Optimization of the Parameters for the Molding Process of Small-Size Rice Straw Insulating Blocks *via* Response Surface Methodology

Weili Yuan, Anhong Bao,* Xinlei Han, and Qiu Luo

Rice straw, which is considered an excellent insulation material, can be filled into the hollows of concrete block after being pressed, thereby improving the thermal performance of the concrete block. This new type of straw-concrete composite block will have good mechanical and thermal properties. In this study, to explore the feasibility of this new type of block, the response surface method was introduced. The goal was to find the effects of processing parameters on the forming quality of straw blocks. The quadratic regression model was established, and the processing parameters were optimized. It was found that the forming density, vertical pressure, pressure-holding time, and the interaction between the forming density and pressure-holding time had significant effects on the forming quality of the straw blocks. The optimal conditions obtained by RSM optimization were a forming density, a vertical pressure, and a pressure-holding time of 319.7 kg/m^2, 2.5 kN, 33.68 s, respectively. Under these conditions, the volumetric contractivity of straw blocks was 11.17%, the horizontal failure strength was 21.74 kPa, and the natural moisture content was 16.37%. The parameters calculated *via* the prediction model were highly consistent with the results produced *via* the actual measurements, which showed that the prediction model was reliable and potentially useful in guiding industrial production.

Keywords: Rice straw; Forming density; Volumetric contractivity; Response surface methodology

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INTRODUCTION

Insulation materials for the construction of housing has attracted the attention of researchers who are striving to find a path to alleviate the conflict between nature and human beings. The usage of environmentally friendly materials, especially those produced from local raw materials, could greatly contribute to decreasing the overall emissions of greenhouse gases (FAO 2019). In China, rice is one of the most widely grown food crops, and China generates the most rice out of all the rice-growing countries, according to the database of the Food and Agriculture Organization of the United Nations (Fig. 1). Statistics indicate each ton of rice produced would generate 1 ton to 1.5 tons of rice straw, which means that China is extremely rich in rice straw resources (Bi *et al.* 2011).

Rice straw was considered an agricultural waste in the past, but it is also a type of biomass material. The composition of the rice straw varies according to breeds and regions, but all rice straw consists of lignins, cellulose, hemicellulose, and ash. Rice straw can be considered as a fibrous porous material, and the inner fiber structure is coated with a complicated net structure consisting of lignins and cellulose. These structural features provide rice straw with a strong heat-retaining capacity and hygroscopic ability. The hygroscopicity affects the balance of indoor temperature and humidity, thereby making people feel more comfortable (Conti *et al.* 2016).

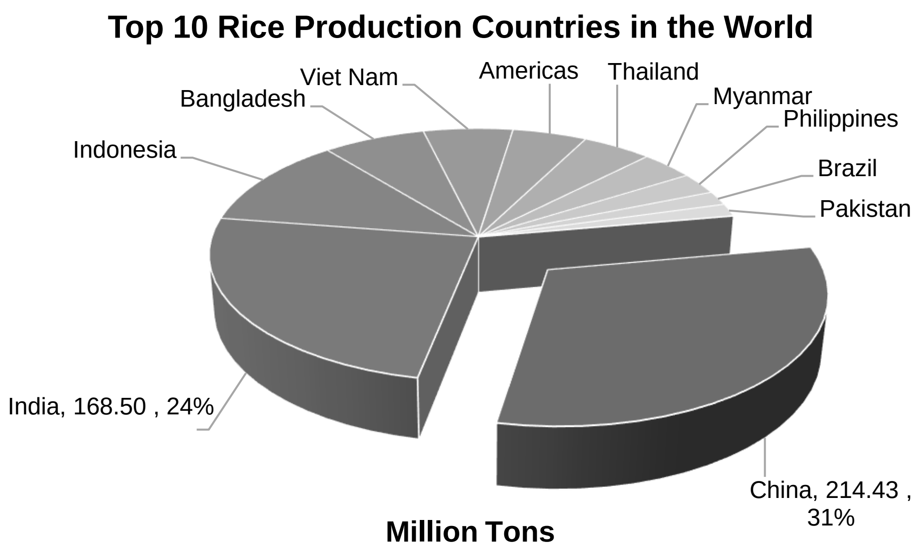

Fig. 1. Rice production levels of various countries in the world

Based on these considerations, the usage of rice straw as a construction material has been found to be a viable alternative for residential or agricultural construction. Compared to traditional construction materials, *e.g.*, brick and concrete, rice straw houses may provide lighter weight, lower heating energy loads, and higher-quality physical properties, *e.g.*, sound insulation and seismic stability (Schiavoni *et al.* 2016). While synthetic products still account for more than 90% of the market for traditional thermo-acoustic insulators (Asdrubali *et al.* 2015), their remaining disadvantages, *i.e.*, unsustainable production and emission of greenhouse gases, cannot be ignored (Thomson and Walker 2014).

China is a fast-growing developing country with a large population that generates a huge amount of rice straw. Making use of the rice straw as a construction material not only can serve as a way to recycle the rice straw and offer comfortable living spaces, but it also offers energy savings and reduces the air pollution caused by burning the rice straw (Li *et al.* 2008; Kim and Ward 2019). The most common design for using rice straw in construction is using rice straw bales as a primary structural element. There are multiple designs and construct processes that have been developed in recent years. Classically, rice straw was formed into a bale with an average length of 80 cm to 100 cm and a density of 100 kg/m^3 to 150 kg/m^3, using a straw baler and a pressure molding machine (Palermo *et al.* 2014; Lecompte and Le Duigou 2017; Maraldi *et al.* 2017; Garas *et al.* 2009). According to the stress conditions of straw bale, the straw bale construction could be divided into load-bearing and non-load-bearing straw bale. The non-load-bearing rice straw construction usually uses wood, concrete, or steel to construct the column and beam of the house and fills the walls with rice straw bales (Li *et al.* 2008; Jones 2009). To increase the monolithic stability of rice straw construction, pinning systems are introduced to connect each bale, as well as the bale and column (Holzhueter and Itonaga 2014; Yin *et al.* 2018). Subsequently, mortar or lime rendering is applied to the straw bale wall, which improves the appearance as well as ameliorating the hygrothermal environment (Holzhueter and Itonaga 2014).

