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Bonding Strength Characteristics of Antibacterial PF/Wood Bioboard from *Vitex negundo*

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The effect of phenolic resin impregnation on the internal bonding strength of small-diameter *Vitex negundo* reconstituted timber was explored. Functional group and internal microscopic structure changes caused by phenolic resin impregnation were also investigated. The adhesion of the impregnated board improved remarkably compared with that of the plain board; the internal bonding strength increased by 70.36%. Infrared spectra of the impregnated board showed a more intense C-O-C stretching vibration at 1047 cm"1 than the plain board. C-O-C groups may have formed during the impregnation process, which helped to increase intermolecular forces and improve the adhesion of the impregnated board. Scanning electron microscopy demonstrated that the internal microscopic structure of the impregnated board differed from that of the plain board.

Key words: Antibacterial bioboard; treatment *Vitex negundo*; Bonding strength; Dipping treatment; Phenolic resin.

Reconstituted timber is a new kind of artificial low-carbon board manufactured from low-quality wood, the technology of which has developed rapidly in recent years. Traditional reconstituted timber is produced from materials like fast-growing thinned wood, waste from wood machining, and wood from split-billet processing. These materials are then processed into bunches by rolling equipment. In these wood bunches, the pieces are not broken in the transverse direction or lengthwise; instead they are loosely connected to one another to form an interlaced structure. The materials used to manufacture traditional reconstituted timber are then exposed to a series of processes like peeling, softening, rolling (three times), drying, gluing, paving, pressing, edging and sanding[1-3]. Based on successful examples of traditional reconstituted timber, reconsolidated bamboo and bamboo-based fibre composites[4-6], we decided to investigate if reconstituted timber for outdoor furniture with a small-diameter raw material could be produced from wood using plates made by hot pressing after pre-impregnation treatment with low-molecular-weight phenolic resin. Here, we use *Vitex negundo* wood with a diameter of less than 4 cm as a model material to manufacture reconstituted timber for outdoor furniture.

Resin-impregnation is an effective method to improve wood adhesion, as discussed in many studies. The basic principle is that the resin penetrates into the cell walls of wood where it interacts with the hydroxyl groups of cellulose and other materials to reinforce the wood[7-13]. *Vitex negundo* contains many defects. To counteract these defects we crushed pieces of the wood with small diameter into bunches and then treated the bunches with resin to improve their bonding strength[23-42]. Our experiment provides a theoretical foundation for manufacturing reconstituted timber with small-diameter wood, and offers a new approach for developing reconstituted timber.

MATERIALS AND METHODS

Test materials

Wood with a small diameter (<4 cm) from

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Vitex negundo grown in Shaoyang, Hunan, China, was tested. Bunches of *Vitex negundo* wood were prepared by crushing 40-cm-long pieces three times and removing bark. Two test bunches of *Vitex negundo* wood were manufactured. One was dried at 105 °C for 10 h, and then preserved in sealed bag until it was dip treated. The other bunches were placed in a drying cabinet at constant temperature and humidity until the water content decreased to about 5%, and then stored in a sealed bag until they were used to prepare a pressure plate.

Phenolic resin (3212, Hua Kai Resin Co., Ltd, Jining, China) was used to impregnate the wood bunches. The resin had a relative molecular mass of 300, viscosity of 12–17 MPa·s at 25 °C, solid content of 40–42%, cure time of 80–100 s, and water solubility of e"10×. The phenolic resin was diluted with water to give a resin to water ratio of 3:2 for later use.

Phenolic resin (2152, Hai Na Environmental Protection S&T Co., Ltd, Yutai, China) was used for gluing. This resin has a viscosity of 1450–2000 mPa·s at 25 °C, solid content of e"75%, curing temperature of 150 °C, and free phenol d"16%.

