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ORIGINAL ARTICLE

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Strength, decay and termite resistance of oriented kenaf fiberboards

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Abstract The development of oriented fiberboards made from kenaf (*Hibiscus cannabinus* L.) and their suitability as a construction material has been investigated. Three different types of boards consisting of five layers with individual orientations were prepared using a combination of low molecular weight and high molecular weight phenol–formaldehyde (PF) resin for impregnation and adhesion purposes. Additional boards with the same structure were prepared using high molecular weight PF resin only. The mechanical properties of the boards have been examined as well as their resistance against fungal decay and termite attack. All kenaf fiberboards showed elevated mechanical properties compared with medium-density fiberboard made from wood fibers, and showed increased decay and termite resistance. Differences in the decay and termite resistance between the board types were caused by the presence of the low molecular weight PF resin for the impregnation of the fibers. No significant difference was found for the mechanical properties. The effect of the PF resin for impregnation was much clearer in fungal decay resistance than for termite resistance; however, fiber orientation had no effect on both decay and termite resistance of the specimens.

Key words Kenaf fiber · Oriented fiberboard · Phenol resin · Decay resistance · Termite resistance

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Introduction

Kenaf (*Hibiscus cannabinus* L.) has gained high importance in recent years as a sustainable plant fiber resource for composite products. The utilization of the stem bast fibers and core for the production of composite boards has been developed worldwide[1–7] at a time when the need for well-suited construction materials made from renewable resources in countries with insufficient forest resources is evident.

Considerable research has been performed to evaluate the utilization potential of kenaf fibers in composite products. Grigoriou et al.[8] stated that urea–formaldehyde (UF)-bonded kenaf boards consisting of fibers and core in the proportion of 92:8 were found to satisfy the American standards concerning particleboards but not those applying to fiberboards. Chow et al.[9] indicates that phenolic-resin-bonded boards are preferred in building construction for protection against water and high humidity. However, decay by fungi in the phenolic-bonded board is as severe as that in the urea-bonded board.[10] There is also a need to evaluate decay and termite resistance of boards produced from kenaf fibers to determine whether they can be used in outdoor or severe degradation conditions without any biocides.

The aim of this study was to evaluate the suitability of kenaf fibers for the development of construction materials and to determine their decay and termite resistance under service conditions.

Materials and methods

Board preparation

The boards were produced using kenaf bast fibers from Anhui Province in East China. The fibers were refined and mechanically orientated in the longitudinal direction with a carding machine to a web of 12 cm in width and then coiled up on a roll.

Three types of oriented kenaf fiberboard were developed. The boards consisted of five individual layers, each with a certain orientation. A unidirectional board (type I) was created with all layers oriented in the longitudinal direction (0°-0°-0°-0°-0°). The second version (type II) 1consisted of a plywood-type board with an orientation of 0°-90°-0°-90°-0° and the third version (type III) was built up with a 0°-45°-90°-135°-0° orientation. The size of the boards was set to 500 × 500 mm with a thickness of 4 mm. The target density of all boards was 800 kg m^{-3}.

Two types of phenol–formaldehyde (PF) resin were chosen for impregnation and adhesive purposes: (1) low molecular weight (LM) PF-resin type PL-3725 (Gun Ei Chemical), solid resin content 53.5%; and (2) high molecular weight (HM) PF-resin type PL-2818 (Gun Ei Chemical), solid resin content 73.6%. Both resins were mixed and an impregnation solution of the resins was prepared by adding ethanol and water to decrease the viscosity and to maintain a solid resin content of 12.5% high molecular weight PF resin and 12.5% low molecular weight PF resin. The low molecular weight PF resin was found to penetrate the cell wall to reduce swelling and shrinkage effects[11] and to increase the decay and termite resistance.[12] The high molecular weight PF resin was found not to penetrate the cell wall during previous tests and it acts as an adhesive between the fibers.[11]

Two sets of boards were produced using both PF resins for type I, II, and III (so-called type Ia, IIa, IIIa) whereas another set was produced using the high molecular weight PF resin only for type I and II (so called type Ib and IIb) to compare the mechanical properties and the decay and termite resistance effects of the impregnation. Board type IIIb was not manufactured due to limitations in raw material supply.