As implied by early studies, thermal properties of a material are usually measured by thermal conductivity and thermal diffusivity. In some recent works, the classical measurement technique of the thermal properties, the guarded hot plate apparatus, while not as simple and quick as the transient techniques, is still widely used to test the thermal properties of straw bale, since it still provides benefits in terms of its accuracy. Goodhew and Griffiths (2004) reported a thermal conductivity of 0.067 (0.002) $W·m^{-1}·K^{-1}$ for straw bales with an average density of 60 $kg·m^{-3}$. Wei *et al.* (2015) introduced a high-frequency hot-pressed strawboard with a thermal conductivity of 0.052 $W·m^{-1}·K^{-1}$. However, many factors could lead to variation in thermal conductivity. For example, many studies have already shown the relation between the density and the thermal conductivity of straw bales (Ashour 2003; Vėjelienė 2012; Costes *et al.* 2017). In 2016, Palumbo *et al.* (2016) proposed that the thermal conductivity of straw bales is related to the ambient relative humidity. Carfrae (2011) introduced the concept of the effects of compaction of the moisture content in rice straw on the hygroscopic properties of the straw bales. Moreover, the void space between each bale, as well as the orientation of fibers, could also influence the thermal properties of the straw bale. But it is noteworthy that Chaussinand *et al.* (2015) reported thermal conductivity of rice straw bale material in a range of 0.052 $W·m^{-1}·K^{-1}$ to 0.12 $W·m^{-1}·K^{-1}$.

Overall, the construction of straw bale buildings, as well as their hygrothermal properties, have been sufficiently studied and an increased number of straw bale constructions have been reported all over the world. However, traditional straw bale construction was not able to increase its application rate against the increasing straw production rate in China, especially in the southern region, for which the reasons could be as follows:

(1) The average length of a straw bale has been reported to exceed 80 cm in many studies (Krick 2008; Vardy and MacDougall 2013; Lecompte and Le Duigou 2017; Maraldi *et al.* 2017), which is quite large. The large straw bale blocks would increase the volume of the structural component and compress floor space, as well as limit the extension of the floorplan, which would be undesirable, considering the lack of land faced by many Chinese cities. However, large structural elements require a hoisting machine to install and more trained workers to operate, which is hard to provide in the Chinese countryside.

(2) The climate in the south of China is rainy and humid, which can cause considerable harm to the straw bale. Traditional mortar rendering or wooden board coating may not protect the straw from water very well when it is being subjected to a long-lasting rainfall. As a result, the straw will be softened and become subjected to mildew in a humid ambient environment, losing its strength and hygrothermal properties, as well as decreasing the durability of the material.

(3) The production, transportation, and use of straw bale require specific large straw balers and cranes. These machines require extra workers to operate, of which the additional labor costs could not be ignored. The total cost of straw bale construction is not cheap enough to challenge the position of classical brick and concrete structures.

Therefore, the authors have developed a new type of straw-concrete composite block. This kind of composite block is produced by filling a small-sized hollow concrete block with rice straw blocks made with rice straw pretreated with a low concentration of NaOH *via* manual work or compress tester. The blocks are made of concrete to provide physical strength and the role of the straw is to improve thermal performance. Straw is isolated from the air due to the protection of concrete, which can effectively avoid dampness, mildew, insects, and other problems, and improve the durability of materials. Therefore, this type of material not only has appreciable strength and hygrothermal properties but also possesses better waterproofing abilities and durability. For further understanding and applications of this composite block, the following issues were studied:

(1) Introduction of an improved rice straw pretreatment method and straw block low-pressure forming process; and (2) Evaluation of the volumetric contractivity, horizontal failure strength, and natural moisture content of the straw blocks formed under various conditions and assess the impaction of each variable.

EXPERIMENTAL

Rice Straw Preparation

The rice straw (XiDaYou216) was obtained from an experimental farm at the Southwest University in Chongqing, located at 106.40°E, 29.80°N, in southwest China. The rice straw was selected, cleaned, and trimmed into small pieces (1 cm to 2 cm) with a grass cutter (Xianglong Hardware Machinery, Shandong, China) and put into a series heat-drying oven (DHG-9245A) at a temperature of 60 ℃ to ensure dryness. The pretreatment method, which was previously used by the authors, was to soak the straw in 1% concentration NaOH solution (w ≥ 96%) (Chuandong Chemical Industry Ltd., Chongqing, China) for 6 h. The NaOH could dissolve the hydrophobic wax layer and the irregular protrusion on the surface of straw fibers, which made the surface smooth. The straw could be in full contact with water and become soft and hydrophilic. The contact area between the fiber molecules of straw is thereby increased, and the adhesion between straw pieces also is increased so that the self-bonding property is improved (Han *et al.* 2019; Sun *et al.* 2020). After pretreatment, the mass loss rate of the rice straw was 7.82%. However, this pretreatment method has the following defects: (1) the pretreatment time is too long, which is not conducive to industrial production; and (2) the total water consumption of soaking the straw is large, and more waste liquid is produced during the pressing process. Therefore, to solve the above problems, the authors adopted an improved pretreatment method for this experiment. The water consumption was reduced when the NaOH solution was configured, and the ratio of straw to water was reduced from 1: 5 to 1: 2, while the concentration of the NaOH solution remained unchanged. Meanwhile, the straw was soaked with the addition of mechanical stirring for 20 min to ensure the straw was fully soaked. The experiment showed that the mass loss rate of rice straw treated *via* this method reached 6% to 7%, which had a minimal difference from the previous pretreatment method, but the treatment efficiency was increased, and the volume of polluted waste liquid output was greatly reduced. Therefore, from the perspective of industrial production, the novel pretreatment method from this experiment is better.

Molding Technology of the Straw Blocks

The molding pressure was applied *via* a YAD-2000 microcomputer-controlled electron universal tester, as shown in Figs. 2a and 2b. The pressure loading speed was set at 0.1 kN/s. First, the rice straw was pressed slowly by the universal tester to squeeze excess water after being soaked in the NaOH solution. Then, the rice straw was filled into a customized wooden mold (130 mm x 130 mm x 190 mm). Next, the pressure head of the universal tester was moved downward with the beam in order to press the straw into a straw block. Finally, the wooden mold was removed after 24 h, and the straw block was allowed to cure at a standard atmosphere and temperature for 28 days. The molded straw block is shown in Fig. 2c.

