A WOOD REPLACEMENT MATERIAL OF SANDWICH STRUCTURE USING COIR FIBER MATS AND FIBERGLASS FABRICS AS CORE LAYER

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The tensile strength and bending strength of natural coir fiber are lower than many other natural fibers. Therefore, coir fiber is unsuitable for many fiber reinforcement applications. This study exploits the better shock resistance and toughness of coir fiber, which suggest that coir fiber can be used as a type of replacement material in plywood. Fast-growing poplar was chosen as the surface material, and coir fiber was selected as the core layer material for their buffering ability and toughness, and fiberglass fabrics were added in the core layer as strengthening components. The optimization of this plywood structure was carried out with an orthogonal experiment and the intuitive analysis method. The mechanical performance of some samples even exceeded that of natural wood. Through analysis of test results and scanning electron microscope (SEM) observations, the buffering and toughening mechanisms of the coir fiber mats were revealed. This new material can be used to replace wood in plywood and in the transportation industry as a packaging material and as platform floors for freight vehicles.

Keywords: Coir fiber; Sandwich Structures; Scanning electron microscopy; Buffering mechanisms

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INTRODUCTION

Due to growing shortages of resources and strengthening of awareness about environmental protection, the use of natural fibers as reinforcements for composites to replace synthetic fibers has continued to grow during recent decades. Natural fibers have many desirable characteristics, including biodegradability, low density, non-toxic nature, lower abrasiveness to processing equipment, better mechanical properties, and lower cost, compared with synthetic fibers (Bledzki et al. 1999).

Coir fiber is one kind of natural bast fibers that comes from coconut fruits. The large amount of annual coconut shell production in tropical countries and regions ensures an abundant availability of coir fiber (Monteiro et al. 2008). The structural characteristics and chemical compositions of coir fiber make the tensile strength and elastic modulus of coir fiber relatively low among natural fibers. Therefore, coir fiber is not suitable as natural fiber reinforcement in many cases. Its special advantages, such as high elongation at break, large micro-fibril angle, low density, and excellent weatherproof ability are all attractive for the use of coir fiber as a matrix for the functional material.

Satyanarayana and colleagues from the regional research laboratory of India (Satyanarayana et al. 1981, 1986, 1989, 1990; Kulkarni et al. 1981) have comprehensively and extensively studied the physical and mechanical properties of coir fiber. This research has guided the later development of coir fiber application. Other research related to coir fiber has mainly focused on applications using coir fiber for reinforcements. Coir fiber has been added to thermosetting resin, thermoplastic resin, cement, and natural rubber (Aggarwal 1992; Rout et al. 2001; Geethamma et al. 2005; Monteiro et al. 2008; Wang and Huang 2009; Ferraz et al. 2011). In these studies, chemical treatments of coir fiber were tested. Silane coupling agent, resorcinol formaldehyde latex, formalin solution, and sodium hydroxide were employed as chemical modifiers. The properties of the fiber-matrix interface can be improved by creating more bonds between the hydroxyl groups of coir fiber and the functional groups of these reagents; thus the mechanical properties may be enhanced. SEM images and early experiments (Yao et al. 2011) show that the surface roughness of coir fiber is well suited for adhesion, so that the use of environmentally unfriendly pretreatment of coir fiber has been avoided in the study.

In the studies cited above, coir fiber has been adopted due to its reinforcement effect in a wide range of brittle materials, such as rubber and cement, but it was still inferior to other natural fibers (flax fiber, jute fiber, bamboo fiber, etc). Fully exploiting the unique advantages of coir fiber may help to find out its potential applications. Future use of coir fiber should mainly concentrate on its toughening nature (Bakri and Eichhorn 2010). Hence, the buffering and toughening performance of coir fiber was examined in this study.

