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# **Design and Test of Horn Comb-type Adhesive-Material Mixing Device for Straw Boards**

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Abstract: In the process of manufacturing straw boards, whether the adhesive can be evenly covered and infiltrated into the surface of the straw material is one of the important factors affecting the performance of straw boards. Aiming at the problem that the conventional mixers in the market cannot achieve uniform mixing and the efficiency is low, a horn comb-type adhesive-material mixing device is designed. The simulation with the EDEM discrete software and the kinetic analysis show that the horn comb-type adhesive-material mixing teeth and the fan blade can promote the circulation of the material and improve the mixing effect of the two materials. With the ratio of material masses before and after combustion as the evaluation indicator, the mixing shaft speed, the mixing tooth spacing and the mixing time as the parameters, the ternary quadratic regression orthogonal combination test was designed, combined with the response surface method. Through the analysis on the main parameters affecting the material mixing uniformity, it is indicated that the order of the factors affecting the material mixing uniformity should be: mixing shaft speed> mixing tooth spacing> mixing time; the optimal parameter combination is: mixing shaft speed 133 r min<sup>-1</sup>, mixing tooth spacing 13mm, and mixing time 287 s. In this combination, the mixing uniformity of the material can reach 91%. It is verified that the mixing parameters obtained by the response surface analysis method are feasible, and they can achieve the best mixing effect of adhesive and material. This study can provide theoretical reference and practical basis for the design and improvement of the horn comb-type adhesive-material mixing device for straw boards.

# **1** Introduction

In recent years, manufacturing straw boards is an important way to rationally use of corn straws <sup>[1-4]</sup>, for which the mixing uniformity of adhesive and straw material is an important factor affecting the quality of straw boards <sup>[5]</sup>, and the mixing effect affects the performance parameters of straw boards

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such as compressive strength and internal binding strength <sup>[6-7]</sup>. Therefore, it is particularly important to develop an adhesive-material mixing device for manufacturing of straw boards.

The current types of mixers mainly include paddle type, thumb wheel type, drum type, frame type and anchor type<sup>[8]</sup>. So far, there are no reports about the mixing device for corn straw and composite adhesives at home and abroad. A paddle-type mixer usually has only two blades, featured as simple structure and low power consumption<sup>[9]</sup>, but it can only withstand small weight and cannot handle large quantities of straw material. The thumb wheel mixer<sup>[10]</sup> consists of a thumb wheel and a set of horizontal spiral mixing blades. The thumb wheel pushes the material into the spiral mixing area. Under the action of multiple mixing blades, the material is put into convection to achieve uniform mixing<sup>[11]</sup>. However, when handling long and tough materials with this type of mixer, the mixing blades are often entangled, resulting in increased power consumption and inconvenient maintenance. In addition, and the area occupied by the thumb wheel and the mixing blades is large, which seriously affects the effective mixing of the adhesive and the straw material. The drum-type mixer pushes the material through the switch-plate into the drum, and the material is turned over for mixing when it is pushed forward. However, the mixing effect is not ideal when the material in the drum is too much, limiting the utilization rate of the drum volume <sup>[12-13]</sup>. The outer diameter of the rotating part of the frame-type and anchor-type mixers is only smaller than the inner diameter of the drum. The shape is determined by the shape of the mixers. They are often applicable to the elliptical or dish-bottom tank <sup>[14-15]</sup>as their impeller and drum diameters are large, the speed at the wall of the container is large as well, which hinders the quick movement of the internal mixture, and heat is easily generated, thereby affecting the uniform mixing of the adhesive and material.

The main function of the Adhesive-Material Mixing Device for Straw Boards is to make the adhesive fully cover and infiltrate into the surface of all straw materials to achieve uniform mixing. As the mixer shell is designed into a cylindrical shape <sup>[16]</sup>, the utilization of electric energy can be improved, and the mixing efficiency under the same conditions will be 2 to 3 times than that of the mixers with other shapes <sup>[17-18]</sup>. Therefore, it is necessary to design an adhesive-material mixing device with a cylindrical shape to improve the covering effect of the straw material and the adhesive.

# 2. Design of Adhesive-material mixing device

The adhesive-material mixing device designed in this paper is mainly composed of a transmission component, a mixing component and a frame. The overall structure is shown in Figure 1.

