Manufacturing Technology and Parameter Optimization for Composite Board from Corn Stalk Rinds

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To improve the bonding strength between adhesive and enhance the performance of composite board made from corn stalk rinds, a method for preparing three-layer composite boards was proposed. Accordingly, corn stalk rinds with the epidermis removed, were used as the core layer, while crushed aggregates from the epidermis were used as the surface layer of the composite board. Single-factor and orthogonal experiments were conducted to analyze the effects of the sampling height of corn stalk rinds, the surface layer proportions, and the hot-pressing temperature and time on the physico-mechanical properties of composite board. The resulting composite board from corn stalk rinds showed enhanced properties, except for the internal bond strength ($P < 0.01$). The physical properties of the composite board were significantly improved ($P < 0.01$) by removing the crushed aggregates of the epidermis, forming a single layer of composite board. The optimal parameters were as follows: the sampling height below the ear part of the corn stalk rinds; 12% surface layers; 150 °C hot-pressing temperature; and 6 min time. Under these conditions, the physico-mechanical properties of the composite board met the requirement level for particleboard. This research supports the use of corn stalk rinds as composite boards.

Keywords: Corn stalk rind; Epidermis; Three-layer composite board; Manufacturing technology

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INTRODUCTION

Although corn stalks are abundant in China, the resource has not been well utilized (Wang *et al*. 2014). An effective approach to increase the added value of corn stalk involves the utilization of the rinds, pith, and leaves separately (Wang *et al*. 2012; Zeng *et al*. 2012a; Zeng *et al*. 2012b). As the main component of corn stalks, corn stalk rinds present fiber morphology similar to that of wood. However, corn stalk rinds have a higher mechanical strength than wood, and therefore can serve as an alternative to wood when producing non-structural particleboard (He and Wang 2015a).

Nano-SiO_2 composites in the epidermis of corn stalk rinds are unfavorable for the gluing process (Akgul *et al*. 2010; Zeng *et al*. 2014). Corn stalk rinds are smashed to produce particleboard (Lu *et al*. 2012); however, the preparation process involves a complicated treatment and large amount of energy consumption (Zhang *et al*. 2012). When preparing boards using intact corn stalk rind, the epidermis must be removed. Nano-SiO_2 composites in the epidermis of corn stalk rinds is beneficial for the bending strength, thermal stability, and hydrophobicity of materials (Song and Zheng 2013). Therefore, it is of practical significance to use both the intact corn stalk rind and its epidermis for manufacturing composite boards.

The fiber morphology parameters and the tensile properties of corn stalk rind at various sampling heights were significantly different; corn stalk rind had greater tensile strength in the axial direction than the radial direction; and the tensile properties and fiber morphology of corn stalk rind were correlated (He and Wang 2015a). Removal of the epidermis can significantly improve the hydrophilicity of corn stalk rind (He and Wang 2015b). Therefore, the epidermis of corn stalk rinds was removed to improve the gluing properties, and then, the crushed aggregates of the epidermis were recycled to prepare the composite board from corn stalk rinds in this study. Consequently, the three-layer composite board consisted of crushed aggregates of the epidermis and corn stalk rinds without the epidermis as the surface layers (upper and bottom layers) and core layer, respectively. The effects of the biological characteristics (sampling height) of the corn stalk rinds, structure of the composite board (the proportion of the surface layers), hot-pressing temperature, and hot-pressing time on the physico-mechanical properties of the composite board were studied. This research provided a theoretical basis and a technical reference for optimizing the manufacturing process of composite boards from intact corn stalk rinds.

EXPERIMENTAL

Materials

Xianyu 335-variety corn stalks were cultivated on the Maozhuang farm in the suburb of Zhengzhou, Henan Province, China, and harvested in October 2014. The corn stalks were more than 2.0 m high, with an average number of 15 sections. The diameter of the root was between 23 and 28 mm, and the fifth and sixth sections along the growth direction of the corn stalks formed the ear, with an average ear height greater than 900 mm.

Intact corn stalk rinds were separated by rind-pith-leaf separating equipment. The epidermis (approximately 0.04 mm thick) was removed, and the rest of corn stalk rinds were used to prepare samples, which had widths between 8 and 16 mm and lengths of 150 mm. The samples were dried until a moisture content of 10% was reached. The removed epidermis was collected and ground until it reached a size of 80 to 120 meshes. The chemical compositions of the corn stalk rinds before and after the removal of the epidermis are listed in Table 1.

Table 1. Composition of Corn Stalk Rinds Before and After Epidermis Removal

Type of Corn Stalk	Elemental Composition			Chemical Composition		
	Si (%)	C (%)	O (%)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Before epidermis removal	21.74	24.76	46.22	35.10	23.98	26.02
After epidermis removal	0.12	53.17	41.58	35.85	25.20	24.83

Polymeric diphenylmethane isocyanate (pMDI) was used as the adhesive in this experiment. The solid mass fraction, Brookfield viscosity, and pH of the pMDI were 60 ± 1%, 10,000 to 13,000 MPa·s (25 °C), and 6.6 to 7.5, respectively.