A sandwich structure design was employed for preparation of a type of plywood in this project. Peeled poplar veneer was selected as the surface layer to ensure the surface quality of the materials. Coir fibers and fiberglass meshes were adopted as the core layer of the sandwich structure. Non-woven coir fiber needle mats were used to overcome the unevenness in the laying-up process of random orientation coir fibers, which can result in poor mechanical properties. Fiberglass meshes were added as the reinforcement component to obtain higher strength. An orthogonal experimental design and the intuitive analysis method were adopted to obtain optimal performance. The new type plywood of hybrid sandwich structure has excellent mechanical performance, especially for better buffering and toughness characteristics.

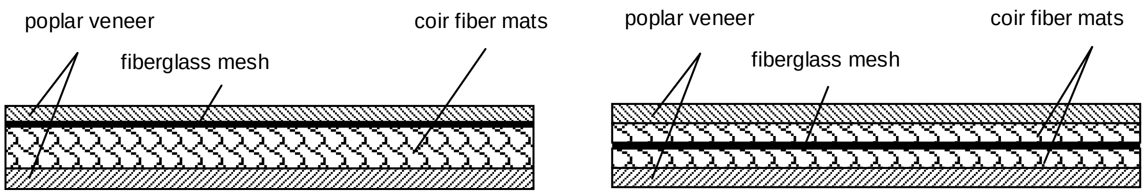
EXPERIMENTAL

Materials

Peeled poplar veneer was obtained from Yichun, China, with 10% water content and 3 mm thickness. The non-woven needle mats of coir fiber used as the core layer of the plywood were processed at Juxin Coconut Palm Products Co. Ltd., Weifang, China, with 8% water content. Fiberglass mesh fabrics were purchased from Bocheng Co. Ltd, Jinan, China, with 160 g/m^2 mass/area, and 5mm * 5 mm mesh size. 14L960 type phenolic resin produced by Dynea Chemical Industry Co. Ltd (Beijing, China) and Wannate 6112 type isocyanate produced by Wanhua polyurethanes Co. Ltd (Yantai, China) were the selected adhesives in the study.

Experimental Design

Because of the need to consider various factors in the experiment, a method based on an orthogonal experimental design was used, based on an assumption that this would reveal the significant effects of different factors, while requiring a reduced number of experimental conditions (Cheng. 2005). An orthogonal experiment of the type $L_8\,(2^7)$ was adopted. The four selected factors and two levels were: T as sample thickness (10 or 12 mm), A as adhesive type for fiberglass mesh part (phenolic resin or isocyanate adhesive), M as weight percentage of coir fibers (35 wt% or 50 wt%), and P as the position of the fiberglass mesh - either between coir fiber mats (between C+C), or between the veneer and a coir fiber mat (between V+C), the assemble pattern details can be seen in Fig. 1. The interaction effect of A×P, M×P, and T×P can also be analyzed by this orthogonal experiment. Table 1 shows the details of the experiment design.



a) Fiberglass mesh between V+C **b)** Fiberglass mesh between C+C

Fig. 1. Different assemble pattern of samples

Table 1. Experiment Design

Sample number	T (mm)	A	M (wt%)	P
1	10	phenolic	35	between C+C
2	10	phenolic	50	between V+C
3	10	isocyanate	35	between V+C
4	10	isocyanate	50	between C+C
5	12	phenolic	35	between V+C
6	12	phenolic	50	between C+C
7	12	isocyanate	35	between C+C
8	12	isocyanate	50	between V+C

Processing Technique

The phenolic resin used on the veneer was 10% by weight of veneer, and only the inner side of the veneer was coated. The phenolic resin used on the coir fiber mat was also 10% by weight of coir fiber, and both sides of the mat were equally sprayed. The fiberglass mesh was dipped into adhesive to obtain an adhesive loading around 2.5 times the weight of the mesh. The adhesive type used for the fiberglass mesh part was phenolic resin or isocyanate adhesive for different samples, as indicated in Table 1. If isocyanate adhesive was adopted to bond the fiberglass mesh, phenolic resin would be saved for the adjacent interface of veneer or coir fiber mat to reduce the cost. All the above materials were held for at least 30 minutes at room temperature to allow the glue to pre-cure before being subjected to hot pressing. According to the process parameters of isocyanate and phenolic resin, the temperature of the hot press was set at 135 °C, and the total pressing time was set for 12 or 15 minutes, depending on the thickness of the samples.