The crushed straw material and the composite adhesive are fed into the mixing drum 11, and the motor 7 transfers the same to the rotary mixing shaft 15 through the belt 5. The rotary mixing shaft 15 rotates and drives the horn comb-type mixing teeth 14 and the fan blade 16 to enhance the axial movement of the mixture to achieve uniform mixing. The small shaft support piece 9 and the rolling support shaft 10 facilitate the disassembly of the mixing drum, and the drum baffle plate 2 and the drum retaining ring 1 facilitate the installation of the rotary mixing shaft 15 and prevent the material in the drum from leaking out, and the horn comb-type teeth 14 are arranged in a spiral form. The fan blade 16 is installed at both ends of the horn comb-type teeth, which is favorable for generation of convection during rotation at a high speed. The speed of the rotary mixing shaft 15 can be changed by the inverter control motor 7, and the rotary mixing shaft 15 has four rows of threaded through-holes, and the horn comb-type mixing teeth 14 and the fan blade 16 are screwed onto the rotary mixing shaft 15, so that the mixing tooth spacing (the distance from the tip of the horn comb-type teeth 14 to the inner wall of the mixing drum 11) is controlled by the distance of the spiral expansion and contraction.





a. Schematic diagram of the whole structure

b. Schematic diagram of rotating stirrup shaft

# Fig.1 Schematic diagram of mixed agitator

1.Roller retaining ring; 2.Roller retaining plate; 3.Support roller fixed frame; 4.Pulley; 5.Bearing; 6.belt; 7.Motor; 8.Switch; 9.Small shaft support; 10.Rolling support shaft; 11.Mixing drum; 12.Mixing drum door; 13.Rack; 14.Ox angle comb type tooth; 15.Rotating stirrer shaft; 16.Fan leaf plate;

# 3. Kinetic Analysis of the Mixture





Fig.2 Simplified structure of the mixer



As shown in Fig. 2, for the simplified structure of the mixing teeth, it is assumed that there are mixed material particles with the mass *m* at any position A of the mixing tooth. The mixing radius is r, the angular velocity is  $\omega$ , the rotation is clockwise, *V*<sub>A</sub> is the absolute speed, and *V*<sub>V</sub> is the axial speed. The support reverse force onto the mixture by the mixing teeth is *R*, and the friction force is *F*; the friction coefficient between the mixture and the mixing tooth is  $\mu$ : the friction coefficient between the materials to be mixed is  $\mu$ , the radius of the arc along the direction of the mixing teeth is  $\rho$ , The force balance equations of the materials are:

$$\sum Y = R\cos\alpha - mg - F_f \sin\gamma - F_s \sin\alpha = 0$$
(3.1)

$$\sum X = F_f \cos \gamma - R \sin \alpha - F_s \cos \alpha = 0$$
(3.2)

And because:

$$R\cos\alpha - F_s\sin\alpha = R(\cos\alpha - \mu_s\sin\alpha) = R(\cos\alpha - \tan\varphi_s\sin\alpha) = \frac{R\cos(\varphi_s + \alpha)}{\cos\varphi_s}$$
(3.3)

$$R\sin\alpha + F_s\cos\alpha = R(\sin\alpha + \tan\varphi_s\cos\alpha) = \frac{R\sin(\varphi_s + \alpha)}{\cos\varphi_s}$$
(3.4)

In the formulas:  $\varphi^{s}$  is the friction angle between the material and the mixing teeth, and the force conditions during the material mixing process are obtained as follows:

$$F_{f}\left[\frac{1}{\tan(\varphi_{s}+\alpha)}-\tan\gamma\right] = \frac{mg}{\cos\gamma}$$
(3.5)

As shown in Fig. 3, after the time  $\Delta t$ , the edge of the spiral mixing blade moves from *BC* to  $B_1C_1$ . Due to the friction between the materials, the material moves at a peripheral speed of  $\omega_m r$  ( $\omega_m < \omega$ ), and the material moves in the horizontal direction by  $\overline{AA'}$ . Where,  $\overline{AA'} = \omega_m r \Delta t$ , the material has a relative movement along the spiral mixing blade by  $\overline{A_1A_2}$  and the absolute movement of the material is  $\overline{AA_2}=V_{\Delta}\Delta t$ , then we obtain:

$$\left(\overline{AA_2}\right)^2 = \left(\overline{A'A_2}\right)^2 + \left(\overline{AA'}\right)^2 = \left(\overline{A'A_2}\right)^2 + \left[A'A_1 - \frac{\overline{A'A_2}}{\tan\alpha}\right]^2$$
(3.6)