Test methods

Preliminary treatment by phenolic resin impregnation

One of the *Vitex negundo* wood bunch test pieces was impregnated with 3212 phenolic resin by immersion in an aqueous solution of phenolic resin (3:2 resin/water) for 30 h at ambient pressure and temperature. The impregnated *Vitex negundo* wood bunch was dried under natural conditions for 2 days, and then placed in a dry box at fixed temperature and humidity until the water content decreased to about 5%.

Compression moulding of *Vitex negundo* reconstituted timber

Impregnated and plain boards were made by hot pressing the different *Vitex negundo* wood bunches. Each test piece was soaked in the 2152 resin for 90 to 120 s, and then dried for 2–3 days until micro-dry glue solution emerged on the surface of the wood bunches. Test pieces were formed into boards by hot pressing at a temperature is 160 °C and pressure of 4 MPa for 3 min.

Determination of internal bonding strength for *Vitex negundo* reconstituted timber

The internal bonding strength of *Vitex negundo* reconstituted timber impregnated with phenolic resin was quantified using standard GBT 17657-2013 (*Test Method for Physical & Chemical Properties of Wood Based Panels and Decorated Wood Based Panels*).

Infrared spectroscopy and scanning electron microscopy

Infrared spectroscopy was used to explore the effect of phenolic resin impregnation on *Vitex negundo* reconstituted timber with by measuring relevant molecular constitution data. The experimental apparatus was an IR100 Fourier transform infrared spectrometer from the Thermo Nicolet Company. Impregnated and plain boards were crushed and sifted to prepare wood powders.[16-22] The wood powders were dried at 105 °C for 3 to 4 h and then stored in a drying apparatus. Potassium bromide crystals were ground, sieved, dried at 120 °C for 2 h to remove water and then stored in a drying apparatus. Potassium bromide and wood powder were mixed in a ratio of 100 to 1 by repeated grinding under infrared light, and then pressing to form tablets. Infrared spectra were obtained for the tablets.

The cross sections of impregnated *Vitex negundo* reconstituted timber were observed by scanning electron microscopy (SEM; JSM-5310LV, JEOL, Japan). A test piece coated with gold was scanned at different magnifications ranging from ×500 to ×3000.

RESULTS

Weight gain of *Vitex negundo* wood bunches impregnated with phenolic resin

Vitex negundo wood bunches were impregnated with phenolic resin by immersion in an aqueous solution of phenolic resin (mass fraction 60%) for 30 h at room temperature and pressure. The weight gain of the impregnated sample was 12.8%.

Internal bonding strength of *Vitex negundo* reconstituted timber

Internal bonding strengths obtained by experimental analysis are given in Table 1. In Table 1, the S in the sample names refers to a plain board, while JZ indicates an impregnated board.

Table 1 reveals that the average internal bonding strength of the plain and impregnated boards was 2.53 and 4.31 MPa, respectively.

Compared with the plain board, the internal bonding strength of the impregnated board increased by 70.36%.

Infrared spectroscopy of Vitex negundo reconstituted timber

The components of Vitex negundo reconstituted timber impregnated with phenolic resin differed from those of the plain board. The change in functional groups induced by resin impregnation was studied by the position and strength of peaks in the infrared spectra of the boards.14-15 The infrared spectra of an impregnated wood bunch and plain Vitex negundo wood are shown in Fig. 1.

The characteristic absorption peaks at 3434, 1756 and 1600 cm”1 markedly increased in intensity following impregnation because a large amount of phenolic resin was left in the wood, and there were no other new absorption peaks.[16-22]. Infrared spectra of the plain and impregnated boards are presented in Fig. 2, and the characteristic peak assignments are given in Table 2. Figure 2 and Table 2 reveal that the intensity of the peak at 3353 cm”1 was higher for the impregnated board The higher free phenol content in the board after hot pressing caused the intensity of the peak from phenolic hydroxyl groups increase slightly. The intensity of absorption peaks characteristic of phenyl ring double bonds at 1648, 1599 and 1524 cm”1 increased because the impregnated board had a weight gain of 12.78% compared with that of the plain board. The C-O-C stretching vibration peak observed at 1047 cm”1 was more intense for the impregnated board than the plain board. It is suggested that the impregnated board forms C-O-C groups during the treatment process, and these

