Manufacturing and process optimization of porous rice straw board

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Abstract: Development and utilization of straw resources and the production of straw board can dramatically reduce straw waste and environmental pollution associated with straw burning in China. However, the straw board production faces several challenges, such as improving the physical and mechanical properties, as well as eliminating its formaldehyde content. The recent research was to develop a new straw board compound adhesive containing both inorganic (MgSO4, MgCO3, active silicon and ALSiO4) and organic (bean gum and modified Methyl DiphenylDiisocyanate, MDI) gelling materials, to devise a new high frequency straw board hot pressing technique and to optimize the straw board production parameters. The results indicated that the key hot pressing parameters leading to porous straw board with optimal physical and mechanical properties. These parameters are as follows: an adhesive containing a 4:1 ratio of inorganic-to-organic gelled material, the percentage of adhesive in the total mass of preload straw materials is 40%, a hot-pressing temperature in the range of 120 °C to 140 °C, and a high frequency hot pressing for 10 times at a pressure of 30 MPa. Finally, the present work demonstrated that porous straw board fabricated under optimal manufacturing condition is an environmentally friendly and renewable materials, thereby meeting national standard of medium density fiberboard (MDF) with potential applications in the building industry.

1. Introduction

Tons of agricultural crop residues are generated every year in China. Abundant availability of the agricultural crop residues makes them highly attractive for producing of high quality fiberboard or particleboard. In order to promote the use of these huge biomass resources, local governments have introduced several specific policies, and allocated special funds to promote academic and industrial scientific research targeting the development of new straw products. Straw board production represents one of most rational usage of straw resources at the same time enabling a truly sustainable rural economy [1][2]. In order to protect the environment and reduce the energy cost of building materials, considerable effort has been devoted to the development of environmental friendly and energy-efficient building materials, such as fiberboard and particleboard [3]. Particleboard is common
manufactured under pressure and temperature using wood particles or other lignocellulosic materials and any kind of binder[4]. Presently, particle boards are made from urea formaldehyde, formaldehyde or phenolic aldehyde[5][6][7][8]. However, formaldehyde-free products are preferred, due to health and safety concerns. Other straw board production challenges are associated with rice straw morphological differences and the fact that wax and silica adversely affect the properties of particle boards[9]. For example, synthetic resin are incompatible with the straw raw materials in that it was reported that UF resin hard to effectively penetrate the rice straw surface because of the hydrophobic wax and inorganic silica exist the straw outer surface. Consequently, there is the need for involve mechanical, chemical or biological pretreatments for breaking down the wax layer the rice straw and for improving the diffusion and penetration of the resin into straw fibers [9][10][11]. Parviz (2004) employed a combination of pressure, heat and carbonation reaction to produce cement-bonded particleboard[12]. Hydrothermal or chemical pretreatments are usually applied after the process of materials mechanical smashed. Hydrothermal processes include carbon dioxide explosion[13], steam explosion[14] or hot water treatment [15]. Chemical treatments include dilute-acid treatment[16], organosolv by organic solvents [17], alkali treatment [18], ammonia fiber explosion and ozonolysis[19]. Many of these methods degraded lignocellulose components to by-products or are carried out under extreme conditions (high temperatures and/or pressures, strong acids or bases) requiring specialized processing equipment. In addition, many of the above methods involve hazardous and toxic chemicals and therefore are not environmentally friendly. Consequently, the development of cost-effective and green technologies for straw board manufacturing remains challenging.

The objectives of this paper are to investigate a new type of adhesive compound based on such materials as MgSO₄, MgCO₃, active silicon and AlSiO₄ as inorganic gelled material and bean pulp and modified MDI as organic gelled materials and to optimize the straw board production parameters by means of an orthogonal array L₁₆(4⁵) experiment. The study shows that the straw board manufactured under these technological parameters is formaldehyde-free, non-toxic, and fireproof. The board performance exceeds that of wood-based particleboard and equals that medium density fiberboard(MDF) currently available on the market.