Test Equipment

The test equipment included self-designed, rind-pith-leaf separating equipment, a RE-8030 microcomputer control-based hydraulic Servo universal testing machine (Shenzhen Reger Instrument Co., Ltd, Shenzhen, China), an RGT-10 microcomputer control-based electronic universal material testing machine (Shenzhen Reger Instrument Co., Ltd., Shenzhen, China), and a DHG-9420A thermostatic blast drying oven (Shanghai Yiheng Scientific Instrument Co., Ltd., Shanghai, China). Moreover, a BSA3202S electronic balance purchased from Sartorius Scientific Instrument Co., Ltd., Beijing, China, a DF-15 desk-type continuous feeding pulveriser provided by the Wenling Linda Machinery Co., Ltd., Zhejiang, China, and a scanning electron microscope (SEM; S-3400N, Hitachi, Tokyo, Japan) were used. To automatically control the heating temperature (0 to 300 °C), the die set had an inner cavity size of 150 mm × 150 mm and contained of a concave die, an upper convex die, and a lower convex die.

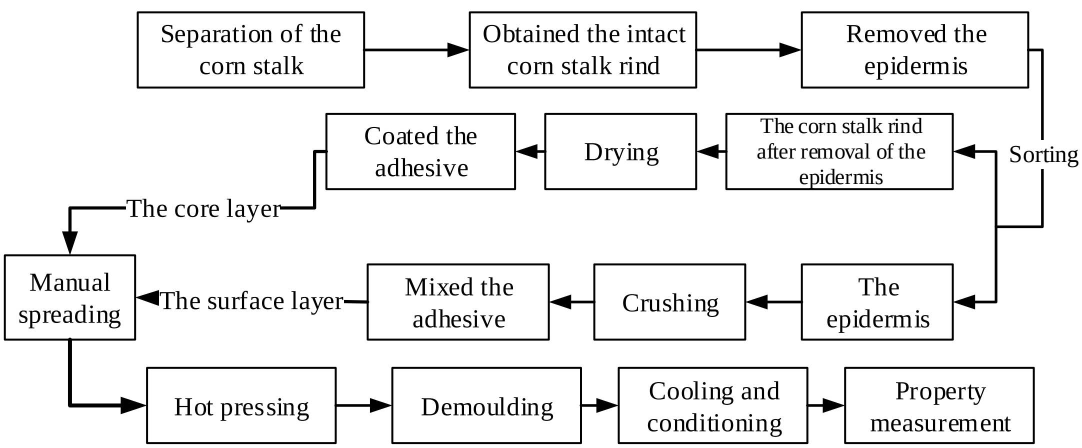


Fig. 1. Process for manufacturing composite board from corn stalk rinds

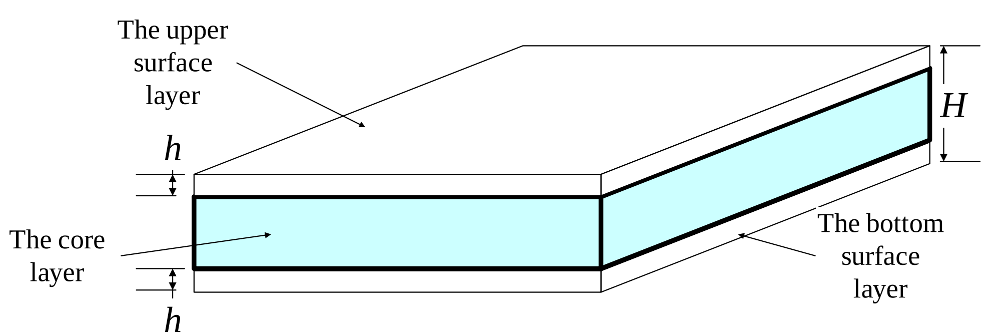


Fig. 2. Structure of the corn stalk rind composite board

Test Methods

Manufacturing composite board from corn stalk rinds

The process for manufacturing composite board from corn stalk rinds is illustrated in Fig. 1, and the materials were oriented as shown in Fig. 2. The crushed aggregates of the epidermis mixed with adhesives were placed in the upper and lower surface layers, while the corn stalk rinds (without the epidermis) were coated with adhesives and laid on the core layer. The adhesive content was 12% in both cases. Because the total thickness *H* (generally 50 mm) of the slab of the three-layer composite board was constant, the layer thickness *h* of the surface layers kept changing with the amount (or proportion) of added crushed aggregates of the epidermis.

In the core layer, the corn stalk rinds in each laminate were placed parallel to the axial direction (to a thickness of 1 to 2 mm), and each laminate was laid at 90° across its adjacent laminates. Tinfoil was positioned between the composite board and the upper and lower convex dies to facilitate demoulding. During hot-pressing, the setting pressure, loading speed, and target thickness of the board were 180 kN, 5 mm/min, and 10 mm, respectively.

Experimental design

The corn stalk rinds with various sampling heights show significant differences in terms of their tension and shear properties (He and Wang 2015a), and the board exhibits favorable performance with 10 to 12% adhesive (Lu *et al*. 2012). Single-factor experiments were used to investigate the biological characteristics of corn stalk rinds, the effect of the structure of the composite board (sampling height and proportion of the surface layers), and the hot-pressing process conditions, *i.e*., the hot-pressing temperature and the hot pressing time, on the properties of the composite board.

The sampling height refers to the section of the corn stalk, while the proportion of the surface layers refers to the proportion of the dried, crushed aggregates of the epidermis in the upper and lower surface layers of the composite board, with respect to the total mass of the composite board. Thereafter, the values of each experimental factor were selected according to the results obtained by the single-factor experiments. An L_9 (3^4) orthogonal table was used to carry out the multi-factor experiments (Table 2), which were repeated three times.