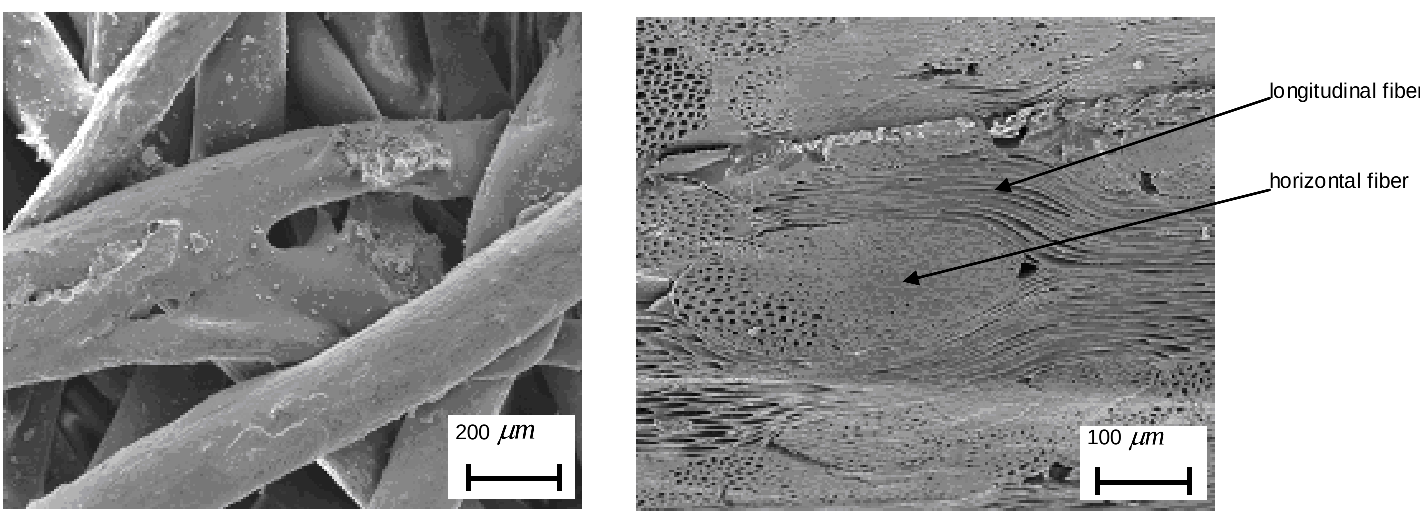
Experimental Method

ISO16978-2003 and GB/T17657-1999 are the two major standards determining internal bonding strength (IB), impact toughness (IT), and modulus of rupture (MOR). A SANS-CMT5504 Universal Mechanical Testing Machine was used for the IB values and for the three point bending test. A MW-4 Lumber Testing Machine was adopted to get the IT values via the impact experiment. Five samples were made for each test. SEM was used to investigate the morphology of samples by using the FEI Model Quanta 200 (FEI Company, USA), the samples were observed using an applied tension of 12.5 kV.

RESULTS AND ANALYSIS

SEM Images of Coir Fiber Mats

Figures 2 a) and b) present images of the cross section and longitudinal section of the non-woven coir fiber needle mats in the plywood. The interior reciprocating interweave of the coir fibers can be observed in Fig. 2 a). A uniform distribution of the fibers can be ensured by using non-woven coir fiber needle mats, and thus any instability in the overall performance of the plywood can be avoided. Coir fiber mats were compressed by the hot press in the production process of the plywood. The interwoven nature of the warp and weft is more obvious in Fig. 2 b).



a) Cross-section image **b)** Longitudinal section image

Fig. 2. SEM of coir fiber non-woven needle mats

The close association among the coir fibers and good interfaces between the adhesive and coir fibers are critical for good mechanical properties of the sandwich structure. From the analysis above, the buffering effect obtained by using directional coir fiber mats was better than when random orientation coir fibers were used in the plywood.