2. Materials and Methods

2.1 Materials

Rice straw used for experiment was transported from local farmers in Shenbei New District of Shenyang City (Longitude: 42.12; Latitude: 123.47). Trial sites were located in the workshop of Shenyang Huachuang Industrial Co., Ltd. These straw materials were placed in the field after harvest in October under the natural drying situation for a period of over 2 months. The rice straw with the moisture content approximately 13% variety is the Shendao 47. Straw in the workshop were cut with 9FX-80 type straw pulverizer manufactured by FengTai District Farming Machinery Plant in Tai’an City, Shandong Province. The productivity of the pulverizer is 1500kg/h with motor power of 30KW. The smashed straw (with particle size ranging from 0.5 to 5cm) materials are ejected through the cyclone discharge spout.

Preparation of adhesive: Adhesives were obtained by compounding an inorganic gelling material and an organic binder. The inorganic gelling material was a mixture of MgO, MgSO₄, MgCO₃, active silicon additives, active AlSiO₄, in various proportions) stirred in warm water (temperature in the range 25°C ~ 40°C). The organic gelling material contained bean gum derived from soy bean pulp after alkaline treatment, and the acid separation processing. The bean gum and modified MDI (Diphenylmethanediisocyanate) were subsequently mixed with the deionized water to obtain an organic gelling material.
2.2 Test equipment

Test equipment used in addition to the above mentioned type of 9FX-80 straw pulverizer, include an NZF1000 horizontal mixer for preparing the inorganic gelling material and an organic binder mixer, manufactured by Hongxin Machinery Factory of RongYang City in Henan Province. The multi-frequency hot pressing apparatus were used comparatively for manufacturing of the porous rice straw board. The supplementary material apparatus and the heating apparatus are specialized production equipment ordered by Huachuang company and made by Guosen Machinery Co., Ltd. in Qingdao City Shandong province. The supplementary material apparatus is composed of two conveyor belts and a container, which consists of two rotating bulk feeders allowing the material to be evenly spread into the compressing mold of the multi-frequency hot pressing apparatus. The porous straw board exiting the hot press is trimmed with a plunger cutter. Heating is provided by a straw pellet fuel boiler, which feeds hot oil into the compressing mold and hollow heart stick.

The thermal gravimetric tests performed before and after coating with adhesives were carried out by using a thermogravimetric analyzer (TGA) with weighing accuracy of ± 0.01%, sensitivity 0.1ug, temperature accuracy of ± 1 ℃ produced by TA Instrument in United States and assembled in Canada. The test apparatus with ceramic sample trays (volume ~100ul) was cooled by forced flow of nitrogen provided by a gas cylinder.

2.3 Experimental design

The significant manufacturing parameters of this study include the proportion of inorganic to organic gelling materials (PIO), the adhesive added ratio (AAR), the pressing pressure, the temperature, and the pressing frequency. The organic gelling material was composed of a mixture of bean pulp and MDI(100:1 mass ratio) dissolved in deionized water by vigorous stirring. We have used four PIO's prepared by thoroughly mixing inorganic and organic gelling materials with various ratios, denoted as following: T1: (inorganic : organic ration of 1:4), T2:(1:6 ratio), T3:(4:1 ratio), and T4(6:1ratio). The experimental adhesive addition ratio(AAR), defined as the percentage of adhesive in the total mass of preload straw materials, was 10%, 20%, 40%, and 60%, respectively. The hot pressing pressure levels investigated were 5 MPa, 10 MPa, 20 MPa, 30MPa, and the pressing temperature levels were 100 ℃, 120 ℃, 140 ℃, 160 ℃, respectively. The hot pressing frequency was 6, 8, 10, and 12 times per minutes. Table 1 shows the experimental factors and levels. Experimental parameters obtained by a L16(4^5) orthogonal array experiment are shown in Table 2. The experimental data represent averages over four independent measurements.