A laboratory-scale continuous impregnation routine was established to dip the fiber web into the PF resin solution (board type "a" with low and high molecular weight PF resin, board type "b" with high molecular weight PF resin only). Redundant impregnation solution was squeezed out by passing the fiber web through a pair of rollers. The impregnated fiber webs were then cut into strips with a length of 50 cm and dried at room temperature for 12 h.

Thereafter, the fiber mats where laid by manually orienting the strips for each layer. One oriented layer in the mat consisted of five strips in height and five strips in width overlapping the previous strips to align the distribution of the fibers in the mat.

The oriented mats were consolidated in a laboratory hot press with a specific pressure of 4.5 MPa and at a pressing temperature of 160°C for 10 min to completely cure the PF resin. Afterward, all boards were conditioned at 20°C and 65% relative humidity (RH) and the samples for the tests were prepared. The macroscopic view of the structure of the oriented layers of the type IIa kenaf fiberboard can be seen in Fig. 1.

The type Ib and IIb boards reached the target density of 800 kg m^{-3} whereas the Ia, IIa, and IIIa boards reached an average density of 750 kg m^{-3} due to deviations in the weight of the kenaf raw material. The density difference of 7% between the type a and b boards was taken into consideration and it is displayed in Tables 1–4.

The mechanical and physical properties of the oriented boards were measured according to the Japanese Industrial Standard JIS A 5905-1994 for fiberboard. The tests included the testing of bending strength (modulus of rupture; MOR), the calculation of the modulus of elasticity (MOE), measurement of the internal bond strength (IB), and the thickness swelling in cold water (TS) for 24 h. Additional measurements of length and width changes of the samples after immersion in water were also included. The properties of the specimens from the kenaf fiberboards used in decay and termite resistance tests are shown in Table 1.

Decay resistance tests

A monoculture decay test was conducted with the brown-rot fungus, *Fomitopsis palustris* (Berk. et Curt) Gilbn. & Ryv. (FFPRI 0507), and the white-rot fungus, *Trametes versicolor* (L.: Fr.) Pilat. (FFPRI 1030), according to JIS K 1571 standard method.[13] A 100-ml aliquot of liquid medium containing 4% glucose, 0.3% peptone, and 1.5% malt extract was inoculated with stock culture of either *T. versicolor* or *F. palustris*. The inoculated liquid medium was incubated

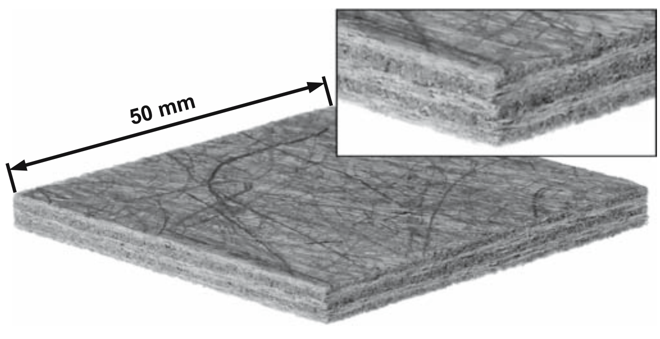

Fig. 1. Structure of a 50 × 50 × 4 mm oriented kenaf fiberboard (type IIa) showing the detail of the laminate structure (*inset*)

Table 1. Properties of the kenaf board specimens used in decay and termite resistance tests

Type	Fiber orientation	Adhesive	Impregnation	Density (kg m^{-3})
Ia	Unidirectional	HM PF resin (12.5%)	LM PF resin (12.5%)	750
IIa	0°-90°-0°-90°-0°	HM PF resin (12.5%)	LM PF resin (12.5%)	750
Ib	Unidirectional	HM PF resin (12.5%)	–	800
IIb	0°-90°-0°-90°-0°	HM PF resin (12.5%)	–	800

PF, Phenol–formaldehyde; HM, high molecular weight; LM, low molecular weight on a shaker (120 rpm) at 26°C for 10 days. The medium of 250 g of sea sand in a glass jar was permeated with 80–85 ml of nutrient solution containing 4% glucose, 0.3% peptone, and 1.5% malt extract for *T. versicolor* or containing half as much of each component for *F. palustris*. The jars were then inoculated with 3–4 ml of the liquid fungal stock culture previously prepared. After measuring oven-dry weights, kenaf fiberboard specimens were sterilized with gaseous ethylene oxide. When the mycelium fully covered the medium in the jars, three specimens were placed onto the top of growing mycelium in the glass jar, with either a plastic mesh spacer for *F. palustris* or without a plastic mesh spacer for *T. versicolor*. The test jars were then incubated at 27°C and for 12 weeks. Nine replicates were tested for each decay fungus for each board type. The extent of the fungal attack was expressed as the average of mass loss (percent) calculated from oven-dry weights of nine specimens before and after the decay procedure.