The following formula is obtained through calculation:

$$V_{A^{2}} = V_{V^{2}} + \left(\omega r - \frac{V_{V}}{\tan \alpha}\right)^{2}$$
(3.7)

Finally, the expression of the relations between the material axial speed and the mixing structure parameters:

$$\mu r \left(\omega - \frac{2\pi V_{\nu}}{S}\right)^{2} \left[\frac{1}{\tan(\varphi + \alpha)} - \frac{V_{\nu}}{\omega r - \frac{V_{\nu}}{\tan \alpha}}\right] = g \sqrt{1 + \left(\frac{V_{\nu}}{\omega r - \frac{V_{\nu}}{\tan \alpha}}\right)^{2}}$$
(3.8)

According to the formula, the mixing material in the mixing drum is mainly affected by the mixing shaft speed, the mixing tooth spacing and the mixing time. According to the material dynamics analysis, the reasonable adjustment of the mixing shaft speed can directly change the uniformity of the mixture. By controlling the mixing shaft speed and the mixing tooth spacing, the axial speed of the mixture in the drum can be effectively increased, thereby ensuring the mixing uniformity of the adhesive and material.

# 4. EDEM Software Analysis

In order to clarify the motion state of the two materials, the simulation analysis on the adhesive-material mixing device was carried out using the EDEM software, and the model parameters <sup>[19]</sup> were determined as follows: straw density 163.5 kg/m<sup>3</sup>, Poisson's ratio 0.4, shear modulus  $1 \times 10^{6}$  pa, steel density 7850 kg/m<sup>3</sup>, Poisson's ratio 0.3, shear modulus  $1 \times 10^{10}$  pa, composite adhesive density 2800 kg/m<sup>3</sup>, Poisson's ratio 0.15, shear modulus  $1 \times 10^{8}$  pa, straw - straw recovery coefficient 0.30, static friction factor 0.25, dynamic friction factor 0.25, adhesive recovery coefficient 0.001, static friction factor 0.7, dynamic friction factor 0.1, straw-adhesive recovery coefficient 0.005, static friction factor: 0.75 and dynamic friction factor: 0.15.

The adhesive and the straw were fed separately at different time points. The axial movement of the material is as shown in Fig. 4. The speed of the material near the mixing shaft was obviously higher than that in other areas, indicating that the horn comb-type mixing teeth and the fan blade could enhance the axial movement of the material instead of preventing the material from forming a circulating flow. Under the action of the horn comb-type mixing teeth and the fan blade, the material speed gradually approached the linear velocity of the mixing shaft, forming a circulating flow around the shaft. The quantity of high-speed materials was small, so the convection mixing method was mainly adopted. The rotation of the fan blade has a function of pushing the material and make it turn over, it can prevent the material from being piled up at both ends. The material under convection would be quickly transferred.

According to the description about the particle mixing distribution in Fig. 5, the adhesive gradually entered the clearance of the straw under the action of the horn comb-type mixing tooth and the fan blade. The collisions between the straw material and the wall surface as well as the horn comb-type mixing tooth and the fan blade formed a complex motion trajectory. After a period, the adhesive fully filled the clearance of the straw material. The mixture of the adhesive and the straw material were full of the mixing space. At this time, the movement of the material no longer depended on the free collision of material, but the convection of the material achieved by the turn-over and movement-by-push of the horn comb-type teeth and the fan blade. Under the action of convection, the

material at one end of the mixing drum was rotated and pushed to the other end, wherein temporarily accumulated, and then quickly turned up to form a boiling effect, which enabled the straw material and the adhesive have a uniform mixing effect.