| Table 1 Factors levels and code of variables |
|-------------------------------|-------------------|-----------------|-----------------|-------------------|-------------------|
| Level | A PIO | B AAR/% | C Hot pressure/MPa | D Hot pressing temperature/℃ | E Hot pressing frequency |
|-------|--------|---------|---------------------|-----------------|-------------------|
| 1     | (A1)T1 | (B1)10  | (C1)5               | (D1)100         | (E1)6             |
| 2     | (A2)T2 | (B2)20  | (C2)10              | (D2)120         | (E2)8             |
| 3     | (A3)T3 | (B3)40  | (C3)20              | (D3)140         | (E3)10            |
| 4     | (A4)T4 | (B4)60  | (C4)30              | (D4)160         | (E4)12            |
3. Results and Analysis

3.1 Experimental results

The key indicators of the orthogonal test target include the density of the porous straw board (ρ), internal bond strength of (IB), modulus of rupture (MOR) and thickness swelling after 2 hours (TS ). The results of the orthogonal test are shown in Table 2.

| Number | A     | B     | C     | D     | E     | ρ(g·m⁻³) | IB(MPa) | MOR(MPa) | Ts2h(%) |
|--------|-------|-------|-------|-------|-------|----------|---------|----------|---------|
| 1      | A1    | B1    | C1    | D1    | E1    | 0.41     | 0.44    | 21.5     | 1.21    |
| 2      | A1    | B2    | C2    | D2    | E2    | 0.64     | 0.53    | 22.1     | 1.03    |
| 3      | A1    | B3    | C3    | D3    | E3    | 0.82     | 0.96    | 25.4     | 0.93    |
| 4      | A1    | B4    | C4    | D4    | E4    | 0.89     | 1.13    | 28.5     | 0.82    |
| 5      | A2    | B1    | C2    | D3    | E4    | 0.53     | 0.87    | 23.2     | 1.11    |
| 6      | A2    | B2    | C1    | D4    | E3    | 0.49     | 0.66    | 22.1     | 1.07    |
| 7      | A2    | B3    | C4    | D1    | E2    | 0.86     | 0.71    | 24.2     | 0.83    |
| 8      | A2    | B4    | C3    | D2    | E1    | 0.88     | 1.07    | 24.6     | 0.85    |
| 9      | A3    | B1    | C3    | D4    | E2    | 0.85     | 1.06    | 23.8     | 0.87    |
| 10     | A3    | B2    | C4    | D3    | E1    | 0.87     | 1.12    | 29.8     | 0.83    |
| 11     | A3    | B3    | C1    | D2    | E4    | 0.63     | 0.97    | 24.5     | 0.97    |
| 12     | A3    | B4    | C2    | D1    | E3    | 0.78     | 1.04    | 25.7     | 0.88    |
| 13     | A4    | B1    | C4    | D2    | E3    | 0.88     | 1.13    | 28.5     | 0.82    |
| 14     | A4    | B2    | C3    | D1    | E4    | 0.83     | 1.08    | 27.7     | 0.93    |
| 15     | A4    | B3    | C2    | D4    | E1    | 0.77     | 0.97    | 26.7     | 0.98    |
| 16     | A4    | B4    | C1    | D3    | E2    | 0.76     | 0.88    | 25.7     | 1.03    |