Table 1. Internal bonding strength of samples

No.	Test piecesize Length (mm)	Width (mm)	Dimensions (mm^2)	Maximum damage (N)	Internal bonding strength (MPa)
S-1	50.22	50.82	2552.18	7587.3	3.030
S-2	49.88	50.61	2524.43	7120.3	2.844
S-3	49.67	50.98	2532.18	5334.4	2.122
S-4	50.55	50.95	2575.52	1904.2	2.53
S-5	50.45	51.26	2586.07	6486.8	2.508
S-6	50.97	51.29	2614.25	5540.2	2.119
JZ-1	50.01	50.07	2504.00	9606.1	3.837
JZ-2	49.76	50.42	2508.90	13486.6	5.376
JZ-3	49.92	50.37	2514.47	11941.6	4.721
JZ-4	50.88	50.02	2545.02	8725.6	3.429
JZ-5	50.84	50.25	2554.71	7009.7	2.744
JZ-6	50.81	49.83	2531.86	14541.5	5.743

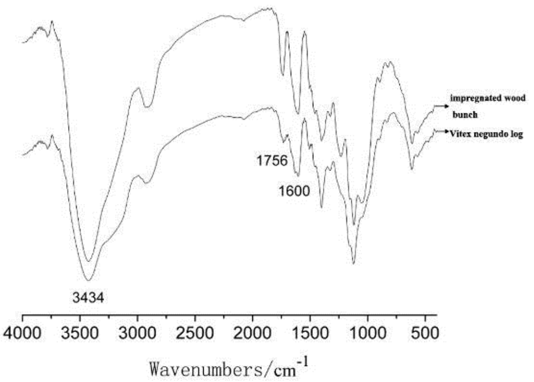

Fig. 1. Infrared spectra of an impregnated wood bunch and *Vitex negundo* log

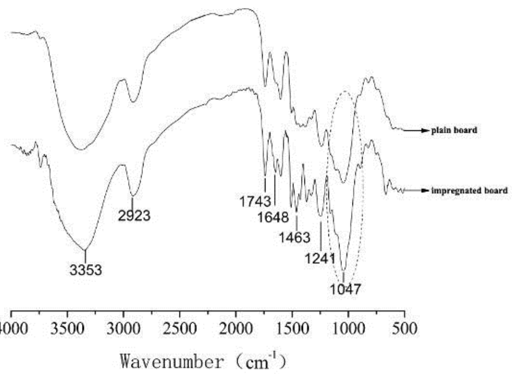

Fig. 2. Infrared spectra of impregnated and plain boards

C-O-C groups increase the bonding strength of the impregnated board by increasing intermolecular forces.

SEM analysis of *Vitex negundo* reconstituted timber

Cross-sectional and longitudinal SEM images of impregnated and plain boards are presented in Fig. 3.

Table 2. Characteristic infrared peaks of the impregnated board

Wave number (cm^{-1})	Assignment
3353	-OH stretching vibration
2923	C-H stretching vibration
1743	non-conjugated carbonyl groups on aromatic rings
1648	phenyl ring double bond
1599	
1524	
1463	C-H bending vibration
1241	C-C stretching vibration
1047	C-O-C stretching vibration

Comparing the images of the impregnated and plain boards revealed that the internal microscopic structure of the impregnated board was different from that of the plain board. In the impregnated board, the majority of vessels and cell lumens were filled with adhesive, allowing the wood to maintain its internal microscopic structure at high temperature and pressure. Meanwhile, the internal microscopic structure of the plain board suffered from serious compression and twist deformations under the same conditions. The width of the plain board adhesive layer also far outweighed that of the impregnated board, as seen in Fig. 3c and d. Whereas the plain board contained loosely bonded pieces of wood, the impregnated board contained a tightly bonded adhesive layer, which increased its bonding strength.