Table 2. Codes and Levels of Experimental Factors

Levels	Experimental Factors			
	Sampling Height	Proportion of the Surface Layers (%)	Hot-Pressing Temperature (°C)	Hot-Pressing Time (min)
1	Bottom part (3rd section)	4	130	3
2	Ear part (5th section)	8	150	6
3	Top half part (7th section)	12	170	9

Property tests of the composite board

The mechanical and physical properties of the composite board were evaluated according to Chinese standards GB/T 4897.3 (2003) and GB/T 17657 (2013). The mechanical properties tested were the modulus of rupture (MOR), the modulus of elasticity (MOE), and the internal bond strength (IB). The physical properties tested were the thickness swelling (TS) and the water absorption (WA) in 2 h at room temperature. Modulus of rupture (MOR) and modulus of elasticity (MOE) of the composite board (50 mm × 150 mm) were obtained by a RE-8030 microcomputer control-based hydraulic Servo universal testing machine at a crosshead speed of 5 mm/min. Internal bond strength (IB) of the composite board was measured by pulling the specimen (50 mm × 150 mm) apart in the cross section direction at a crosshead speed of 1 mm/min. Thickness, length and weight of the specimens (50 mm × 150 mm) were measured before and immediately after soaking. The dimensional size and weight measured before and after soaking were used to calculate TS and WA, which were expressed as percentages of the data after soaking to the data before soaking.

RESULTS AND DISCUSSION

Effect of Corn Stalk Sampling Height on Composite Board Properties

The conditions of hot-pressing were 8%, the surface layers, 150 °C, and 6 min. The root (first section), bottom (third section), ear (fifth section), top half (seventh section), and top part (ninth section) of corn stalk rinds were selected as sampling heights, and the properties of the resultant composite boards were studied (Fig. 3).

Increased sampling height decreased the MOR and MOE of the composite board, while the IB, TS, and WA increased. This was because corn stalk rinds at various sampling heights exhibited different chemical compositions and fiber morphologies. Furthermore, the characteristic parameters of the chemical composition and fiber morphology were correlated with the mechanical properties and water absorption capacity (He and Wang 2015b). When the sampling height increased from the first section to the fifth section, the MOR and MOE decreased by 6.84% ($P < 0.05$) and 5.84% ($P < 0.05$), respectively, while the IB, TS, and WA increased by 5.88% ($P < 0.05$), 14.62% ($P < 0.05$), and 8.61% ($P < 0.05$), respectively.

When the sampling height was increased from the fifth to the ninth section, the MOR and MOE decreased by 19.21% ($P < 0.01$) and 16.71% ($P < 0.01$), respectively, while the IB, TS, and WA increased by 15.36% ($P < 0.01$), 25.10% ($P < 0.01$), and 18.11% ($P < 0.01$), respectively.

Therefore, the composite board from corn stalk rinds above and below the ear part exhibited different properties. Specifically, corn stalk rinds from below the ear resulted in composite board with superior properties (except IB). To promote the application of intact corn stalk rinds in wood-based boards, the bottom part (third section), ear part (fifth section), and top-half part (seventh section) were separately evaluated in the orthogonal experiment.

Effect of Surface Layer Proportion on Composite Board Properties

When the sampling height was the ear part (fifth section) and the hot-pressing temperature and time were 150 °C and 6 min, respectively, the properties of the composite board were studied with surface layer proportions of 0%, 4%, 8%, 12%, and 16% (Fig. 4). With an increasing proportion of surface layers in the composite board, the MOR, MOE, TS, and WA were reduced, but there was little variation in IB. As the proportion of surface layers increased from 0% to 16%, the MOR, MOE, TS, and WA of the composite board decreased by 22.69% ($P < 0.05$), 26.22% ($P < 0.05$), 30.21% ($P < 0.01$), and 26.02% ($P < 0.01$), respectively.