3.2 Strawboard process optimization

Range analysis of the test results, shown in Table 3, indicates that the pressing pressure is the main factor influencing the key indicators ρ, IB, MOR and TS, followed by the adhesive addition ratio(AAR) and the adhesive type (the proportion of inorganic to organic gelling materials in the adhesive being denoted PIO). The results also shows that the pressing temperature and pressing frequency have relatively little influence on the test parameters. However, a hot pressing temperature of 120 °C to 140 °C and pressing frequency control rate of less than 10 times per minute are necessary to maximize production energy efficiency. The results of test factor A show that the ratio of the inorganic gelling material and the organic gelling material influence performance indicators results. Specifically, it was found that the A3 and A4 protocols improve the density of the straw board, IB and MOR while minimizing the thickness swelling after 2 h (TS). Consequently, the addition of inorganic gelling materials not only enhance the straw board flame resistance but its density and mechanical strength alike. Adding more adhesive to the pre-pressing straw also greatly influence the performance of the straw board, specifically the performance indicators indicate an optimal AAP value of 40%. However, by increasing the AAP up to 60% does not significantly compromise performances. Our
multi-parameter optimization analysis indicates that the optimal, most energy efficient straw board manufacturing process is $C_4A_3D_3E_3$. The key parameters of the fabrication process are: a pressing pressure 30MPa, an inorganic to organic gelled material ratio of 4:1, the proportion of adhesive in straw board mass ratio of 40%, a pressing frequency control less than 10 times per minute, and a pressing temperature between 120 °C and 140 °C.

Table 3 Range analysis of the test results

| Performance Indicator | Factors     | Primary and secondary optimization |
|----------------------|-------------|-----------------------------------|
|                      | coeff       | A   | B   | C   | D   | E   |
| **P**                | K1          | 0.69| 0.6675| 0.5725| 0.72| 0.7325|
|                      | K2          | 0.69| 0.7075| 0.68 | 0.745| 0.7775|
|                      | K3          | 0.7825| 0.77 | 0.845| 0.745| 0.7425|
|                      | K4          | 0.81 | 0.8275| 0.875| 0.75 | 0.72 |
|                      | R           | 0.12| 0.16 | 0.3025| 0.03| 0.0575|
| **IB**               | K1          | 0.765| 0.875| 0.7375| 0.8175| 0.9375|
|                      | K2          | 0.8275| 0.8475| 0.8525| 0.9 | 0.765|
|                      | K3          | 1.0475| 0.9025| 1.0425| 0.9575| 0.9475|
|                      | K4          | 1.015| 1.03 | 1.0025| 0.955| 1.0125|
|                      | R           | 0.2825| 0.1825| 0.305| 0.14 | 0.2475|
| **MOR**              | K1          | 24.375| 24.25| 23.45| 24.775| 25.65|
|                      | K2          | 23.525| 25.425| 24.425| 24.925| 23.95|
|                      | K3          | 23.95| 25.2 | 25.375| 26.025| 25.425|
|                      | K4          | 27.15| 26.125| 27.75| 25.275| 25.975|
|                      | R           | 3.625| 1.875| 4.375| 1.25 | 2.025|
| **TS**               | K1          | 0.9975| 1.0025| 1.07| 0.9625| 0.9675|
|                      | K2          | 0.965 | 0.965| 1.0125| 0.9175| 0.94 |
|                      | K3          | 0.8875| 0.9275| 0.895| 0.975| 0.925|
|                      | K4          | 0.94 | 0.895| 0.825| 0.935| 0.9575|
|                      | R           | 0.11 | 0.1075| 0.245| 0.0575| 0.0425|

3.3 Factors influences on strawboard performance

The results of the analysis of variance demonstrate that both the pressing pressure, and the AAR have a very significant influence ($P < 0.01$) on the performance indicators. The PIO also has a highly significant influence on the density of the straw board and the TS after 2h ($P < 0.01$), whereas the influence on the IB and the MOR is slightly less significant ($P < 0.05$). The pressing temperature and the hot pressing frequency have relatively lesser ($P < 0.05$) influence on the performance index. The data in Table 2 also show that adding more adhesive to the materials (by increasing the AAR) significantly enhanced the modulus of rupture (MOR), the internal bond strength (IB) and the density ($\rho$) while decreasing the thickness swelling (TS) after 2 hour. These results also suggest that the pressing
pressure, pressing temperature, and pressing frequency rate also influence the performance of the straw board, albeit to a lesser extent. This result is due to the straw moisture content being held at 20%. A higher moisture content means the pressing time needs to be increased by either lowering the pressing frequency or increasing the hot temperature, both of which promote the evaporation of water.