Intuitive Analysis of Test Result

The purpose of this study was to increase the flexibility of the sandwich structure of the plywood. Thus, IB, IT, and MOR were the key mechanical indices to be considered. The mechanical properties of the plywood can be seen in Table 2.

Table 2. Mechanical Property of Plywood

No.	IB(MPa)	IT(kJ/m^2)	MOR(MPa)
1	0.66	80	94.4
2	0.34	74	55.6
3	1.01	82	93.6
4	1.4	142	106.5
5	0.28	46	41.0
6	0.31	53	43.7
7	1.29	89	89.6
8	0.92	76	42.6

The optimal structure design can be obtained by the intuitive analysis (Cheng. 2005) of IB, IT, and MOR, as shown in Table 3. Through a comparison of the factors with extreme difference, which is the difference between the average value of level 1 and level 2, the relative importance of each factor can be determined for each mechanical index.

The quality of bonding inside the materials is reflected in the value of IB. From the values with extreme difference in Table 3, the order of the impact of each factor on IB was A2 > M×P2 > P1 > T1 > A×P2 > T×P1 > M1. Note that M×P and P were more important than M; level 2 of the interaction effect of M×P was better; and to ensure P1 was adopted, M2 must be adopted as the optimized design scheme. The final optimized design scheme of IB was: T1A2P1M2, where T1 was 10 mm thickness, A2 was isocyanate adhesive, P1 was the fiberglass position between the coir fiber mats (C+C), and M2 was 50% mass loading of coir fiber.

From Table 2, the order of the impact of each factor on IT was A2 > M×P2 > T1 > P1 > A×P2 > M2 > T×P1. According to the intuitive analysis above, M had the smallest influence among all the four factors, but 50 wt% of coir fiber was still better than 35 wt% of coir fiber, showing that the coir fibers do enhance the impact toughness. The optimized scheme was T1A2P1M2.

Through the three point bending test, the MOR values can be obtained. The optimized scheme for MOR was determined as T1, M×P2, P1, A2, M1, A×P2, and T×P1. The effect of T was the most significant one, and the interaction effect of M×P was the next. The optimized combination was M2×P1. Thus, M2 was adopted in the optimized design. The optimal scheme of MOR was the same as that for IB and IT.

From the results of intuitive analysis, the optimized design was determined as T1A2P1M2 to obtain the best overall mechanical performance. Sample 4 was prepared with the optimized combination of factors, and therefore it was expected to give the best results. The IT and MOR values of natural cathay poplar (Liu and Wang 2007) are 77 kJ/m^2 and 75 MPa, respectively. Samples 3, 4 and 7 reached or even exceeded these values. These data confirmed that these materials can be used as wood replacement materials.

Table 3. Intuitive Analysis of Experiment Results

Mechanical property	Factors	Average values of level 1	Average values of level 2	Extreme difference	Optimum plan
IB (MPa)	T	0.8525	0.7000	0.1525	T1
	A	0.3975	1.1550	0.7575	A2
	M	0.8100	0.7425	0.0675	M1
	P	0.9150	0.6375	0.2775	P1
	A×P	0.7250	0.8275	0.1025	A×P2
	M×P	0.8025	1.2050	0.4025	M×P2
	T×P	0.8150	0.7375	0.0775	T×P1
IT (kJ/m^2)	T	94.50	66.00	28.50	T1
	A	63.25	97.25	34.00	A2
	M	74.25	86.25	12.00	M2
	P	91.00	69.50	21.50	P1
	A×P	72.75	87.75	15.00	A×P2
	M×P	79.75	112.00	32.25	M×P2
	T×P	86.00	74.50	11.50	T×P1
MOR (MPa)	T	87.525	54.225	33.30	T1
	A	58.675	83.075	24.40	A2
	M	79.650	62.100	17.55	M1
	P	83.550	58.200	25.35	P1
	A×P	68.575	73.175	4.60	A×P2
	M×P	70.550	100.050	29.50	M×P2
	T×P	71.125	70.625	0.50	T×P1