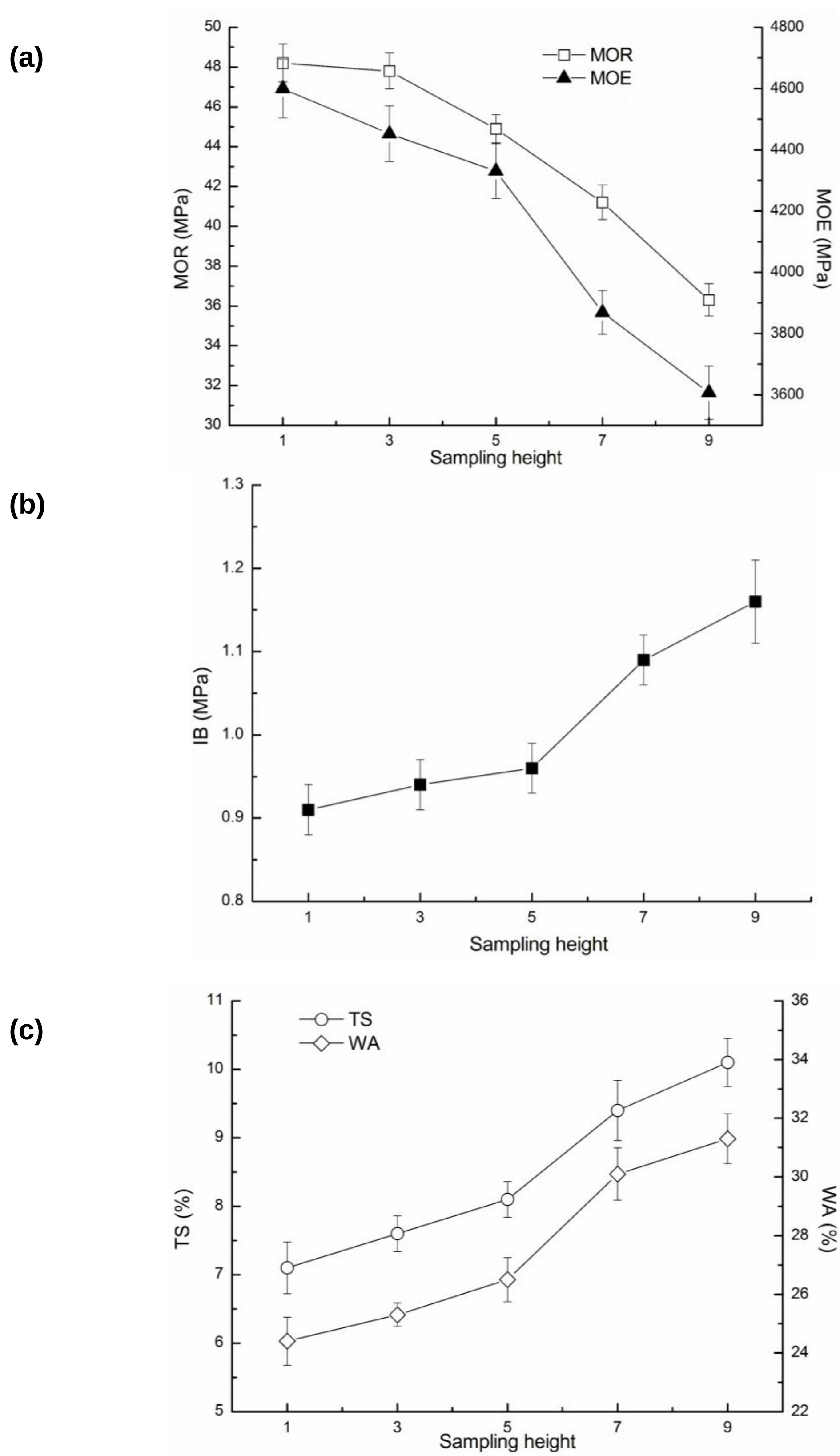


Fig. 3. Effect of sampling height on corn stalk rind composite (a) MOR and MOE; (b) IB; and (c) TS and WA. The numbers 1, 3, 5, 7, and 9 indicate the root, bottom, ear, top half, and top part of the corn stalk rind, respectively.

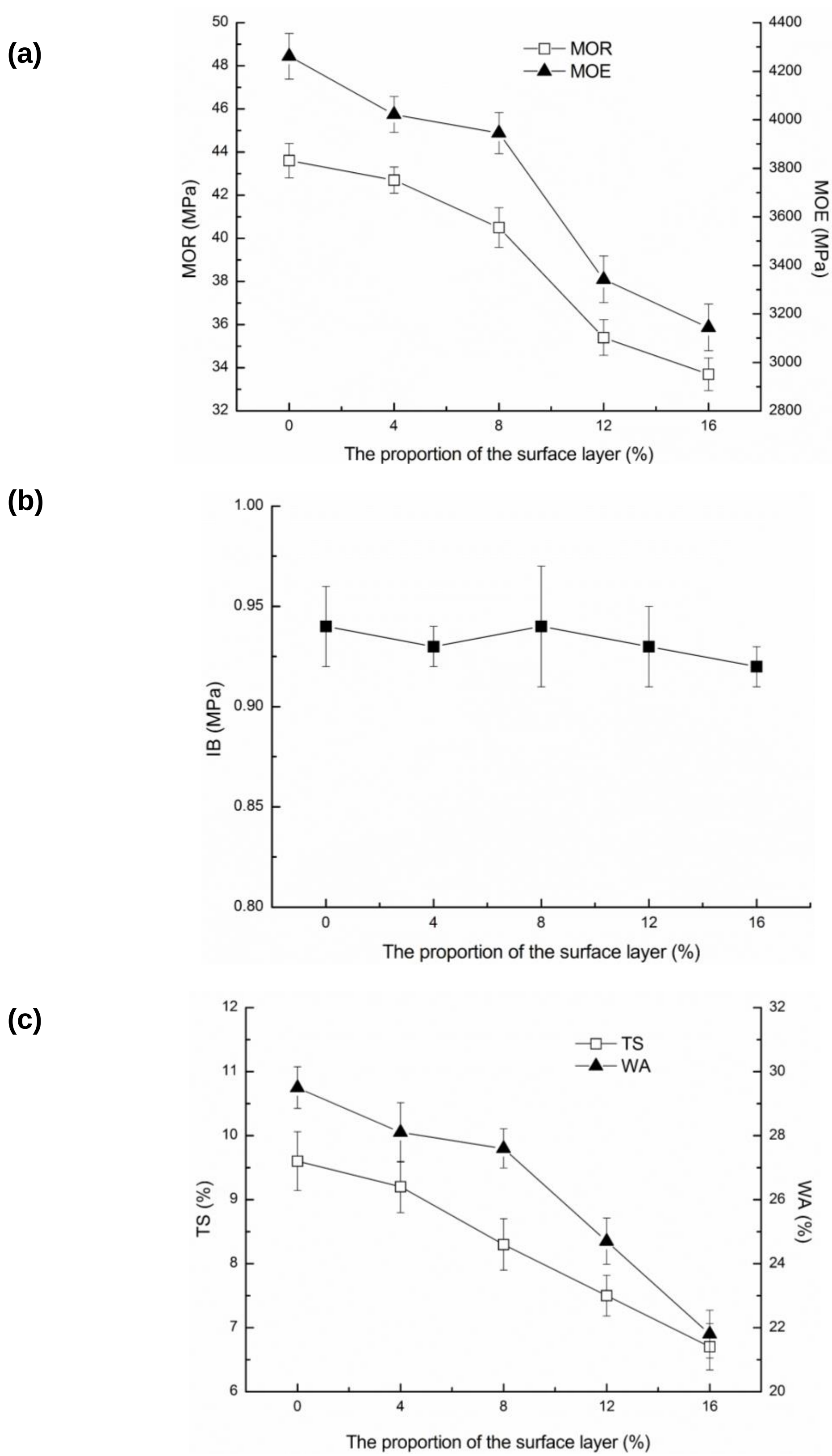
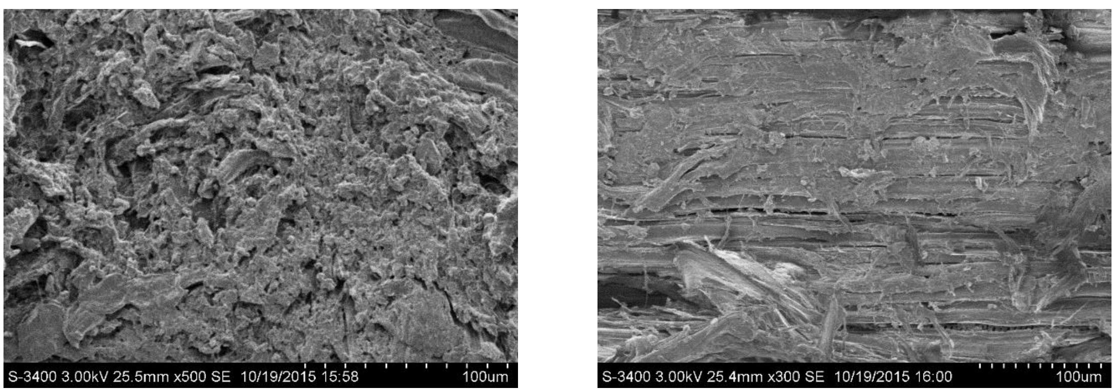