In order to assess the impact of adhesive composition on the properties of the straw board, the quality and temperature variation of the rice straw before and after coating with adhesive were studied using thermogravimetry. The results, shown in Figure 1, indicated that the quality of rice straw material before coating with the adhesive decreases significantly when the temperature reaches 100 °C, due to water evaporation. The quality of the rice straw material further sharply decreased by approximately 25% and the material began to burn when the temperature reached 180 °C. Differential thermogravimetric curve shows that the maximum weight loss rate occurs at a temperature of 340 °C.

Figure 1 The thermogravimetry of the rice straw before and after coating with adhesive

Figure 2 The straw board under condition of the optimal technological parameters
The curve 3 of figure 4 shows that the mass loss was significantly lower when adhesive was added to the bare straw material. The curve 3 of figure 1 also shows a maximum mass loss rate of approximately 48% after the test material was coated with adhesive and a carbonization reaction occurring when the temperature reached 340 °C. Altogether, these findings suggest that the adhesive acts as a flame retardant. During the thermoforming process, the pressing temperature and pressing time promote the solidification of the adhesive, and its chemical reaction with the surface of the straw material[20]. Insufficient hot pressing temperature or pressing time prevent the complete solidification of the adhesive thereby affecting the performance of straw board. However, an excessive pressing time causes the thermal decomposition of the isocyanate in the adhesive, also resulting in poor mechanical performances[21]. Based on actual production data, the suitable pressing time and pressing temperature are in the range of 1 to 3 min and 120 °C to 140 °C, respectively. However, the effect of the pressing time and the pressing temperature on the adhesive solidification deserves further study.

4. Validation test

Based on the test results and optimization analysis, the following optimal technological parameters was established: ratio of inorganic : organic gelling material in the adhesive equal to 4:1, adhesive to straw material mass ratio is 40%, hot-pressing pressure equal to 30 MPa, pressing frequency less than 10 times, and pressing temperature between 120 °C and 140 °C. Validation experiments and performance tests were also conducted. The straw board manufactured under the optimal technological parameters shown in figure 2. The test results, shown in Table 4, indicated that the rice straw artificial board met or exceeded the performance index of the national medium density fiber board (MDF) under the optimal fabrication conditions describe above.

| Performance index | Performance values of the rice straw board for validation tests |
|-------------------|---------------------------------------------------------------|
| Density ρ/g·m⁻³ | Test Value 0.9 29.4 13 3570 1750 0 30 180 60 |
| or M (M Pa) | Standard 0.88 ≥20 ≥18 ≥115 0 70 ≥15 ≤200 ≤75 |
| IB (M Pa) | 2hT (%) | MOR (MPa) | NHP (N) | Average burning residual length (cm) | Average Flue gas temperature / °C | Smoke density grade SDR | Form a-
| a-
| aldehy
de-
| emission |

5. Conclusions

In the pressing process of straw board, the hot pressing pressure and the adhesive added ratio(AAR) have a significant impact on various performance indicators(P<0.01). The ratio inorganic to organic gelling materials have a very significant impact on the board density and its thickness swelling ratio in water after 2h(P<0.01). The ratio even more significantly influences the internal bond strength(IB) and the modulus of rapture (MOR) (P<0.05). Conversely, the effect of hot pressing temperature and hot pressing frequency on the performance index is minor (P<0.05).

A L₁₆(4⁵) orthogonal experiment was used to optimize the production process of rice straw board.
The optimal production process parameters for this experiment were observed to be inorganic to organic gelling material ratio of 4:1, adhesive content and straw material mass ratio of 40%, hot-pressing pressure of 30 MPa, hot-pressing temperature in the range of 120 °C to 140 °C, and hot pressing frequency of 10 times per minute. The results indicated that this optimized manufacturing process yields straw board meets the national standard for medium density fiberboard (MDF).

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