Termite resistance tests

The specimens were exposed to the subterranean termite *Coptotermes formosanus* Shiraki according to Japan Wood Preserving Association (JWPA) standard JWPS-TW-P.1.[14] An acrylic cylinder (80 mm in diameter, 60 mm in height) which had the lower end sealed with a 5-mm-thick hard dental plaster (New Plastone, GC Corp.) was used as a container. A test specimen was placed at the center of the plaster bottom of the test container. A total of 150 worker termites and 15 soldiers collected from a laboratory termite colony at RISH, Kyoto University, were introduced into each test container. Five specimens per board type were assayed against termites. The assembled containers were set on damp cotton pads to supply water to the specimens and kept at 28°C and >85% RH in darkness for 3 weeks. The mass loss of the specimens due to termite attack was calculated based on the differences in the initial and final oven-dry weights of the specimens after cleaning off the debris from termite attack.

Results and discussion

Physical and mechanical properties

The moisture content of the type a and b samples was measured after conditioning and it was found that the type a samples had a moisture content of 5.14% [standard deviation (SD) 0.19%], whereas the type b samples had a moisture content of 5.93% (SD 0.07%), which indicated the reduced moisture uptake effect of the low molecular weight PF resin used for impregnation. Additional results were found regarding the thickness swelling and dimensional changes after immersion in water for 24 h displayed in Table 2. The board types Ia, IIa, and IIIa fulfill the requirements of JIS A 5905-1994 for fiberboards (17% or under required) with a thickness increase of 13%. The type Ib and IIb boards showed a significantly increased thickness swelling of 32% which is more than double that of the type Ia and IIa boards.

Slight dimensional changes in length and width occurred due to the sample size of 50 × 50 mm, but they indicate the plywood-like behavior of the type II and III boards with lower expansion in width compared with the type I boards. The bending strength of all board types shown in Table 3 is elevated regarding the requirements of the JIS A 5905-1994 with 30 N mm^{-2} except for the type I boards that have a lower bending strength perpendicular to the main board

Table 2. Mean values of the thickness swelling test results and the dimensional changes after 24-h immersion in water

Type	Density (kg m^{-3})	Thickness swelling ratio (%)	Dimensional change ratio	
			Length(%)	Width(%)
Ia	750	13.30 (0.51)	0.08 (0.05)	0.13 (0.07)
IIa	750	13.21 (0.49)	0.04 (0.03)	0.06 (0.05)
IIIa	750	13.29 (0.38)	0.03 (0.02)	0.06 (0.04)
Ib	800	32.46 (1.72)	0.20 (0.09)	0.40 (0.06)
IIb	800	31.04 (1.40)	0.22 (0.07)	0.24 (0.10)

Values in parentheses are standard deviations

Table 3. Mean values of the bending test results with modulus of rupture (MOR) and modulus of elasticity (MOE)

Type	Density (kg m^{-3})	MOR (N mm^{-2})		MOE (GPa)	
		Parallel	Perpendicular	Parallel	Perpendicular
Ia	750	99.08 (11.05)	21.76 (4.54)	15.48 (0.95)	2.53 (0.36)
IIa	750	69.60 (14.73)	41.26 (8.63)	12.64 (1.98)	5.09 (0.71)
IIIa	750	75.57 (6.72)	33.01 (5.13)	13.52 (0.64)	3.34 (0.54)
Ib	800	88.23 (5.67)	19.70 (1.81)	24.85 (5.67)	3.98 (0.59)
IIb	800	72.89 (13.22)	44.82 (8.52)	19.65 (1.32)	8.36 (0.78)