Fig. 4. Effect of surface layer proportion on corn stalk rind composite board (a) MOR and MOE; (b) IB; and (c) TS and WA

Figure 5 shows the micro-morphology of the surface and core layers in the composite board. The epidermis particles in the surface layer were surrounded and inlaid with adhesives, and the corn stalk rinds in the core layer were superimposed layer-by-layer and lapped, although some gaps were seen. Therefore, increasing the surface layer affected the properties of the composite board in two ways: (i) the mass fraction of corn stalk rinds that supported the composite board decreased; and (ii) the lignocellulose content of the composite board also decreased (Li *et al*. 2009; Xu *et al*. 2009). As a result, the composite board resistance to bending and stiffness was decreased, and the MOR and MOE were reduced. In contrast, the specific surface area of the crushed aggregates of the epidermis was large, contributing to the gluing effect. In this way, a film of adhesive coated the crushed aggregates of the epidermis, and both sides of the core layer were covered by the surface layer. Hence, the surface layer prevented water penetration into the gaps in the core layer, which reduced the TS and WA.

Because the amount of crushed aggregates of the epidermis stripped from the surface of corn stalk rinds was limited for each corn stalk, it was determined that 4%, 8%, and 12% were the best concentrations for the proportion of the surface layers in the orthogonal test by combining the results of the single-factor experiment.



(a) (b)

Fig. 5. Microscopic observation of (a) the surface layer (500X) and (b) the core layer (300X)

Effect of Hot-Pressing Temperature on Composite Board Properties

The effects of different hot-pressing temperatures on the properties of the composite board were investigated with a sampling height in the ear part (fifth section), 8% surface layers, and a hot-pressing time of 6 min (Fig. 6). As the hot-pressing temperature increased, the MOR, MOE, and IB of the composite board initially decreased and then increased, while TS and WA of the composite board presented the opposite trend. Thus, higher hot-pressing temperatures positively affected gluing between the adhesive, the crushed aggregates of the epidermis, and corn stalk rinds as well as accelerated the solidification process; thereby, the mechanical and physical properties of the composite board were improved.

A high mass fraction of the crushed aggregates of the epidermis promotes thermal stability in composite board (Azizi *et al*. 2011). If the temperature was too high, however, the thermal decomposition of hemicellulose in the surface and core layers and the aging of the adhesive were accelerated (Werner *et al*. 2014), which gradually decreased the MOR, MOE, and IB and increased the TS and WA.

