682	5.30	2.98	84.44
15	0	0	0	5.23	2.92	84.21
16	0	0	0	5.27	2.94	84.37
17	0	0	0	5.27	2.93	84.40
18	0	0	0	5.23	2.96	84.36

Analysis of variance was performed on the regression model of the compression ratio of the forming blocks and the F = 29.86 was greater than the $F_{0.01}$[9,8] (5.91) (p-value was less than 0.0001); thus, the regression model was extremely significant. The R^2 = 0.9711, the F (8.43) was less than the $F_{0.05}$[5,3] (9.01), and the Pr = 0.0555 was greater than 0.05, which indicated that the objective function strongly correlated with each factor, and that the regression-equation fitting effect was good. Factors X_1, X_2, and X_3 had a significant effect on the compression ratio of the forming block, with the order of their influence as follows: the pressure (X_1) was greater than the holding time (X_3), which was greater than the compression speed (X_2). Excluding the insignificant items in the model, X_1X_2, X_1X_3, X_2X_3, X_2^2, and X_3^2, the regression equation for the compression ratio of the forming block is shown in Eq. 14,

$$\hat{Y}_2 = 5.26 - 0.2739X_1 - 0.0027X_2 - 0.0045X_3 + 0.0079X_1^2 \quad (14)$$

where X_1, X_2, and X_3 refer to the factors pressure, compression speed, and holding time, respectively.

Analysis of variance was performed on the regression model of the dimensional stability of the forming block and the F = 228.19 was greater than the $F_{0.01}$[9,8] (5.91) (p-value was less than 0.0001). The regression model was extremely significant, the R^2 = 0.9961, the F = 8.68 was less than $F_{0.05}$ (5,3) = 9.01, and the Pr = 0.0526 was greater than 0.05, which indicated that the objective function strongly correlated with each factor, and that the regression-equation fitting effect was good. The factors X_1 and X_3 had a significant influence on the dimensional stability of the formed block, with the order of their influence as follows: the pressure (X_1) was greater than the holding time (X_3). Excluding the insignificant items in the model, X_2, X_1X_2, X_2X_3, and X_3^2, the regression equation for the dimensional stability of the forming block is shown in Eq. 15,

$$\hat{Y}_3 = 17.02 + 3.4X_1 + 0.34X_3 - 0.0083X_1X_3 - 0.069X_1^2 - 0.0001X_2^2 \quad (15)$$

where X_1, X_2, and X_3 refer to the factors pressure, compression speed, and holding time, respectively.

Fig. 5. Compressed briquettes

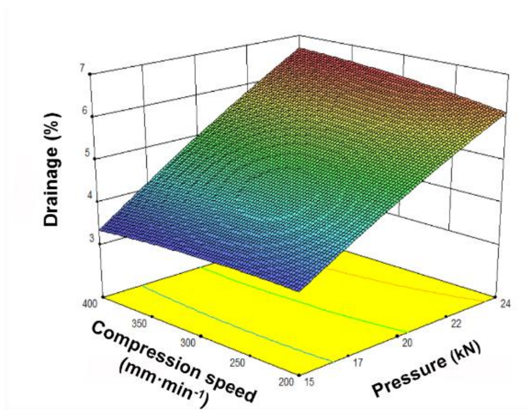
Table 3. Variance Analysis of the Regression Equation of the Drainage, Compression Ratio, and Dimension Stability

Variation Sources	Y_1		Y_2		Y_3	
	F	p-value	F	p-value	F	p-value
Model	311.32	< 0.0001	29.86	< 0.0001	228.19	<0.0001
X_1	2715.15	< 0.0001	231.94	< 0.0001	1843.310.30	<0.0001
X_2	10.21	0.0127	6.45	0.0347	0.03	0.5971
X_3	6.35	0.0358	16.30	0.0037	36.72	0.0003
X_1X_2	8.22	0.0209	0.67	0.4376	-	0.9424
X_1X_3	12.90	0.0071	0.042	0.8426	6.83	0.0310
X_2X_3	1.53	0.2581	0.031	0.8653	0.058	0.8151
X_1^2	4.58	0.0648	22.77	0.0014	67.07	< 0.0001
X_2^2	2.60	0.1455	0.86	0.3820	44.66	0.0002
X_3^2	0.65	0.4451	0.42	0.5345	3.93	0.0828
Loss of fitting	6.41	0.0786	8.34	0.0555	8.68	0.0526
Note: F is the lack of fit						