Values in parentheses are standard deviations

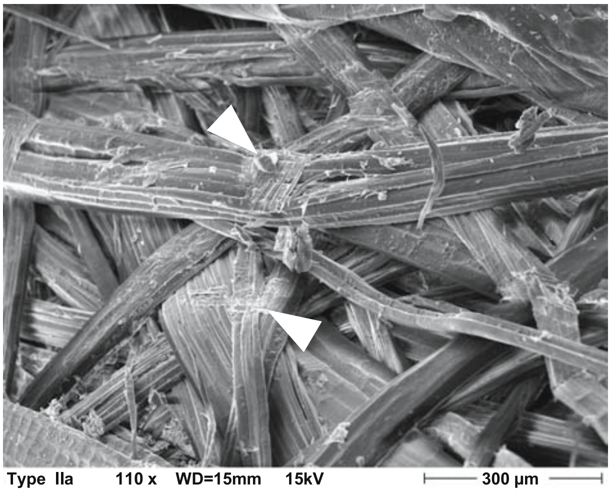

Fig. 2. Internal structure of type IIa kenaf fiberboard after internal bonding strength test. *Arrowheads* indicate former bonded areas

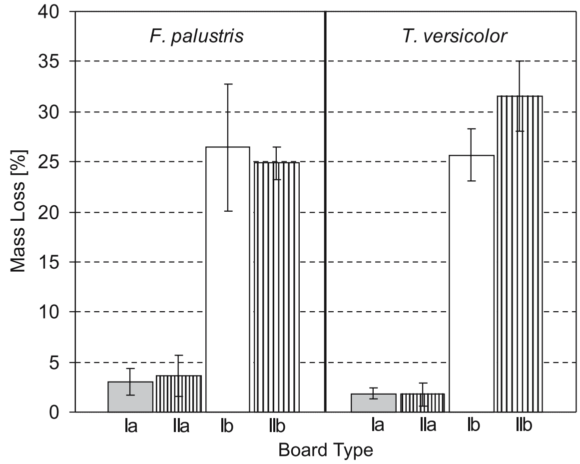

Fig. 3. Mass losses in the specimens exposed to fungal decay resistance tests with brown-rot fungus, *Fomitopsis palustris* (*left*), and white-rot fungus, *Trametes versicolor* (*right*)

Table 4. Mean values of the internal bond strength

Type	Density ($kg\,m^{-3}$)	Internal bond strength (MPa)
Ia	750	0.44 (0.17)
IIa	750	0.30 (0.10)
IIIa	750	0.44 (0.18)
Ib	800	0.42 (0.15)
IIb	800	0.43 (0.16)

Values in parentheses are standard deviations

orientation. This effect is significant due to the unidirectional fiber orientation. A plywood-like effect is caused by using oriented layers of the type II and III boards with a reduction in bending strength perpendicular to the main board orientation because of the influence of the top and bottom layer having the same orientation. A delamination defect between the layers was observed rather than a failure of the fiber bundles.

The modulus of elasticity was calculated by the testing machine based on the settings given before the test. All results are above the Young's modulus in bending recommended by the standard. It shows that the elastic behavior of the boards is higher than medium-density fiberboard (MDF) made from wood fibers.

The internal bond strength results displayed in Table 4 showed comparable results for all boards but with a high standard deviation for each type. The coefficient of variation is between 33% and 35%, which indicates the high variability of the results. A double-sided *t*-test revealed that there was no significant difference within the board types. It can be assumed that the density difference of 7% between the type IIa and IIb boards was too low to cause a significant effect on the internal bond strength results. In fact, the IB strength of the boards is just below the JIS standard of $0.5\,N\,mm^{-2}$ for fiberboards. Mostly, delamination defects between the layers shown in Fig. 2 occurred during the IB test and they can be claimed to be responsible for the poor bonding behavior of the boards. The magnified fiber bundles shown in Fig. 2 seem to be nearly intact and only small areas on the surface of the fiber bundles indicate former bonded areas with residues of PF resin and parts of the adjacent cell wall. The poor results of the internal bond test were not expected after the good results found in bending and the dimensional stability tests. This indicates that the bonding of the fibers can be improved.

Decay and termite resistance

The mass losses that occurred in the specimens during the 12-week fungal decay tests are shown in Fig. 3. There was a significant effect of impregnation with the low molecular weight 12.5% PF resin on the susceptibility of the kenaf board specimens. Fiber orientation had no significant effect on the fungal resistance of the specimens against the brown-rot fungus. However, a slight increase was found for the mass losses of the type II specimens compared with type I specimens.