(a)

(b)

(c)

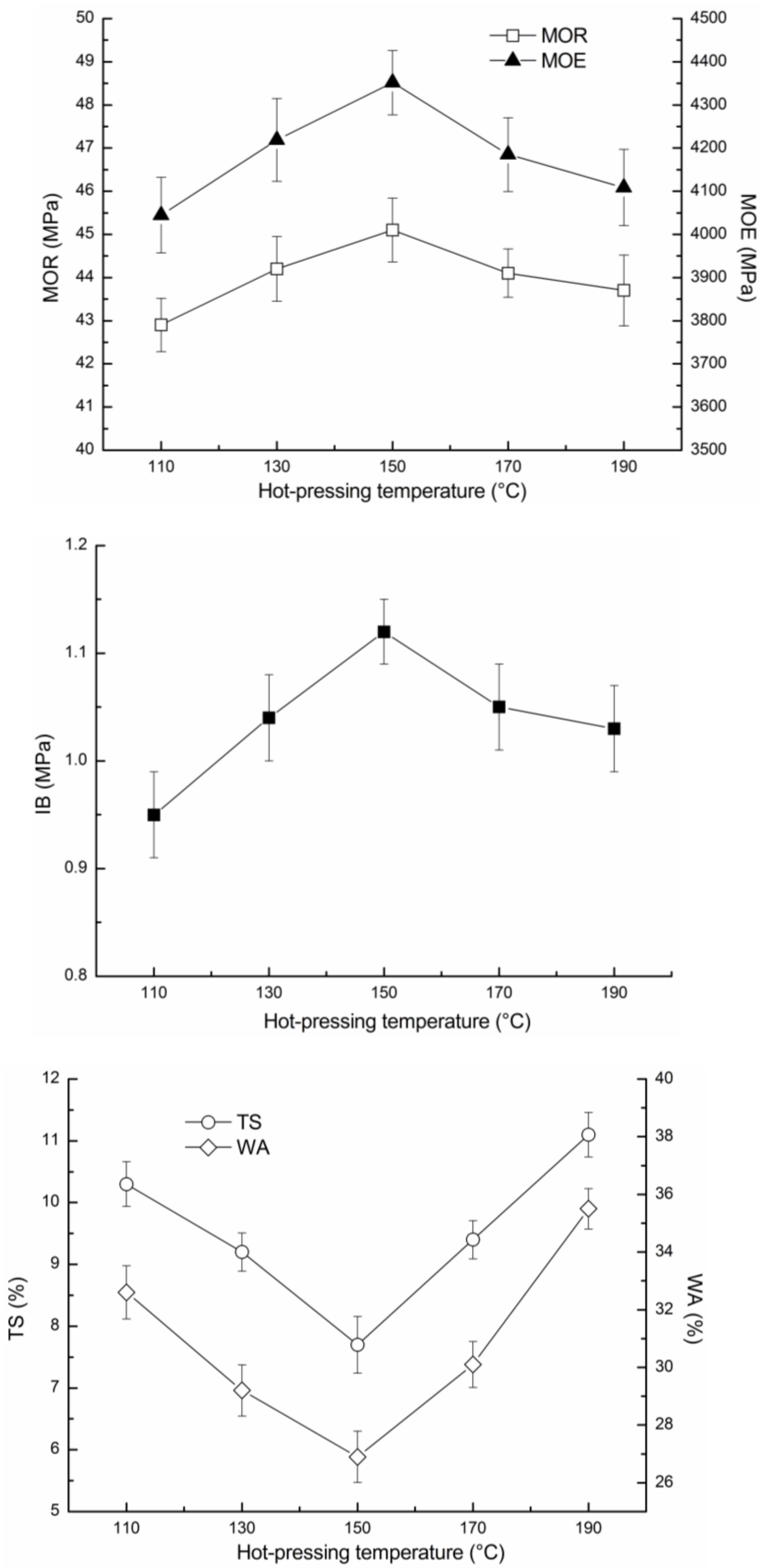


Fig. 6. Effect of the hot-pressing temperature on the on corn stalk rind composite board (a) MOR and MOE; (b) IB; and (c) TS and WA

When the hot-pressing temperature was increased from 110 °C to 150 °C, the MOR, MOE, and IB of the composite board increased by 5.21% ($P < 0.05$), 7.59% ($P < 0.05$), and 16.44% ($P < 0.01$), respectively, while the TS and WA of the composite board decreased by 25.24% ($P < 0.01$) and 17.48% ($P < 0.01$), respectively. As the hot-pressing temperature increased from 150 °C to 190 °C, the MOR, MOE, and IB of the composite board decreased by 3.18% ($P < 0.05$), 5.59% ($P < 0.05$), and 8.60% ($P < 0.05$), respectively, while the TS and WA of the composite board increased by 44.16% ($P < 0.01$) and 31.85% ($P < 0.01$), respectively.

The optimal hot-pressing temperature was 150 °C. Considering the energy consumption of the devices and the stratification effect of low hot-pressing pressure on the composite board, 130 °C, 150 °C, and 170 °C were determined as the best hot-pressing temperatures for the orthogonal experiment.

Effect of Hot-Pressing Time on the Properties of Composite Board

The effects of different hot-pressing times (3, 6, 9, 12, and 15 min) on the properties of the composite board were investigated with a sampling height in the ear part (fifth section), 8% surface layers, and a hot-pressing temperature of 150 °C (Fig. 7). As the hot-pressing time increased, the MOR, MOE, and IB of the composite board increased slightly and then decreased considerably, while the TS and WA of the composite board first decreased and then gradually increased. The optimal hot-pressing time was 6 min. As the hot-pressing time increased from 3 to 6 min, the MOR, MOE, and IB of the composite board increased by 5.68% ($P < 0.05$), 5.56% ($P < 0.05$), and 27.38% ($P < 0.01$), respectively, while the TS and WA of the composite board decreased by 10.59% ($P < 0.05$) and 7.13% ($P < 0.05$), respectively. When the hot-pressing time was increased from 6 to 15 min, the MOR, MOE, and IB of the composite board decreased by 15.19% ($P < 0.01$), 35.71% ($P < 0.01$), and 14.95% ($P < 0.01$), respectively, while the TS and WA of the composite board increased by 69.74% ($P < 0.01$) and 48.39% ($P < 0.01$), respectively.