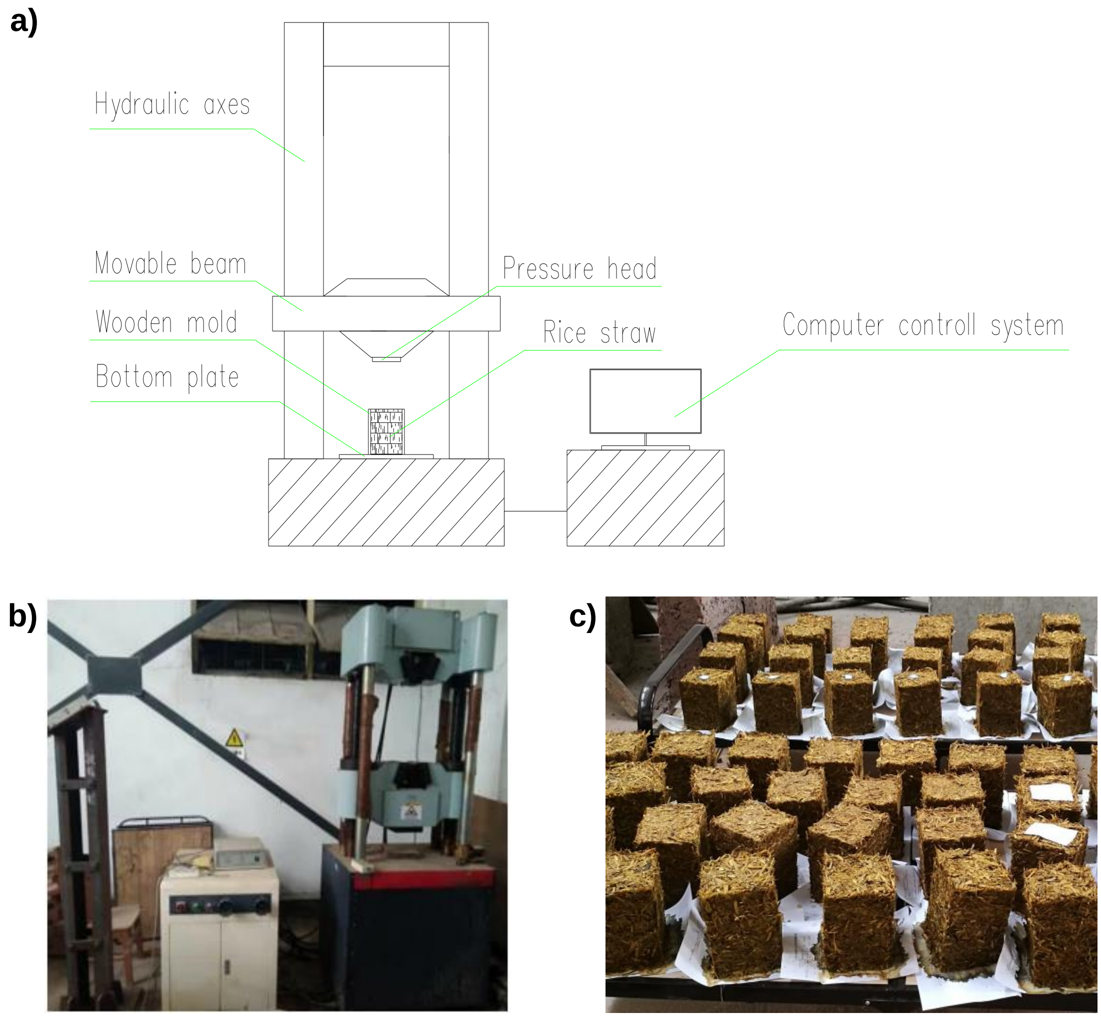

Fig. 2. a), b) Experimental system for rice straw blocks molding optimization and c) rice straw blocks

Optimum Molding Parameters

The study was carried out to determine the constant parameters, *i.e.*, the forming density, vertical pressure, and the pressure-holding time in the molding process. These parameters were determined to obtain the optimum molding block.

Forming density

Forming density represents the density as well as the ramming level of the straw blocks, which plays an important role in the strength of the block, as well as its durability. The forming density can be calculated using Eq. 1,

$$\rho_D = M/V \tag{1}$$

where ρ_D (kg/m^3) is the forming density of the straw blocks, M (kg) is the weight of the straw required for a single block, and V (m^3) is the volume of the wooden mold.

Vertical pressure

The vertical pressure determines an indispensable part of the molding effect. The preliminary experiment demonstrated that a vertical pressure of 2.5 kN to 3.5 kN yielded straw blocks with a good performance.

Pressure-holding time

The pressure-holding time also plays an important role in the molding process. If the holding time is too short, the formation of a stable bond between the straw fibers could not occur, such that the density of blocks cannot reach the expected value. However, if the holding time is too long, the inner structure of the straw block may be destroyed. Both of these outcomes are harmful to the final molding effect.

Evaluation Evidence of the Molding Quality

To determine the impact of various molding parameters on the quality of the straw block molding process, the volumetric contractility of the straw block after pressure molding, the horizontal failure strength, and the natural moisture content were determined to evaluate the straw block.

Volumetric contractility

After the pressure molding process, the volume of the straw block demonstrated a contraction phenomenon; a smaller contracted value (η) indicated a better molding effect. The volumetric contractility can be defined by Eq. 2,

$$\eta = \frac{V_0 - V_t}{V_0} \times 100\% \qquad (2)$$

where η (%) is the volumetric contractility of the blocks, V_0 (kg/m^3) is the initial volume of the straw block when it is formed, and V_t (kg/m^3) is the volume of the block after curing for 28 d.

