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RESEARCH ARTICLE

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Microscopic structure and properties of wood-based foaming composites

Abstract In order to reduce the density of wood-based composites without causing a deterioration of their mechanical properties, we studied the process of manufacturing wood-based composites. A combination of polymer foaming technology and flat hot-pressing technology was used. The microscopic structure of the various wood-based composites was analyzed with a scanning electron microscope (SEM). Modulus of rupture (*MOR*), modulus of elasticity (*MOE*), impact strength, and thickness expansion rate of water sorption (*TS*) were all measured. The results showed that fibers loosely interweave, and fibers had been connected by micropore. They also showed that spaces between fibers had big micropore structure. *MOR*, *MOE* and impact strength were the highest among three levels of ratio. When the total content of resin and foaming agent were 20% by weight, *TS* was higher. A hot-pressing temperature of 120°C was optimal. At the low temperatures of 80°C, the foaming process was uncompleted. At a higher temperature, micropores burst at a certain pressure. Based on the variance analysis and maximum difference analysis, a significance test shows that the optimum conditions for the total content of resin and foaming agent is 20% by weight, with a hot pressing temperature of 120°C for 15 min. Under these conditions, the properties of wood-based foaming composites all achieved the industry standard.

Keywords foaming, wood-based composites, microscopic structure, properties

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1 Introduction

Wood-based composites have been widely used for several decades, but also were limited to some applied areas for higher density. Chemical foaming technology offers the possibility of reducing the weight of a part without causing deterioration of mechanical properties, even improving impact strength, toughness and thermal stability and so on (Mantuna et al., 1999). This paper studied a chemical foaming process of manufacturing a kind of higher strength wood-based composites with lighter weight.

In recent years, researches on materials of foaming technologies had developed from single polymer to composites. Making use of the foaming process in the wood plastic composites industry was relatively late; most products were PVC-based composites (Mantuna et al., 2001a, 2001b, 2001c) produced through cellular foam extrusion process (Bledzki and Gassan, 1999; Bledzki et al., 1998, 1999, 2001, 2005).

Wood-based foaming composites had less tonnage and could enhance partial properties for the existence of micropores. This advantage was needed in many components, automobile, package, athletics appliance, and heat insulation or preservation materials in construction. There is a good foreground for wood-based foaming composites.

2 Materials and methods

2.1 Materials

PAPI (industrial grade): transparent brown liquid. Solid content was 100% and viscosity index was 200 mPa·s. Purchased from Yantai Wanhua Polyurethanes Co., Ltd.

TSU-450L (industrial grade): buff liquid, hydroxyl value was 440–460, pH value was 8–11, viscosity index was 6000–10000 mPa·s. Purchased from Tianjin petrochemical Co., Ltd.

WF (wood fiber): Simao pine (*Pinus kesiya*), moisture content was 2%–6% and packaged in sealed plastic bags.

2.2 Equipment

Flat hot presser: 80 t laboratory hot pressing, made by Shanghai wood-based panel machinery factory. This machine was used to press mat to panels under certain temperature.

Glue mixer: self-made machine. It was used to blend resin, foaming agent and wood fiber well.

Universal testing machine: maximum load was 5 t and made by SHIMADZU Co., Ltd. It was used to test modulus of rupture (*MOR*) and modulus of elasticity (*MOE*).

5J impact test machine: made by Hebei Chengde testing machine factory. This machine was used to test impact strength.

SEM-505: microscope was used to observe the microstructure of samples.

2.3 Methods

2.3.1 Design of experiments

First, the weighted wood fiber was placed in the mixer, and then the mixer was started at a fixed rotation speed to scatter the wood fiber. PAPI and foaming agent (TSU-450L) were sprayed later on the fiber under high pressure. After several minutes, the mixed materials were taken out and formed in a mold by hand. Finally, the mat was placed in a hot press in accordance with the designed hot-pressing parameters.

Orthogonal design (Table 1) was selected and test results were analyzed through variance and range analysis to describe the influence of factors and difference among levels. Three factors were considered to test their influences on the properties of products, including content of resin and foaming agent, hot-pressing time and hot-pressing temperature.