Within a certain range, the hot-pressing time promoted the solidification of the adhesive and ensured that the composite board was uniformly affected by heat, thus improving mechanical properties in the composite. However, a longer hot-pressing time accelerated adhesive aging. Meanwhile, the pyrolysis products of the hemicellulose in the crushed aggregates of the epidermis, the surface layer of the corn stalk rinds, and the core layer of the composite board absorbed more water (Wang *et al*. 2009), so the physical properties of the composite board were rapidly weakened. With regard to the energy consumption of the devices used and uniform heat treatment of the composite board, the optimal duration for hot-pressing in the orthogonal experiment was 3, 6, and 9 min.

Optimization of Process Parameters

The orthogonal experiments were designed based on data from the single-factor experiments, with results listed in Table 3. The optimal parameter combination was determined by analyzing the range and variance of the results (Zhang *et al*. 2015). As indicated by variance analysis, sampling height exerted an extremely significant influence on MOR ($P < 0.01$), MOE ($P < 0.01$), TS ($P < 0.01$), and WA ($P < 0.01$) and an obvious influence on IB ($P < 0.05$). The proportion of the surface layers presented little influence on MOR ($P > 0.05$), MOE ($P > 0.05$), and IB ($P > 0.05$), while it exerted a significant influence on TS ($P < 0.01$) and WA ($P < 0.01$). Meanwhile, MOR ($P < 0.05$) and MOE ($P < 0.05$) were greatly influenced by the hot-pressing temperature, while a highly significant influence was found for IB ($P < 0.01$), TS ($P < 0.01$), and WA ($P < 0.01$).

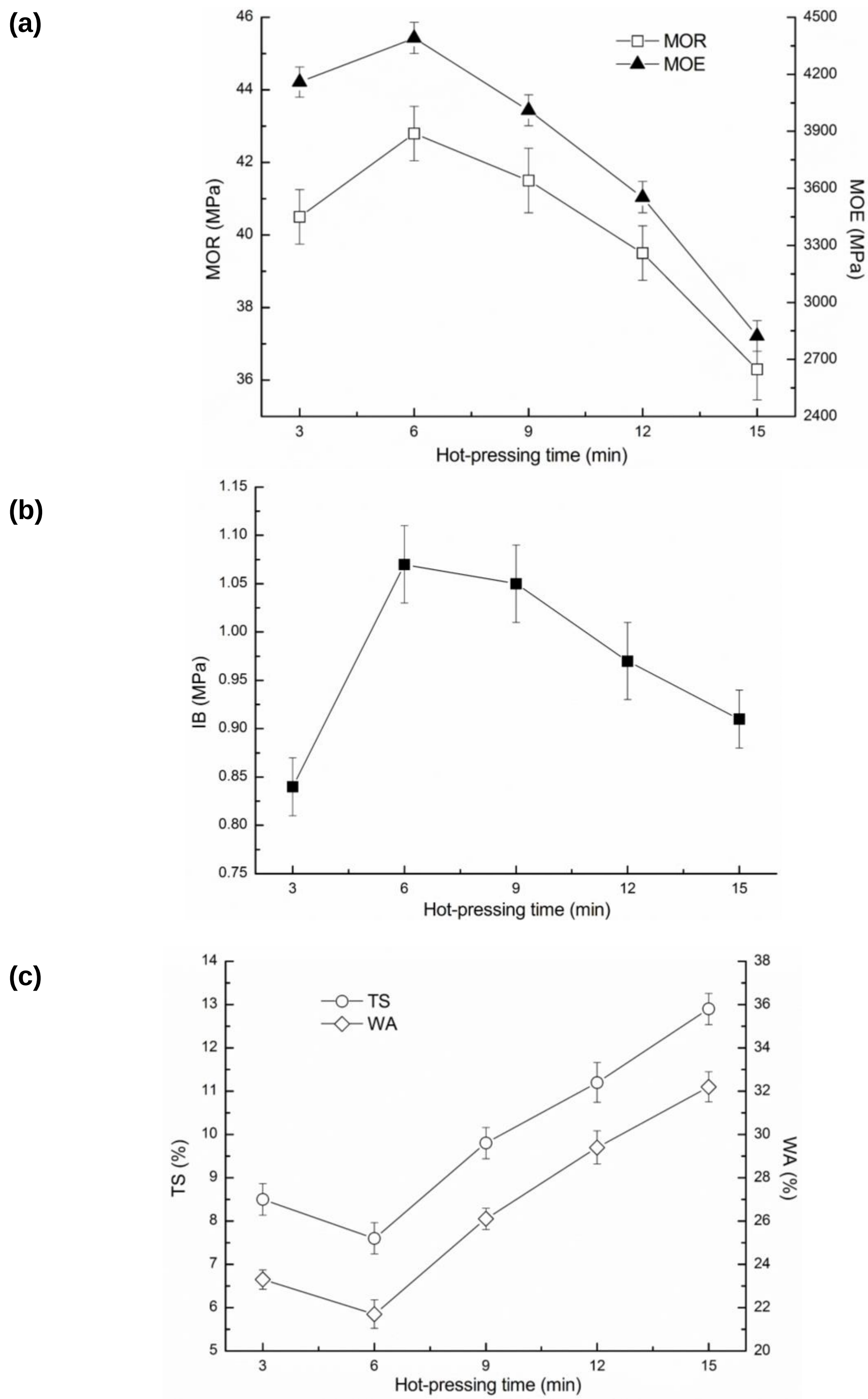


Fig. 7. Effect of the hot-pressing time on corn stalk rind composite board (a) MOR and MOE; (b) IB; and (c) TS and WA