Horizontal failure strength

Due to the vertical pressure molding methodology, the straw blocks are compressed a lot, which generates greater elastic deformation in comparison to plastic when vertical pressure is applied.

a) b)

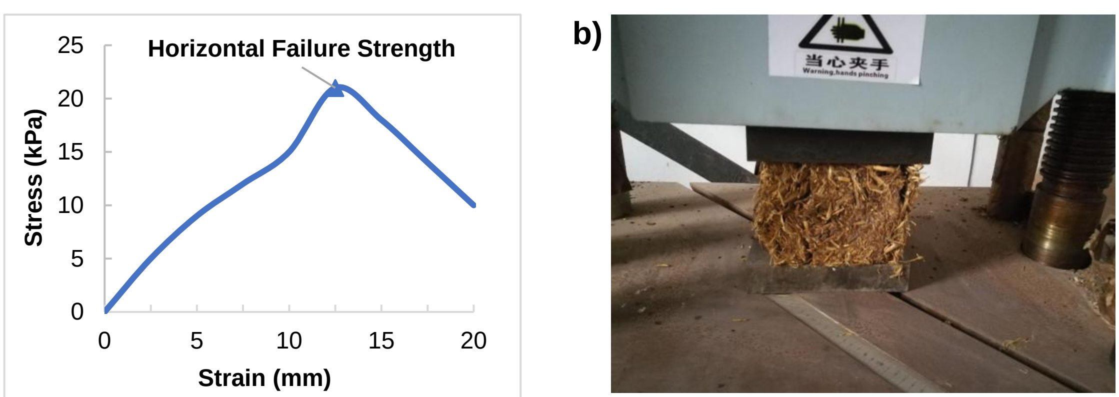

Fig. 3. Sample of a stress-strain curve (a); and the hierarchical destruction of the straw block (b)

After removing the pressure, the blocks would recover a portion of the deformation and become more difficult to destroy. However, the straw blocks are predicted to incur hierarchical destruction when too great a pressure is applied. The horizontal failure strength (*HFS*) was measured with an automatic pressure tester after curing the straw blocks for 28 d. The straw block shows notable hierarchical destruction and observable cracks between each horizontal section. Also, the stress-strain curve gradually rises and finally reaches the top, which indicated the horizontal failure strength of the straw block (Fig. 3).

Natural moisture content

After pretreatment with NaOH solution, some parts of the straw will degrade, which leads to a decrease in cohesion between the molecules, thus increasing the accessibility of the straw fiber to the air (Han *et al.* 2019). The pretreatment process makes the straw fiber prefer to absorb the water in the air, which leads to an increase in the weight of the straw block after curing in ambient conditions. During the final phase of the curing process, the moisture of the blocks would reach a dynamic balance. However, a high moisture content balance level is harmful to the strength and durability of the straw blocks, so the natural moisture content (*NMC*) should be limited *via* the molding process conditions. The *NMC* can be calculated by Eq. 3,

$$NMC = \frac{m_1 - m_2}{m_1} \times 100\% \qquad (3)$$

where *NMC* (%) is the natural moisture content of blocks, m_1 (kg) is the weight of the blocks after curing for 28 d, and m_2 (kg) is the constant weight acquired from blocks dried in a series heat-drying oven at a temperature of 50 °C for 24 h.

Design of the Single Factor Experiment

The single factor effects of forming density, vertical pressure, and pressure-holding time on the quality parameters of the straw block were investigated. The forming density was set to 240, 280, 320, 360, and 400 kg/m^3. Vertical pressure was set to 1.5, 2.0, 2.5, 3.0, and 3.5 kN. Pressure-holding time was set to 10, 30, 50, 70, and 90s.

Design of the Box-Behnken Experiment

A Box-Behnken experimental design was introduced with a total of 17 experiments, with 12 analysis points to study the molding quality, and with 5 replicates at the central point to estimate error (Wang *et al*. 2006). According to the results of the single factor experiment, three variables studied were the forming density (X_1), the vertical pressure (X_2), and the pressure-holding time (X_3), which were demonstrated in a reasonable range. To alleviate the impact of having various dimensions on the data analysis processing, three levels were selected for each independent variable and coded as (-1, 0, 1); the natural and coded values for the independent variables are summarized in Table 1. The levels were coded according to Eq. 4, and the experimental data was fit using the polynomial equation in Eq. 5,

$$X_i = (x_i - x_0)/\Delta x \qquad (4)$$

$$Y_i = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j \qquad (5)$$

where X_i is the code value of each independent variable, x_i is the true value of each independent variable, x_0 is the true value of each independent variable on the experimental central point, Δx is the step variation of each independent variable, Y_i is the response value of the quality evidence, β_i is the coefficient of the linear terms, β_{ii} is the coefficient of the quadric terms, and β_{ij} is the coefficient of the interaction terms.

Table 1. Design of the Experimental Factors and Levels

Code Levels	Forming density (kg/m^3)	Vertical Pressure (kN)	Pressure-holding time (s)
1	360	3.5	50
0	320	3.0	30
-1	280	2.5	10

The regression coefficients of the mean, linear, interaction, and quadratic terms, (β_0, β_i, β_{ii}, and β_{ij}) were respectively calculated from the experimental results *via* the least-squares method. The X_i and X_j are the independent variables in coded values, which ranged from -1 to 1. Response surface methodology analysis software (Design Expert 10, Stat-Eae Inc., Minneapolis, MN) was introduced to analyze the results and optimize the molding conditions. Three optimal response values were tested to check the validity of the model.

RESULTS AND DISCUSSION

Result of the Single Factor Experiment

In order to study the influence of forming density on the quality parameters of the straw block, the vertical pressure was set as 2.5 kN, and the pressure-holding time was set as 30 s. The results of the single factor test are shown in Fig. 4. As can be seen from Figs. 4a and 4b, when the forming density increased, the volumetric contractivity of the straw block gradually decreased, while the horizontal failure strength gradually increased, and reached the minimum and maximum value at 320 kg/m^3 respectively. This is because when the density increases, the bonding between the straw fibers is more compact, forming a compact and stable structure. This tends to resist volumetric changes. Its strength was also significantly enhanced. But when forming density exceeded 320 kg/m^3, the volumetric contractivity started to increase with increasing density, and the horizontal failure strength began to gradually decline. The reason is that the straw fiber had been destroyed by the external force. The fibrous structure began to collapse and lose part of the self-adhesive ability. So after unloading the external force, its strength will start to reduce, and the volume will also have a great change due to the flexibility of the straw itself.