b. t=2s Streamline diagram of particle velocity and mass distribution in the longitudinal section



a. t=11.9s Particle mixed distribution diagram



b. t=11.93s Particle mixed distribution diagram

Fig.5 Particle mixed distribution diagram

# 5. Materials and Methods

#### 5.1 Test materials

(1) Preparation of composite adhesive: The performance of the adhesive is a key factor affecting the performance of straw boards. The composite adhesive used in this test was a mixture of organic cementing material and inorganic cementing material. The inorganic cementing material was prepared by adding MgO, MgSO<sub>4</sub>, MgCO<sub>3</sub>, active silicon additive and active ALSiO<sub>4</sub> into the water within the temperature range of 25~40° according to a certain mass ratio. The organic cementing material was obtained in such way that the soybean meal and soybean powder were hydrolyzed, and then the alkalization treatment was done to get the soybean adhesive; next, the soybean adhesive, modified MDI and deionized water were taken according to the ratio of 12.5%, 2%, and 85.5%, and fully mixed, thus the organic cementing <sup>[20]</sup> was obtained.

(2) Straw material: The corn straw used for the test was derived from the corn straw of Tieyan No. 26 in Xinbin County, Liaoning Province. The raw material of the corn straw had been naturally dried for more than 2 months in the field, the corn straw had a moisture content of 13%, and the pulverized particle size of 0.5~2 cm. The test place is located in the 102 laboratory of the Engineering College of Shenyang Agricultural University. The straw was smashed with a 9FX-80 straw pulverizer, produced by Taiyue Farm and animal husbandry machinery factory, Shandong Province, with a motor power of

**Fig.4** Flow line diagram of particle velocity and mass distribution

3 kW and a production efficiency of 1500 kg·h<sup>-1</sup>. The properties of the straw material before and after mixing are shown in Fig. 6. It can be seen that the straw material after mixing was soft and flocculated.





a. Straw material before mixing

b. Straw material after mixing

(3) Test equipment: In addition to the self-made adhesive -material mixing device, CP423S electronic balance (0.01 g, Beijing Sartorius Balance), SFY-60 far infrared rapid moisture analyzer (Shenzhen Guanya Electronic Technology Co., Ltd.), beakers, iron stand, alcohol lamp, mixing bar, heating net, vibrating screen, etc. were also used in the test.

Fig.6 Straw material before and after mixing

#### 5.2 Test methods

The composite adhesive used in this test is non-flammable. The material with the composite adhesive could not burn under the action of the external flame of the alcohol lamp within a certain time. On the contrary, the part of the material without the composite adhesive had the combustion reaction, and the combustion test results are as shown in Fig. 7. The straw material without the adhesive was powdered after being burned, while the straw material with the adhesive was carbonized after being burned. Because the adhesive has a flame retardant effect, in order to evaluate the mixing uniformity of the straw material and the composite adhesive, the burning test was carried out after the sample was taken at random and then weighed. The sample with the mass n was evenly laid on the heating net, and the alcohol lamp was fired and burned for 20 s. The sample material with the adhesive does not burn within 20 s, and the material without the adhesive burned to ash. After screening, the mass *m* of the residual sample was weighed. The ratio of *m* and *n* was taken as the measure Y for the uniformity. The larger the Y value is, the higher the mixing uniformity will be.





a. Combustion status of material without adhesive b. Combustion of materials with adhesive **Fig.7** Combustion status of material before and after mixing

# **6** Results and Analysis

#### 6.1 Single-factor Test Results

As shown in Fig. 8, the increase of the mixing shaft speed increased the mixing uniformity. When the speed reached 120  $r \cdot min^{-1}$ , the mixing uniformity of the materials reached the maximum. As the speed continues to increased, and the mixing uniformity of the materials began to decrease, the reason for which might be that when the speed was too fast, some materials could not fall smoothly, and the composite adhesive was separated from the surface of the material by the external force, in this case, the mixing speed was too slow, and the force of the material was insufficient to make the adhesive enter the clearance of the straw material. Within the mixing tooth spacing of 5~15mm, the mixing

uniformity of the material increased with the increase of the spacing. Within the mixing tooth spacing of  $15 \sim 25$  mm, the mixing uniformity of the materials decreased with the increase of the spacing, the reason for which is that the spacing was too large, the contact between the mixing teeth and the material was not enough to turn over the material, and the tooth spacing was too small, and the material at the top moved too slow, so the full mixing could not be achieved. When the mixing time was between 120 s and 360 s. The mixing uniformity showed an increasing trend. The final tendency was gentle because the mixing time was too long, and the adhesive on the straw material stuck to the inner wall of the mixing drum, which affected the coverage of the adhesive on the surface of the straw.



a. Influence of rotational speed of mixing shaft on the uniformity





c. Influence of stirring time on uniformity **Fig. 8** The influence of each factor on the uniformity

# 6.2 Response surface analysis test

# 6.2.1 Response surface factors and level selection

The results of the single-factor test were analyzed. According to the design principle of Box-Behnken of Design-Expert 8.0, the 3-factor 3-level response surface test was designed, as shown in Table 1.