Table 1 Orthogonal experiment design of the wood-based composites

number	hot-pressing temperature/°C	hot-pressing time/min	content of resin and foaming agent/%
1	1(80)	1(10)	1(40)
2	1(80)	2(15)	2(30)
3	1(80)	3(20)	3(20)
4	2(100)	1(10)	2(30)
5	2(100)	2(15)	3(20)
6	2(100)	3(20)	1(40)
7	3(120)	1(10)	3(20)
8	3(120)	2(15)	1(40)
9	3(120)	3(20)	2(30)

Note: Hot-pressing pressure was 0.5 MPa, designed density was 0.15 g/cm^3, thickness of panels was 9 mm and the dimensions were 280 mm × 280 mm. Every experiment was run with three replicates. Data in parentheses were actual values in test, weight ratio between resin and foaming agent was 1:1.2.

2.3.2 Microscopic structures

The specimens were prepared with a size 3 mm × 6 mm × 6 mm from chosen test samples. These were then clamped using forceps and placed on the sample desk. After drying in a critical point dryer for several hours, they were placed in an ion sputtering coater for gold plating; finally, the specimens were observed in SEM.

2.3.3 Properties test

The test pieces could only be prepared after the panels had been placed under room conditions for at least 24 h. Density, *MOR*, *MOE* and thickness expansion rate of water sorption (*TS*) were measured according to EN 310-1999 standard. Impact strength was tested according to GB/T 1043-93 standard.

3 Results and discussion

3.1 Microscope structure

Figure 1 shows the microscopic structure in different magnifications. Figure 1a shows that fibers were interwoven and scattered loosely. In Fig. 1b, foaming products PAPI reacted with TSU were filled in gaps occasionally. The fuzzy interface between fiber and foams show that they bonded tightly. Figure 1c magnified the foam structure clearly. Figure 1d is the SEM photograph of the connection of micropores and fibers, foams added bonding points among fibers. Most pores were closed holes (Fig. 1e) and few had open structures, shown in Fig. 1f. When the aiming density was low, cellular foam produced under lower pressure exploded less and stayed closed.

3.2 Physical-mechanical properties

The physical and mechanical properties of wood-based foaming materials are given in Table 2. Results of variance analysis and range analysis are listed in Tables 3 and 4 separately.

In the European standards of insulation boards, when the density is 0.23–0.40 g/cm^3, *MOR* of load-bearing boards was 1.3 MPa under humid conditions; under dry conditions, *MOE* of this kind of boards was 140 MPa and 2 h *TS* was 8%. In this experiment, the target density was only 0.15 g/cm^3, *MOR* of panels was 1.41 MPa, which exceeded the requirements of the insulation board under humid conditions; *MOE* of panels was 112.13 MPa and less than 140 MPa in dry interior; 2 h *TS* was 7.66% and met European standards. Impact strength was 0.85 kJ/m^2. From these data, the foaming composites showed good properties.