As shown in Fig. 4c, the natural moisture content was negatively correlated with the forming density. This is because, with the increase of the density, the pores between the straw fibers become smaller and smaller, the water stored by the straw also decreased. At the same time, it could be seen that when the forming density exceeded 320 kg/m^3, the natural moisture content was still decreasing, but the trend was relatively gentle. In summary, the forming density should be 320 kg/m^3 as the central point of the Box-Behnken experiment, and the test range should be in the range 280 to 360 kg/m^3.

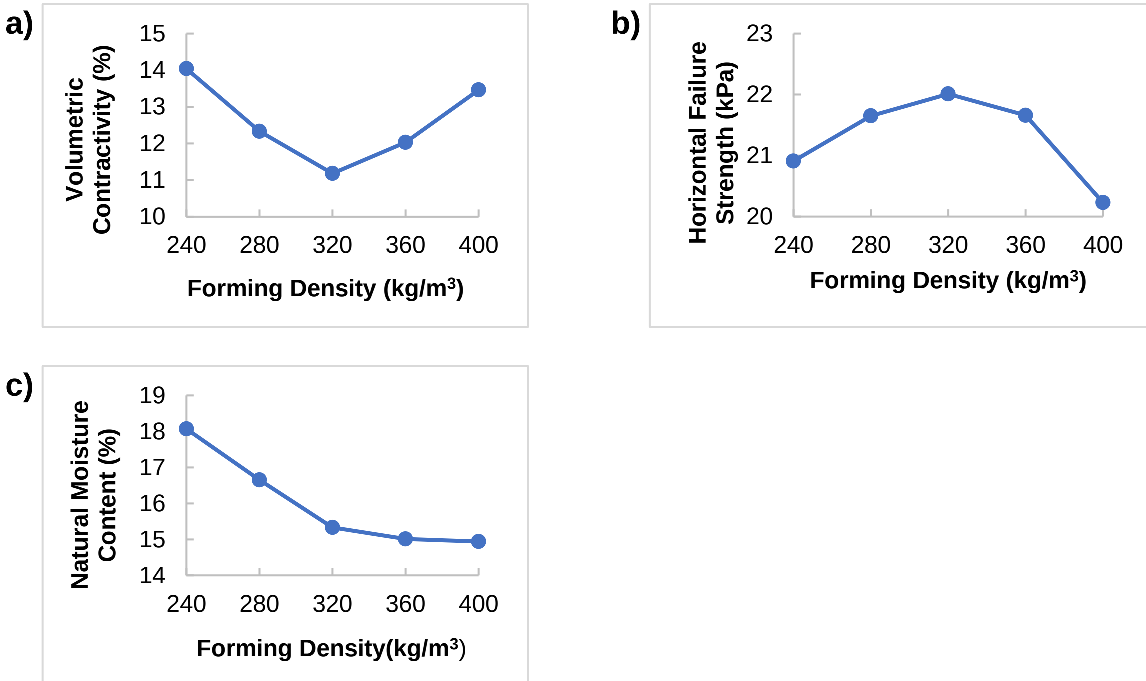

Fig. 4. Effect of forming density on a) volumetric contractivity, b) horizontal failure strength, and c) natural moisture content of the straw block

In order to study the influence of vertical pressure on the quality parameters of the straw block, the forming density was set as 320 kg/m^3, and the pressure-holding time was set as 30 s for the single factor test. According to Fig. 5, when the vertical pressure increased, the volumetric contractivity and natural moisture content of the straw block decreased gradually.

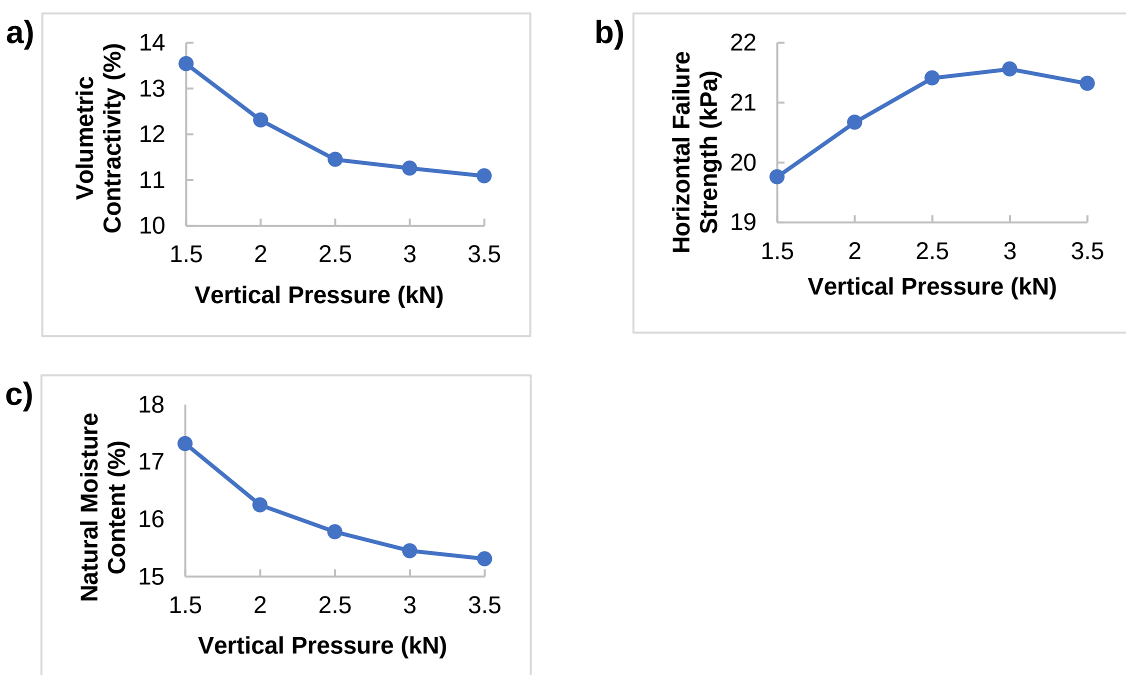

Fig. 5. Effect of vertical pressure on a) volumetric contractivity, b) horizontal failure strength and c) natural moisture content of the straw block

The horizontal failure strength increased at first and reached the maximum when the vertical pressure was 3 kN, and then it decreased gradually. This is because when the straw is extruded by the external force, the self-adhesive fibers will be closely bonded together to form a dense structure. The greater the external force is, the tighter the structure is. Therefore, the pore volume of the fibers will be smaller, and less water can be stored. This phenomenon leads to the continuous decline of the natural moisture content. At the same time, the volume of the straw block will be more stable, and the horizontal failure strength will increase. However, when the vertical pressure exceeded 3 kN, the straw fiber had been destroyed by the external force, and part of the self-adhesive ability had lost, leading to the decrease of the horizontal failure strength. Therefore, in conclusion, 3 kN should be selected as the central point of the Box-Behnken test for vertical pressure, and the test range should be 2.5 to 3.5 kN.