<b>Tab.1</b> Factor level coding table							
	A B		С				
Test level	Rotating shaft speed $(r \cdot min^{-1})$	Pitch of stirred teeth (mm)	Stirring time (s)				
1	90	10	240				
2	120	15	300				
3	150	20	360				

Tab.1 Factor level coding table

6.2.2 Design of the response surface analysis test

According to the Box-Behnken model design test of Design-Expert 8.0 software, 17 groups of tests were designed, 12 groups were used as the analysis points, and 5 groups were used as the central area points. The uniformity of the straw material and the composite adhesive mixture was used as the

Number	Rotating shaft speed $A/(\mathbf{r}\cdot\mathbf{min}^{-1})$	Pitch of stirred teeth <i>B</i> /mm	Stirring time <i>C</i> /s	Uniformity Y/ (%)
1	120	20	240	87
2	120	15	300	89
3	90	15	240	77
4	120	20	360	84
5	90	15	360	82
6	90	20	300	78
7	120	10	360	88
8	120	15	300	93
9	120	10	240	86
10	150	20	300	83
11	120	15	300	91
12	150	15	360	82
13	150	10	300	92
14	120	15	300	94
15	90	10	300	77
16	150	15	240	89
17	120	15	300	92

response value as	shown in	Table 2.
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Tab.2 Box-Behnken test design and results

## (1) Uniformity regression analysis

The results of the uniformity regression analysis are shown in Table 3.

From the results of uniformity regression analysis, the model F value designed by Box-Behnken has an F value of 14.26, P value <0.038, and the correlation coefficient  $R^2$  of 0.9483, which indicates that the response surface model has significant significance. From the significance analysis of the two factors, the P value of the factor BC was 0.2361 (p>0.05), which was not significant, and the other every two factors had significant effects (p<0.05). The signal-to-noise ratio was 10.763, greater than 4 and the missing term value was 0.4743, greater than 0.05, indicating that the equation has a good fit to the test and can be used for the simulation of the mixing uniformity of the recombined materials. Tab 3 Uniform regression analysis of variance results

ab.5 Onnorm regression analysis of variance results							
Source of	Sum of squares	Degree of	Mean square	F Value	Р		
variation		freedom	deviation		Value		
Model	477.71	9	53.08	14.26	0.0010		
A-Speed	128.00	1	128.00	34.40	0.0006		
Speed	15.13	1	15.13	4.06	0.0836		
B-Pitch	1.13	1	1.13	0.30	0.5995		
C-Time	25.00	1	25.00	6.72	0.0358		
AB	36.00	1	36.00	9.67	0.0171		
AC	6.25	1	6.25	1.68	0.2361		
BC	179.27	1	179.27	48.17	0.0002		
A²	32.42	1	32.42	8.71	0.0214		
B <sup>2</sup>	32.42	1	32.42	8.71	0.0214		
$C^2$	26.05	7	3.72				
Surplus	11.25	3	3.75	1.01	0.4743		
Lack of fit	14.80	4	3.70				
Error	503.76	16					
Sum	0.9483	Adj-Squared	0.8818	Adeq-Precisio	10.763		
R <sup>2</sup>				r			

The quadratic polynomial regression fitting on the uniformity response data of the mixture in Table

<sup>6.2.3</sup> Response surface data processing analysis and optimization parameters

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1 was performed with the Design-Expert 8.0 software, and the ternary quadratic regression equation with the mixing shaft speed (A), the mixing tooth spacing(B) and the mixing time (C) as the independent variable were obtained:

*Y*=91.80+4.00*A*-1.38*B*-0.37*C*-2.50*A*×*B*-3.00*A*×*C*-1.25*B*×*C*-6.52*A*<sup>2</sup>-2.78*B*<sup>2</sup>-2.78*C*<sup>2</sup>

The above formula is the uniformity response value model of the mixed material, and Y demotes the uniformity (%) of the mixed material. It can be seen from the equation that the larger the coefficient is, the more obvious effect on the response value will be. The effect of the A factor on the uniformity of the mixed material was the most significant, followed by the B factor, and the weakest was the C factor.