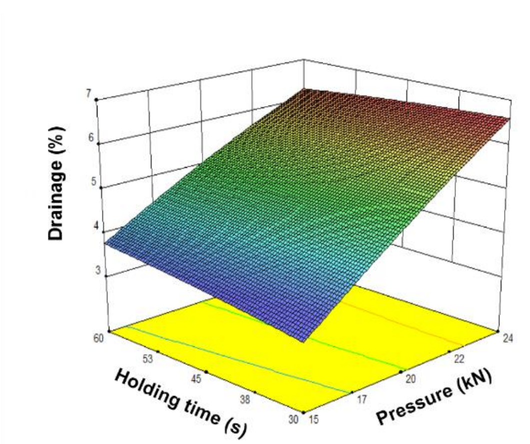
Interaction Analysis of the Experimental Factors

Design Expert 8.0 was used to draw the response surface diagrams and to analyze the influence of their interaction on the drainage of the formed block, including the significant cross-terms X_1X_2 and X_1X_3, respectively. It can be seen from Fig. 6a that under conditions when the holding time was 45 s (0 level), and when the pressure was constant, the drainage increased as the compression speed increased. This indicated that during the compression process, the increase in compression speed compacted the material, and the water was quickly squeezed out. When the compression speed was constant, the drainage increased as the pressure increased, and the amplitude became larger, which indicated that during the compression process, the increase in pressure causes the mixture to fully compress, which increases the amount of material lost. When the pressure was 24 kN and the compression speed was 300 mm/min, the maximum amount of drainage was 6.5%; however, the amount of drainage did not exceed 6.5% for any test conditions.

It can be seen from Fig. 6b that when the compression speed was 300 mm/min (0 level), and the pressure was constant, the drainage increased as the holding time increased. When the holding time was constant, the drainage increased as the pressure increased, and the amplitude got larger, which indicated that during the compression process, the influence of the pressure on the drainage was greater than the influence of the holding time. When the pressure was 24 kN and the holding time was 45 s, the maximum amount of drainage was 6.5%; however, the amount of drainage did not exceed 6.5% for any test conditions.



a. Interactive effect of pressure and compression speed on drainage



b. Interactive effect of pressure and holding time on drainage

Fig. 6. Response surface of the interactions on the drainage of the formed blocks

The influence of the interaction between pressure and holding time was analyzed relative to the dimensional stability of the forming block. It can be seen from Fig. 7 that when the compression speed was 300 mm/min (0 level), and the pressure remained constant, the dimensional stability increased as the holding time increased. When the holding time was constant, the dimensional stability increased as the pressure increased, and the amplitude became larger. This indicated that during the compression process, increasing the holding time or pressure can increase the molecular force between the mixture materials. This makes the materials form better bonds and reduces the volume expansion of the formed block. When the pressure was 24 kN, and the holding time was 45 s, the maximum dimensional stability was 86.4%.