In order to study the influence of pressure-holding time on the quality parameters of straw blocks, the forming density was set as 320 kg/m^3 and the vertical pressure was set as 3 kN for the single-factor test. According to Fig. 6a, the volumetric contractivity of the straw block decreased with the increase of pressure-holding time. Increasing the pressure-holding time can effectively avoid the elastic deformation of straw in a short time, and the pressing effect is better so that the bond between straw fibers is closer to restrain the volumetric contractivity of straw blocks. As can be seen from Figs. 6b and 6c, the curve of pressure-holding time is gentle, indicating that the pressure-holding time has little influence on the horizontal failure strength and natural moisture content, but both reach their maximum and minimum respectively when the pressure-holding time is 30s. Considering the actual production efficiency, 30 s will be selected as the central point of the Box-Behnken test, and the test range is 10 to 50 s.

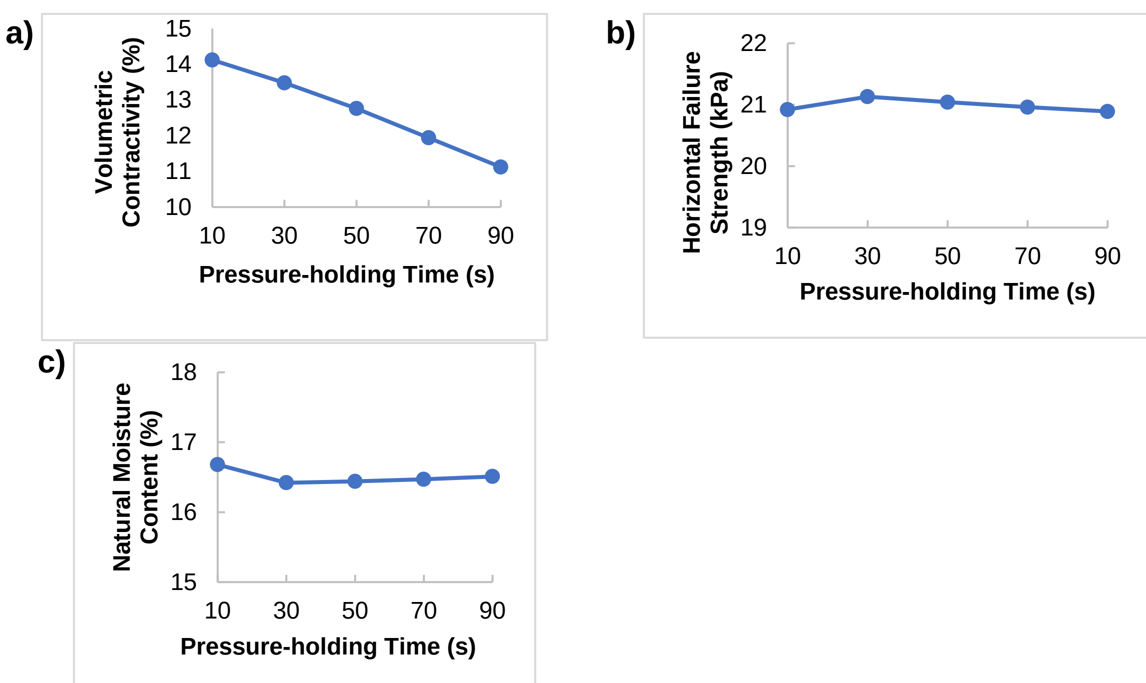

Fig. 6. Effect of pressure-holding time on a) volumetric contractivity, b) horizontal failure strength, and c) natural moisture content of the straw block

Box-Behnken Experimental Results and Model Building

The Box-Behnken experimental design was introduced to study the influence of three variables (the forming density, vertical pressure, and pressure-holding time) on the tested small-size rice straw molding processes. The operational conditions were assayed and the experimental results of the three responses were analyzed, *i.e.*, the volumetric contractivity, horizontal failure strength, and natural moisture content, as shown in Table 2. The volumetric contractivity ranged from 11.17% to 14.96%, the horizontal failure strength ranged from 18.86 to 22.00 kPa, and the natural moisture content ranged from 14.97% to 18.21%.

Based on the BBD experiment results, Design-Expert 10 software was used to analyze the data. A multivariable regression fitting model was chosen to achieve a ternary quadric model of the forming density (X_1), vertical pressure (X_2), and the pressure-holding time (X_3), as they relate to the volumetric contractivity (η), horizontal failure strength (HFS), and natural moisture content (NMC). The equations of each model are shown as Eqs. 6, 7, and 8, respectively,

$$\eta = 11.57 + 0.18X_1 - 0.19X_2 - 0.15X_3 - 0.13X_1X_2 - 0.062X_1X_3 - 0.067X_2X_3 + 2.25X_1^2 - 0.15X_2^2 + 0.41X_3^2 \quad (6)$$

$$HFS = 21.1 - 0.31X_1 + 0.31X_2 + 0.12X_3 + 0.11X_1X_2 - 0.025X_1X_3 - 0.005X_2X_3 - 1.62X_1^2 + 0.94X_2^2 - 0.43X_3^2 \quad (7)$$

$$NMC = 16.22 - 1.27X_1 - 0.26X_2 + 0.11X_3 + 0.0025X_1X_2 + 0.035X_1X_3 - 0.005X_2X_3 + 0.51X_1^2 - 0.14X_2^2 + 0.11X_3^2 \quad (8)$$

where the variables are the same as previously defined.