Table 3. Orthogonal Experiment Results

Experiment Number	Experimental Factors: Sampling Height	Surface Layers (%)	Temperature (°C)	Hot-Pressing Time (min)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS (%)	WA (%)
1	1	1	1	1	45.10 ± 0.92	4404.37 ± 61.41	0.93 ± 0.02	10.87 ± 0.25	31.40 ± 0.62
2	1	2	2	2	47.63 ± 1.04	4569.93 ± 52.10	1.17 ± 0.05	6.43 ± 0.42	26.17 ± 0.35
3	1	3	3	3	46.90 ± 0.62	4439.53 ± 67.20	0.73 ± 0.03	7.87 ± 0.35	28.27 ± 0.32
4	2	1	2	3	44.53 ± 0.74	4374.70 ± 62.55	1.04 ± 0.05	10.03 ± 0.55	30.27 ± 0.59
5	2	2	3	1	42.37 ± 0.87	4240.07 ± 74.09	0.88 ± 0.03	8.43 ± 0.57	28.43 ± 0.65
6	2	3	1	2	42.70 ± 1.01	4296.03 ± 38.64	1.03 ± 0.04	8.77 ± 0.42	28.60 ± 0.75
7	3	1	3	2	41.70 ± 0.56	4136.57 ± 68.81	0.98 ± 0.03	10.43 ± 0.35	30.83 ± 0.31
8	3	2	1	3	40.40 ± 0.85	4036.00 ± 69.63	0.87 ± 0.02	10.33 ± 0.47	31.47 ± 0.67
9	3	3	2	1	39.60 ± 0.62	4079.37 ± 50.59	1.15 ± 0.06	7.23 ± 0.42	27.50 ± 0.53
K_{1a}	46.544	43.778	42.733	42.356					
K_{2a}	43.200	43.467	43.922	44.011					
K_{3a}	40.567	43.067	43.656	43.944					
R_a	5.977	0.711	1.189	1.655					
K_{1b}	4471.278	4305.211	4245.467	4241.267					
K_{2b}	4303.600	4282.000	4341.333	4334.178					
K_{3b}	4083.978	4271.644	4272.056	4283.411					
R_b	387.300	33.567	95.866	92.911					
K_{1c}	0.942	0.982	0.942	0.983					
K_{2c}	0.982	0.972	1.119	1.057					
K_{3c}	0.999	0.969	0.862	0.883					
R_c	0.057	0.013	0.257	0.174					
K_{1d}	8.389	10.444	9.989	8.844					
K_{2d}	9.078	8.400	7.900	8.544					
K_{3d}	9.333	7.956	8.911	9.411					
R_d	0.944	2.488	2.089	0.867					
K_{1e}	28.611	30.833	30.489	29.111	Note: *a*, *b*, *c*, *d*, and *e* indicate the modulus of rupture, the modulus of elasticity, the internal bond strength, the thickness swelling, and the water absorption, respectively				
K_{2e}	29.100	28.689	27.978	28.533					
K_{3e}	29.933	28.122	29.178	30.000					
R_e	1.322	2.711	2.511	1.467					

Hot-pressing time exerted a highly significant influence on MOR ($P < 0.01$), IB ($P < 0.01$), TS ($P < 0.01$), and WA ($P < 0.01$) and a significant influence on MOE ($P < 0.05$). Thus, the optimal parameter combination for preparing this composite board included the corn stalk rind sampling height below the ear part, 12% surface layers, and the hot-pressing temperature and time of 150 °C and 6 min, respectively

Experimental Verification

The optimal parameters were used to generate composite board from corn stalk rinds, and the mechanical and physical properties of the composite boards were tested according to GB/T4897.3 (2003) and GB/T17657 (2013) (Table 4). The physical and mechanical properties of the composite board from corn stalk rinds met the requirements the GB/T4897.3 (2003) standard, thus verifying the optimal parameters.

Table 4. Composite Board Properties under Optimized Parameters

Origin	MOR (MPa)	MOE (MPa)	IB (MPa)	TS (%)	WA (%)
Sample 1	48.3	4432.6	1.18	7.2	24.4
Sample 2	47.7	4425.9	1.21	7.1	24.3
Sample 3	46.8	4503.2	1.23	6.3	22.9
Sample 4	47.4	4595.3	1.15	6.9	22.7
Sample 5	49.1	4471.8	1.16	6.6	23.5
Mean	47.86 ± 0.88	4485.76 ± 68.8	1.19 ± 0.03	6.82 ± 0.37	23.56 ± 0.78
GB/T4897.3 (2003)	≥ 14	≥ 1800	≥ 0.8	≤ 8.0	-

CONCLUSIONS

1. The mechanical and physical properties of the composite board from corn stalk rinds below the ear part were significantly improved over the composite board made from above the ear part, except in the case of its internal bond strength ($P < 0.01$). The utilization of the epidermis as a surface layer significantly ($P < 0.01$) improved the physical properties of composite board.
2. The optimal parameters for the manufacturing process of the composite boards from corn stalk rinds were as follows: sampling height below the ear part of corn stalk rinds, 12% surface layers, hot-pressing temperature of 150 °C, and hot-pressing time of 6 min. Using these parameters, the mechanical and physical properties of the composite board met the Chinese national standard requirements for particleboard.

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