(2) Analysis of interaction between various factors

According to the above ternary quadratic regression equation, the response surface map of the selected three factors was drawn by using Design-Expert 8.0 in the statistical region, and the zero level of one of the factors was selected to examine the interaction effect on the uniformity of the mixed materials of the other two factors, as shown in Fig. 9.



uniformity



a. Influence of interaction between stirring tooth spacing and speed of stirring shaft onb. Influence of mixing time and stirring shaft on speed on uniformity



c. Influence of mixing time and stirring tooth spacing on uniformity Fig.9 The response surface of the influence of the interaction between the two factors on the Uniformity

The response surface map of the factor interaction vs material uniformity is shown in Fig. 9. In the case that a zero level of one factor, both of the interactions of the other two factors show an upward convex shape in the map, and the curved surface will form a stable point, that is, the minimum of the mixing uniformity of the materials. As shown in Fig. 9a, the material uniformity decreases first and then increases with the increase of the mixing tooth spacing and the mixing shaft speed. The response surface changes in the A direction faster than in the B direction, so the effect of the mixing shaft speed on the material uniformity at the test level was more significant than that of the mixing uniformity first increases and then tends to be gentle, and the curved response surface changes slowly in the mixing time direction; and as shown in Fig. 9c, the curved interaction surface between the factor mixing time and the mixing tooth spacing is the most gradual, and the response surface changes faster in the B direction than in the C direction. Therefore, the effect of the mixing shaft speed on the material mixing uniformity is the most significant, followed by the mixing tooth spacing, and the weakest is the mixing time. The results from the response surface method are consistent with the results of the variance analysis.

#### 6.3 Verification of the test

With the maximum mixing uniformity of the materials as the response value, the optimized analysis on all the factors was carried out with the Design-Expert 8.0 software according to the response surface optimization principle. The stable points of the software optimization results are 132.93, 13.03 and 287.33; and theoretical value of the mixing uniformity of the materials is 92.97%, namely, the mixing shaft speed: 133 r·min<sup>-1</sup>, the mixing tooth spacing: 13.03 mm and mixing time: 287 s, which can maximize the mixing uniformity of the materials. Three parallel tests were conducted under the optimized conditions, with the test conditions further corrected, namely the mixing shaft speed 133 r·min<sup>-1</sup>, the mixing 13 mm and the mixing time 287s. The average value of the mixing uniformity of the materials reached 91%, which is closer to the expected optimization result. It can be seen that using the response surface for the statistics of optimized material mixing uniformity is an effective method.

# 7. Conclusion

(1) In this paper, an adhesive-material mixing device for straw boards was designed; the mixing process of straw material and composite adhesive was simulated with the EDEM software; and the distribution characteristics of material mass and velocity in the mixing drum were analyzed. The results show that the two materials can reach the uniform mixing effect, proving that the mixing device is designed reasonably and has good mixing performance.

(2) Through the design of the ternary quadratic regression orthogonal combination test, the results show that the order of the factors affecting the mixing uniformity of the materials is: the mixing shaft speed> the mixing tooth spacing> mixing time. In the interaction, the mixing shaft speed and the mixing tooth spacing, as well as the mixing shaft speed and the mixing time have a significant effect on the uniformity (p<0.05), but the mixing tooth spacing and the mixing time has no significant effect on the uniformity (p>0.05).

(3) The optimal test parameters were obtained using the Design-Expert 8.0 software and the response surface method, and were adjusted with the consideration of the test operability. After the test verification, the optimal test parameters are: the mixing shaft speed:  $133 \text{ r}\cdot\text{min}^{-1}$ , the mixing tooth spacing: 13 mm and mixing time: 287 s. Under these conditions, the mixing uniformity of the material can reach 91%, which satisfied the process requirements of the pressed straw boards.

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