Table 2. Experimental Parameters and the Response Numerical Results

Sample	Forming density	Vertical Pressure	Pressure-holding time	Volumetric Contractivity (%)	Horizontal Failure Strength (kPa)	Natural Moisture Content (%)
1	-1	-1	0	13.54	20.71	17.93
2	-1	0	-1	13.82	19.31	18.21
3	-1	0	1	14.07	19.02	18.01
4	-1	1	0	14.26	21.20	17.78
5	0	-1	-1	11.17	21.49	16.35
6	0	-1	1	11.28	21.23	16.65
7	0	1	-1	11.61	21.76	15.74
8	0	1	1	12.14	22.00	16.02
9	1	-1	0	14.18	19.43	15.39
10	1	0	-1	14.57	18.86	15.61
11	1	0	1	14.80	19.05	15.83
12	1	1	0	14.96	20.38	14.97
13	0	0	0	11.54	21.14	16.32
14	0	0	0	11.58	21.26	15.94
15	0	0	0	11.53	21.20	16.01
16	0	0	0	11.61	21.05	16.49
17	0	0	0	11.49	20.88	16.33

Model Adequacy

The ANOVA for the response surface quadratic model of the volumetric contractivity, horizontal failure strength, and natural moisture (within the significant level of $\alpha = 0.05$), are shown in Tables 3, 4, and 5, respectively.

Table 3. ANOVA for the Response Surface Quadratic Model of the Volumetric Contractivity

Source	SOS	DOF	MS	F-value	p-value
Model	33.64	9	3.74	1359.13	< 0.0001
X_1	0.99	1	0.99	361.47	< 0.0001
X_2	0.98	1	0.98	356.36	< 0.0001
X_3	0.16	1	0.16	57.02	0.0001
X_1X_2	0.0009	1	0.0009	0.33	0.5852
X_1X_3	0.0001	1	0.0001	0.036	0.8542
X_2X_3	0.044	1	0.044	16.04	0.0052
X_1X_1	31.27	1	31.27	11369.38	< 0.0001
X_2X_2	0.0067	1	0.0067	2.45	0.1615
X_3X_3	0.0067	1	0.0067	2.45	0.1615
Residual	0.019	7	0.0028	-	-
Lack of Fit	0.011	3	0.0036	1.65	0.3127
Pure Error	0.0086	4	0.0021	-	-
Cor Total	33.66	16	-	-	-
$R^2 = 0.9994$		$R^2_{Adj} = 0.9987$		C.V.% = 0.41	
Note: SOS = Sum of squares; DOF = Degree of freedom; and MS = Mean square					

Table 4. ANOVA for the Response Surface Quadratic Model of the Horizontal Failure Strength

Source	SOS	DOF	MS	F-value	p-value
Model	16.78	9	1.86	28.32	0.0001
X_1	0.79	1	0.79	12.06	0.0104
X_2	0.77	1	0.77	11.68	0.0112
X_3	0.12	1	0.12	1.82	0.2189
X_1X_2	0.053	1	0.053	0.80	0.3998
X_1X_3	0.0025	1	0.0025	0.038	0.8510
X_2X_3	0.0001	1	0.0001	0.0015	0.9700
X_1X_1	11.02	1	11.02	167.46	< 0.0001
X_2X_2	3.74	1	3.74	56.76	0.0001
X_3X_3	0.77	1	0.77	11.72	0.0111
Residual	0.46	7	0.066	-	-
Lack of Fit	0.37	3	0.12	5.65	0.0638
Pure Error	0.088	4	0.022	-	-
Cor Total	17.24	16	-	-	-
$R^2 = 0.9733$		$R^2_{Adj} = 0.9389$		C.V.% = 1.25	
Note: SOS = Sum of squares; DOF = Degree of freedom; and MS = Mean square					

Table 5. ANOVA for the Response Surface Quadratic Model of the Natural Moisture Content

Source	SOS	DOF	MS	F-value	p-value
Model	14.71	9	1.63	28.19	0.0001
X_1	12.83	1	12.83	221.21	< 0.0001
X_2	0.55	1	0.55	9.42	0.0181
X_3	0.097	1	0.097	1.67	0.2374
X_1X_2	0.0000	1	0.0000	0.0004	0.9840
X_1X_3	0.0049	1	0.0049	0.085	0.7797
X_2X_3	0.0001	1	0.0001	0.0017	0.9680
X_1X_1	1.10	1	1.10	19.05	0.0033
X_2X_2	0.086	1	0.086	1.48	0.2632
X_3X_3	0.055	1	0.055	0.96	0.3607
Residual	0.41	7	0.058	-	-
Lack of Fit	0.19	3	0.063	1.16	0.4295
Pure Error	0.22	4	0.054	-	-
Cor Total	15.12	16	-	-	-
$R^2 = 0.9732$		$R^2_{Adj} = 0.9386$		C.V.% = 1.25	
Note: SOS = Sum of squares; DOF = Degree of freedom; and MS = Mean square					

As shown in Table 3, this model is statistically significant ($p < 0.0001$), and the lack of fit is not significant ($p > 0.05$). Meanwhile, the fitting correlation coefficient is $R^2 = 0.9994$, and the adjustment coefficient is $R^2_{Adj} = 0.9987$, which indicates that the test results fit well with the model. This regression model can be used to guide the production of straw blocks and predict the volumetric contractivity of straw blocks after forming. According to Table 3, the order of influence of each significant term on the volumetric contractivity (from large to small) was forming density (X_1), vertical pressure (X_2), and pressure-holding time (X_3).

Similarly, as shown in Table 4, this model was statistically significant (p=0.0001), and the lack of fit was not significant ($p > 0.05$). Meanwhile, the fitting correlation coefficient was $R^2 = 0.9733$, and the adjustment coefficient was $R^2_{Adj} = 0.9389$, which indicates that the test results fit well with the model. This regression model can be used to guide the production of straw blocks and predict the horizontal failure strength of straw blocks after forming. According to Table 4, the order of influence of each significant term on the horizontal failure strength (from large to small) was forming density (X_1), vertical pressure (X_2), and pressure-holding time (X_3).