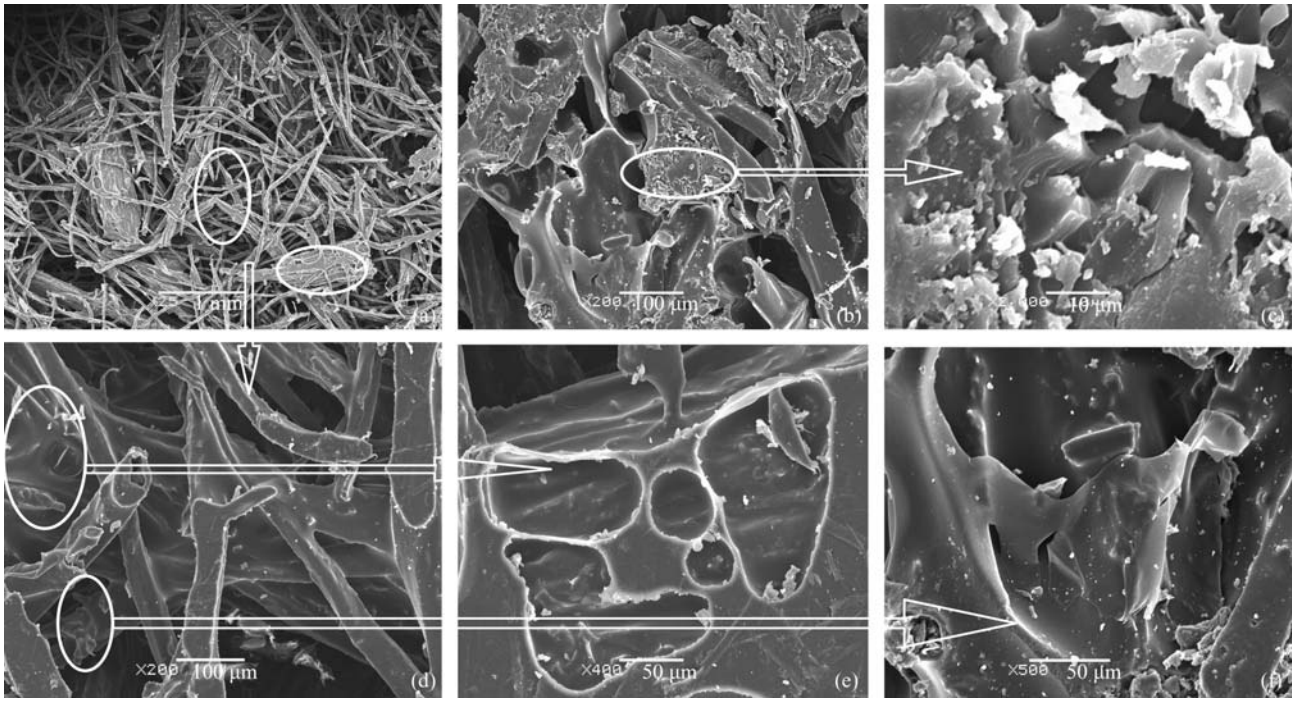

Fig. 1 Scanning electron micrographs of foaming wood-based composites

Table 2 Test results of the wood-based foaming composites

number	density/g·cm^{-3}	*MOR*/MPa	*MOE*/MPa	impact strength/kJ·m^{-2}	2 h *TS*/%
1	0.15	1.04	72.62	0.74	6.73
2	0.17	1.15	92.03	0.75	7.59
3	0.17	1.37	131.16	0.91	8.04
4	0.16	1.41	118.18	0.83	7.03
5	0.17	1.69	140.16	0.97	8.21
6	0.16	1.21	84.41	0.76	7.16
7	0.17	1.63	140.73	1.00	8.17
8	0.17	1.45	96.68	0.80	7.59
9	0.17	1.72	133.19	0.85	8.43
mean	0.17	1.41	112.13	0.85	7.66

Table 3 Range analysis of process factors and levels

factors	levels	content of resin and foaming agent	hot-pressing temperature	hot-pressing time
MOR	1	1.25	1.19	1.36
	2	1.42	1.43	1.44
	3	1.57	1.62	1.43
	R	0.32	0.43	0.08
MOE	1	82.86	97.48	110.71
	2	108.38	113.58	104.10
	3	136.95	117.14	113.38
	R	54.09	19.66	9.28
impact strength	1	0.78	0.80	0.86
	2	0.80	0.88	0.90
	3	1.00	0.90	0.83
	R	0.22	0.10	0.07
2 h *TS*	1	0.060	0.067	0.071
	2	0.073	0.074	0.07
	3	0.085	0.077	0.078
	R	0.025	0.01	0.008

Note: *R* means the maximum difference.

3.2.1 *MOR*

Content of resin and foaming agent influenced *MOR* significantly as shown in Table 4. In Table 3, when resin and foaming agent content was 20%, *MOR* was the highest; when content was 30%, *MOR* was lower; when content was 40%, *MOR* was the lowest. When the aiming density was fixed, more fibers meant smaller spaces in them. Fibers connected more points by foams and more interwoven points increased the strength of the panel.

Hot-pressing temperature had the most significant influence on *MOR* (Table 4). *MOR* increased from 80 to 120°C. Higher temperature resulted in greater flow mobility of glue, so that cellular foam dispersed evenly.

Hot-pressing time had little effect on *MOR* as shown in Table 4. When the pressing time was 10min, the bending strength of the panel was the lowest compared to other levels. PAPI and TSU were insignificant in 10 min, the foam number produced could not make fibers connect well, so *MOR* was not good.

3.2.2 *MOE*

Content of resin and foaming agent had very significant influence on *MOE* as shown in Table 4. With the chemical agents increased from 20% to 40%, *MOE* decreased rapidly (Table 3). This also could be explained as a decrease of fiber content.

Hot-pressing temperature had great effect on *MOE* (Table 4). *MOE* was lowest using 80°C while it differed a little at temperatures of 100 and 120°C. The reason was that resin and blowing agent could not produce much gas to foam and disperse regularly.

Hot-pressing time was not important to *MOE* in Table 4. Fifteen minutes was the best choice for *MOE*.

3.2.3 Impact strength

Content of resin and foaming agent content had significant influence on the impact strength as shown in Table 4. With more glue added, impact strength dropped and impact strength was best when glue addition was 20%. For a kind of fixed low density panel, less fiber caused spaces in fibers to increase; foaming structure could not connect fibers well. Too much glue reduced all strength including impact strength.