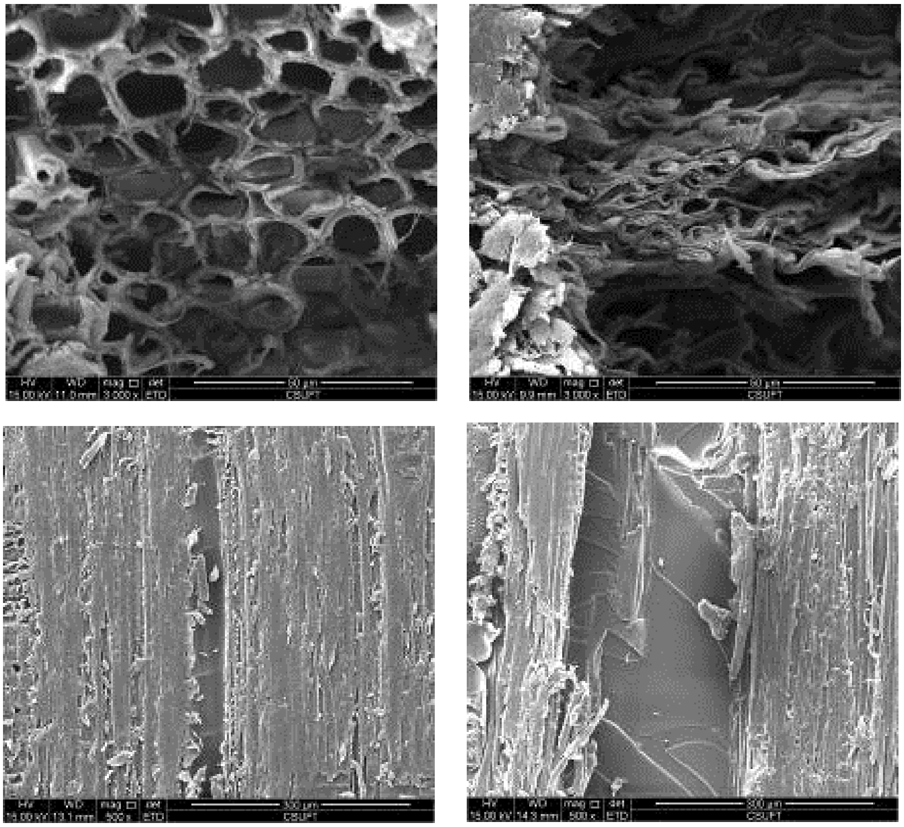

Fig. 3. (a, b) Cross-sectional (×3000) and (c, d) longitudinal (×500) SEM images of (a, c) impregnated and (b, d) plain boards

CONCLUSION

The effect of phenolic resin impregnation on the bonding strength of *Vitex negundo* reconstituted timber was explored experimentally by infrared spectroscopy and SEM analysis. The results showed that the internal bonding strength of the impregnated board was improved by 70.36% compared with that of the plain board. The infrared spectra indicated that the characteristic absorption peaks of the *Vitex negundo* wood bunch impregnated with phenolic resin at 3434, 1756 and 1600 cm"[1] were much more intense than those of the plain board. Therefore, a great quantity of phenolic resin remained in the *Vitex negundo* wood bunch following soaking treatment. The C-O-C stretching vibration at 1047 cm"[1] was more intense for the impregnated board than the plain one. The impregnated board may have formed C-O-C groups during the treatment process. These C-O-C groups had a strong influence on bonding strength, playing a vital role in gluing the wood particles together by increasing intermolecular forces, which made the bonding strength of the impregnated board much higher than that of the plain one. SEM images revealed that the particles in the impregnated board were glued together more strongly that those in the plain board. This study provides a theoretical foundation to manufacture reconstituted timber from small-diameter wood.

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