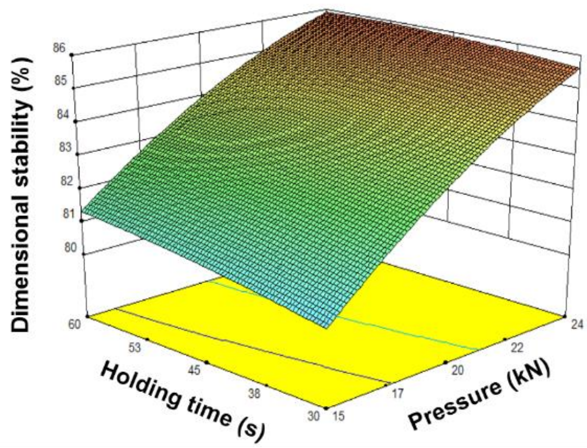


Fig. 7. Response surface of the interactions on the dimensional stability of the formed blocks

Optimization of the Molding Parameters

Parameters such as pressure, compression speed and holding time were optimized according to the Chinese agricultural industry technical specifications (NY/T 3442 2019). For composting livestock and poultry manure, the range of the initial and optimal moisture content of the mixture must be 45% to 65%, and the drainage of the formed block must be less than 20% in order to meet the test requirements. It can be seen in Table 2 that all the drainage amounts under these test conditions did not exceed 6.5%, which met the process requirements. Therefore, since the compression ratio and dimensional stability of the formed blocks met the response values, the target parameters of the compression ratio and dimensional stability were set to the maximum value through the optimization program in the Design Expert 8.0 software; the weight parameters were both 0.5 and the compression mixture was obtained. The optimal process parameters are as follows: when the pressure is 23.9 kN, the compression speed is 276 mm/min, and the holding time is 53.1 s, the amount of drainage of the formed block is 6.29%, the compression ratio is 3.37, and the dimensional stability is 86.5%.

Verification Test

In order to verify the accuracy of the regression model prediction by considering the actual operability of the test, the optimized parameters were reasonably set, *i.e.*, the pressure was set to 24 kN, the compression speed was set to 280 mm/min, the holding time was set to 53 s, and were tested three times and averaged. The test results were verified and the error analysis between the predicted value of the molding index and the test value are shown in Table 4. The results show that the relative error between the experimental value and the predicted value is within 4%, which shows agreement, and the prediction effect of the model is good. This result provides a theoretical basis for the compression molding process of a mixture of silky corn straw and cow manure.

Table 4. Test Verification Results

Parameter	Pressure X_1 (kN)	Compression Speed X_2(mm·min^{-1})	Holding Time X_3 (s)	Drainage Y_1 (%)	Compression Ratio (Y_2)	Dimension Stability Y_3 (%)
Test value	24	280	53	6.45	3.30	86.80
Predicted value	23.90	275.97	53.12	6.29	3.37	86.46
Error/%	-	-	-	2.54	-2.08	3.93

CONCLUSIONS

1. This study tested a compression molding process for a mixture of corn straw and cow manure, after grinding. Under conditions that met the technical specifications for drainage in livestock manure composting, the compression ratio and dimensional stability were integrated into the two molding quality evaluation indicators. The optimal molding process parameters were as follows: a pressure of 23.9 kN, a compression speed of 276 mm/min, and a holding time of 53.1 s. Under these technical conditions, the drainage of the shaped block met the test requirements. In addition, the compression ratio was large, and the dimensional stability was strong.
2. A regression model between the drainage, compression ratio, dimensional stability, pressure, compression speed, and holding time of the mixture of corn straw and cow manure (after grinding) was established and analyzed. The R_2 was greater than 0.9 for multiple correlations for each regression equation, and the fitting effect of the model was improved. Under optimal technical conditions, the relative error between the predicted value of the model and the experimental value was within 4%; therefore, the predicted result of the model is accurate and reliable. As such, it can be used to compress and form a mixture of silky corn straw and cow manure, in order to prepare agricultural organic fertilizer.
3. The quality of biomass briquettes was greatly affected by factors such as pressure, compression speed, and pressure holding time. Pampuro and coauthors have done a lot of research on the compression of pig manure compost and the compression of mixtures with different wood leavening agents. The results showed that factors such as pressure and holding time have a significant impact on the quality of the formed blocks, which are consistent with the conclusions of this study (Pampuro *et al*. 2013, 2017). However, to find out whether the physical properties of the subsequent materials change after long-term storage and a wider range of mixtures, the ratio of compression characteristics require further research.

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