As shown in Table 5, this model was statistically significant (p=0.0001), and the lack of fit was not significant ($p > 0.05$). Meanwhile, the fitting correlation coefficient was $R^2 = 0.9732$, and the adjustment coefficient was $R^2_{Adj} = 0.9386$, which indicates that the test results fit well with the model. This regression model can be used to guide the production of straw blocks and predict the natural moisture content of straw blocks after forming. According to Table 5, the order of influence of each significant term on the horizontal failure strength (from large to small) was forming density (X_1), vertical pressure (X_2), and pressure-holding time (X_3)

Analysis of the Interaction Between the Parameters

The contour map obtained through the analysis of Expert Design 10 software could reflect whether the interaction between the two factors has a significant impact on the process parameters. As shown in Fig. 7, the contour plot of the interaction between the forming density and pressure-holding time on the horizontal failure strength of the straw block is elliptical, indicating that the interaction of these two parameters had a significant impact on the horizontal failure strength.

When the vertical pressure was constant, the horizontal failure strength of straw blocks increased at first and then decreased gradually with the forming density and the pressure-holding time increasing. Meanwhile, the slope of the forming density was larger, indicating that the influence of the forming density on the horizontal failure strength was more significant.

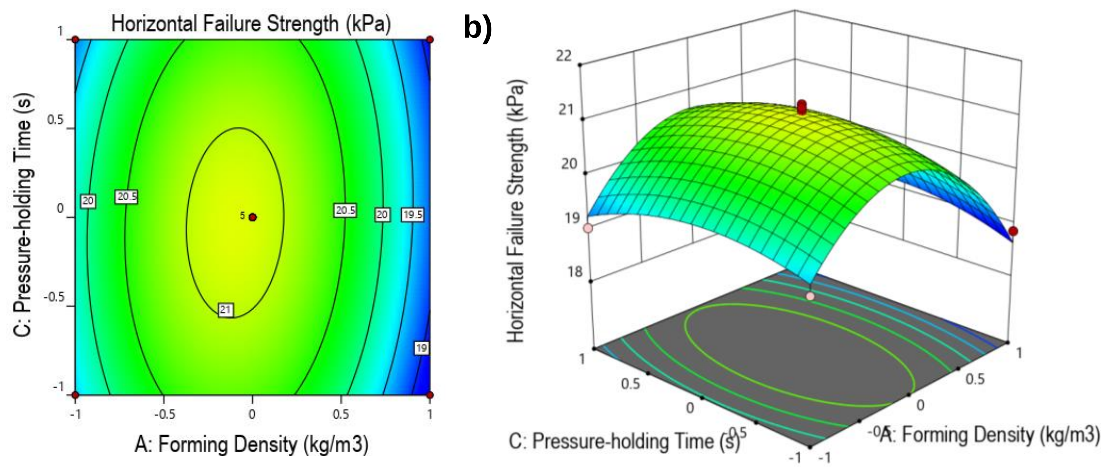

Fig. 7. a) Contour map and b) graphic model of interaction between forming density and pressure - holding time

Parameter Optimization and Testing

To improve the service life of the straw blocks, smaller volumetric contractivity, higher horizontal failure strength, and lower natural moisture content are required. Therefore, the volumetric contractivity could be set to its minimum value, while the horizontal failure strength is set to its maximum value, and the natural moisture content is set to its minimum value. By solving the formula in Design Expert, the optimal technology parameters were obtained when the forming density was 319.7 kg/m^2, the vertical pressure was 2.5 kN, and the pressure-holding time was 33.7 s. Under these conditions, the predicted value of the volumetric contractivity was 11.17%, the HFS was 21.74 kPa, and the NMC was 16.37%.

To verify the reliability of the predicted results of the model, the parameters under the optimized conditions were used to carry out the verification test. The results are shown in Table 6. The relative deviation between the average values of the test and the predicted values of the volumetric contractivity, horizontal failure strength, and natural moisture content were 2.29%, 4.02%, and 7.41%, respectively, which are all less than 10%. The experimental value and the predicted value were highly consistent. Therefore, the model was judged to be reliable.

Table 6. Results of the Parameter Optimization Verification Test

	Volumetric Contractivity (%)	Horizontal Failure Strength (kPa)	Natural Moisture Content (%)
Sample 1	9.92	23.36	15.32
Sample 2	10.72	21.85	15.63
Sample 3	11.56	22.63	14.76
Sample 4	10.66	21.17	14.97
Sample 5	11.74	24.26	15.51
Average of the samples	10.92	22.65	15.24
Calculation *via* models	11.17	21.74	16.37
Related deviation (%)	2.29	4.02	7.41

CONCLUSIONS

1. By reducing the water consumption of straw pretreatment and mechanical stirring, the chemical waste liquid produced during straw block production can be reduced while the softening effect is guaranteed, and the pretreatment efficiency can be accelerated.
2. The order of influence of each factor on the quality parameters of the straw block (from large to small) is: forming density, vertical pressure, and pressure-holding time. The forming density of straw blocks has the most significant effect on the forming quality. With the increase of the density, the volumetric contractivity decreases first and then increases, while the horizontal failure strength increases first and then decreases, and the natural moisture content decreases gradually. The second is the vertical pressure. When the vertical pressure increases, the volumetric contractivity, and natural moisture content decrease gradually, and the horizontal failure strength increases first and then decreases. The smallest effect is the pressure-holding time. When the holding time increases, the volumetric contractivity of straw blocks decreases gradually, but the horizontal failure strength and natural moisture content do not change significantly.
3. The interaction between forming density and pressure-holding time has a significant effect on the horizontal failure strength of the straw block. When the vertical pressure is constant, the horizontal failure strength increases first and then decreases gradually with the increase of forming density and pressure-holding time. Meanwhile, the slope of the forming density is larger, which indicates that the influence of the forming density is more significant.
4. The optimal combination of straw block forming processes was obtained by response surface methodology (RSM). Forming density was 319.7 kg/m^2, vertical pressure was 2.5 kN, and pressure-holding time was 33.7 s. Under these conditions, the predicted value of volumetric contractivity was 11.2%, the horizontal failure strength was 21.8 kPa, and the natural moisture content was 16.4%. At the same time, it was found that the model was close to the predicted value and was highly reliable after the verification test. The model can be used to guide the industrial production of the straw block.

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