The type b specimens without low molecular weight PF resin impregnation gave lower worker termite mortalities than those impregnated with the low molecular weight 12.5% PF resin (Fig. 4). The differences among soldier termite mortalities were found insignificant and the mortalities reached almost 100% at the end of the tests. However, the effect of the layer orientation on termite mortalities was mixed. The results may suggest that the PF resin used in the study is a fast-acting chemical that kills termites when they ingest the fibers. All specimens were found almost intact after a 3-week termite exposure whereas the specimens without low molecular weight PF resin impregnation (type b) showed higher mass losses (Fig. 5). In general, termite mortalities conformed to the mass losses in the specimens.

Fungal decay and termite resistance tests revealed that the PF resin-impregnated kenaf fiberboards seem to be suitable for building purposes. On the other hand, the boards were resistant against termite attack even without low molecular weight PF resin impregnation. In contrast to phe-

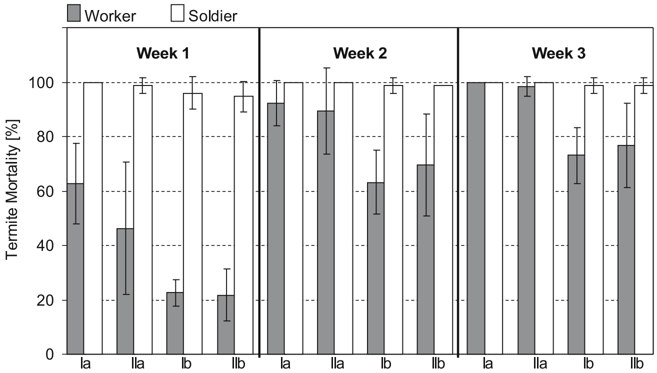

Fig. 4. Termite mortalities during the 3-week exposure of kenaf fiberboard specimens to termites (*Coptotermes formosanus*)

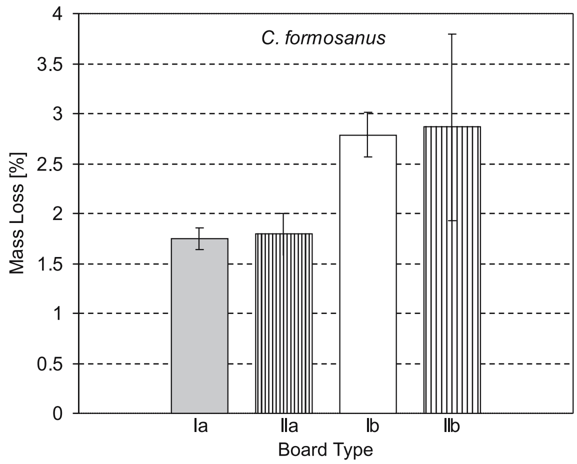

Fig. 5. Mass losses in kenaf fiberboard specimens after a 3-week exposure to termites

nolic resins, urea–formaldehyde resin-bonded, wood-based composites show generally lower water resistance in humid environmental conditions that degrade adhesive bonds formed by the resin; PF resins provide excellent bond durability for such composites.[15] Nzokou et al.[16] showed that the increase in decay and termite resistance of laminated veneer lumber products was attributed to the density and the phenolic resin, which affected moisture equilibrium. Curling and Murphy[17] stated that the chemicals derived from the resins may show inhibitory properties against decay; however, decay susceptibility is dependent on more factors than just the resin type.

Conclusions

The properties of the kenaf fiberboards showed that the production of construction materials made from annual plant fibers is possible. However, the IB values were slightly lower than the requirements of the JIS A 5905-1994 whereas the bending strength of the boards were elevated compared with conventional unoriented MDF made from wood fibers. The reduction in thickness increase after immersion in water, especially for the type a boards, is evident and differences between type a and type b boards are due to the impregnation effect of the low molecular weight PF resin. The total resin content of 25% of the type a boards prohibits the degradation by fungi and termites and moisture uptake from the environment. The use of additional preservatives might not be necessary to withstand severe service conditions.

The mechanical properties and the resistance against fungi and termites seem to be promising for the development of a strong and durable construction material, especially for humid conditions. It might be useful as a supplement or an alternative construction material for regions with a low availability of wood products. The further development of fiberboards from annual plant fibers will mostly depend on the production costs, which relate mainly to the cost of adhesive. Additionally, the use of adhesives made from renewable resources that provide equal strength and decay and termite resistance will be a challenge for the near future in bio-based materials research.

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