Hot-pressing temperature had a significant influence on impact strength as shown in Table 4. Impact strength increased when temperature increased from 80 to 120°C. The foaming chemicals blew fully and the number of micropores increased as temperature increase. The higher temperature also could make foam in better shape which leads to higher impact strength.

Hot-pressing time also had an important effect on impact strength (Table 4). Impact strength had the peak value at the middle level of time. This demonstrated that higher temperature made micropores burst from closed to open, and decreased impact strength.

3.2.4 2 h *TS*

The content of resin and foaming agent content had the most significant influence on 2 h *TS* as shown in Table 4. Swelling ratio was least when its addition was 40% (Table 3). With glue addition increased, the 2 h swelling ratio decreased. Wood fiber was hydrophilic, while products that PAPI and TSU interacted had 5% increased

Table 4 Variance analysis and significance test of the processing factors

properties	factors	*df*	*SS*	mean *SS*	*F* value	*p*
MOR	content of resin and foaming agent	2	1.093	0.546	24.47	0.0001**
	hot-pressing temperature	2	1.943	0.971	43.5	0.0001**
	hot-pressing time	2	0.084	0.042	1.89	0.1601
	error	56	1.251	0.022		
	total error	62	4.371			
MOE	content of resin and foaming agent	2	30758.603	15379.301	70.48	0.0001**
	hot-pressing temperature	2	4610.127	2305.063	10.56	0.0001**
	hot-pressing time	2	960.032	480.016	2.2	0.1203
	error	56	12220.317	218.22		
	total error	62	48549.079			
impact strength	content of resin and foaming agent	2	0.684	0.342	87.85	0.0001**
	hot-pressing temperature	2	0.149	0.075	19.15	0.0001**
	hot-pressing time	2	0.064	0.032	8.27	0.0006**
	error	65	0.253	0.004		
	total error	71	1.151			
2 h *TS*	content of resin and foaming agent	2	0.0044	0.0022	31.11	0.0001**
	hot-pressing temperature	2	0.0008	0.0004	5.77	0.0065*
	hot-pressing time	2	0.0006	0.0003	3.86	0.0298
	error	38	0.0027	0.0001		
	total error	44	0.0085			

Note: $p \leqslant 0.001$ means very significant, ** as symbol; $0.05 \geqslant p \geqslant 0.001$ means significant, * as symbol.

weight ratio at the most. When the target density was very low, more hydrophobic glue meant less hydrophilic fiber; the swelling ratio decreased as glue increased.

Hot-pressing temperature had a big effect on 2 h *TS* (Table 4). Table 3 demonstrates that 2 h *TS* increased a little with the increased temperature from 80 to 120°C.

Hot-pressing time influenced a little on 2 h *TS* (Table 4). In Table 3, 2 h *TS* changed little at three different levels.

3.2.5 Test and verification of optimal parameters

According to the range and variance analysis, optimal levels of factors could be selected.

The level of content of resin and foaming agent was chosen at 20%. It had significant influence on *MOR*, *MOE*, impact strength and 2 h *TS* tested in the experiment. At this level, *MOR*, *MOE* and impact strength had the highest value.

The optimal level of hot-pressing temperature was 120°C. Hot-pressing temperature also had great influence on all properties. Choosing this level, *MOR*, *MOE* and impact strength could reach the highest.

The best level of hot-pressing time was 15 min. Time has some effect on impact strength, but has little effect on *MOR*, *MOE* and *TS*. Therefore, impact strength should be considered when choosing optimal hot-pressing time.

Verification test was carried out according to the optimal levels of factors and results are listed in Table 5.

As shown in Table 5, according to the optimal conditions, the properties of wood-based foaming composites had reached requirements in the EN-622 standard.

Table 5 Results of validation experiment

MOR/MPa	*MOE*/MPa	impatc strength/kJ·m^{-2}	2 h *TS*/%
1.41	150	0.97	6.88

4 Conclusions

Microscopic structure: There were foaming structures in spaces between fibers, which connected fibers together tightly. The micropores mostly were closed holes, few were open holes.

Mechanical properties: Wood-based foaming composites had good physical and mechanical properties. Designed factors had different influences on the properties. Factors including content of resin and foaming agent content and hot-pressing temperature had great influences on *MOR*, *MOE* and impact strength. Glue and foaming agent had a significant effect on 2 h *TS*.

Choosing content of resin and foaming agent at 20%, hot-pressing temperature at 120°C, and hot-pressing time at 15 min to produce foaming composites, the properties of panels could reach the requirements of the EN-622standard.

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