Analysis of IB

The IB values of samples are compared in Fig. 3. Among all the factors, the type of adhesive used on the glass fiber was the most important, as shown in Table 3. Beacause the interface between glass fibers and isocyanate was much better than that between glass fibers and phenolic resin, the IB values of samples with fiberglass meshes and isocyanate adhesive were far higher than those of the other samples, so the IB values of sample 3, 4, 7 and 8 were higher, as shown in Fig. 3. In the other hand, better interface performance of veneer and coir fiber with phenolic resin can ensure higher IB values. Thus, only using isocyanate as the adhesive of the fiberglass mesh can both lower the cost and enhance IB. After the glue dipping process performed on the fiberglass mesh, redundant glue can easily penetrate into the coir fiber mats during the hot pressing process, and form glue joints between the coir fibers. This means that the position of the fiberglass mesh is very important. For the same kind of adhesive at the same thickness, if P was between V+C, the poplar veneer absorbed too much glue, and then the infiltration of the coir fibers would be limited. In addition, none of the redundant glue reached the most inner part of the coir mat, so the overall glue properties were uneven. The IB values of sample 2, 3, 5, and 8 with "P was between V+C" were all lower than the other samples with the same experimental conditions, as shown in Fig. 3. Once a damaging load is reached, the poor interfaces inside the material accelerate the growth of defects and deteriorate the material performance more easily.

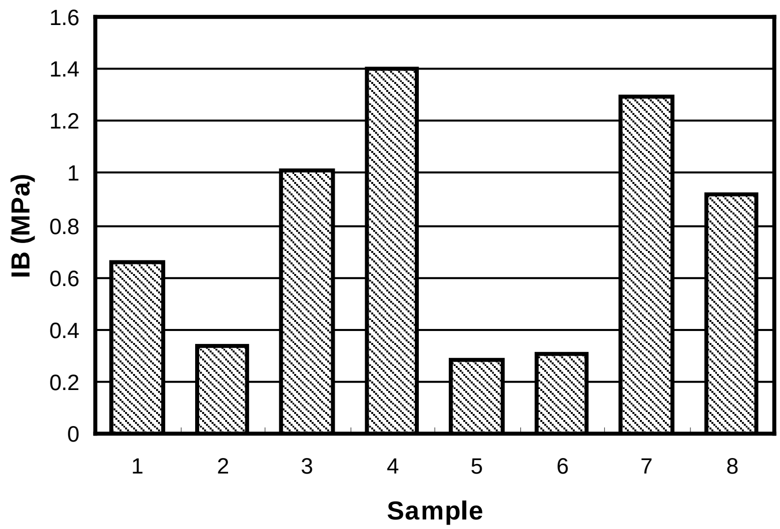


Fig. 3. Comparative histogram of IB

Analysis of IT

IT represents the ability of a material to resist fracture by impact loads. An impact experiment by cantilever beam pendulum was adopted as the test method in this study. The impact resistance of materials is related to the energy consumed during the impact process. When the consumption of energy is larger, the impact toughness would be higher.

After suffering impact loads, the three parts of the plywood were all damaged. Firstly, the popar veener part suffering pendulum impact directly was destroyed. For the coir fibers part, the interfaces between coir fiber and isocyanate or phenolic were destroyed, and the woven structure of the coir fibers mats was damaged. The spiral structure of the coir fiber itself was also damaged in the process of resisting the impacting load. The pullout of the glass fibers followed and finally the whole sample was damaged. A SEM image of sample 4 after impact is shown in Fig. 4; the interfaces between coir fiber and isocyanate were destroyed, leaving lots of holes. Moreover, the cross sections of coir fibers also showed an irregular distribution after impact load. The interwoven needle structure of coir fibers, combined with the powerful binding by isocyanate, resisted the force together. More of the impact energy was dissipated in sample 4 than in other samples, and thus this sample displayed the highest impact resistance.

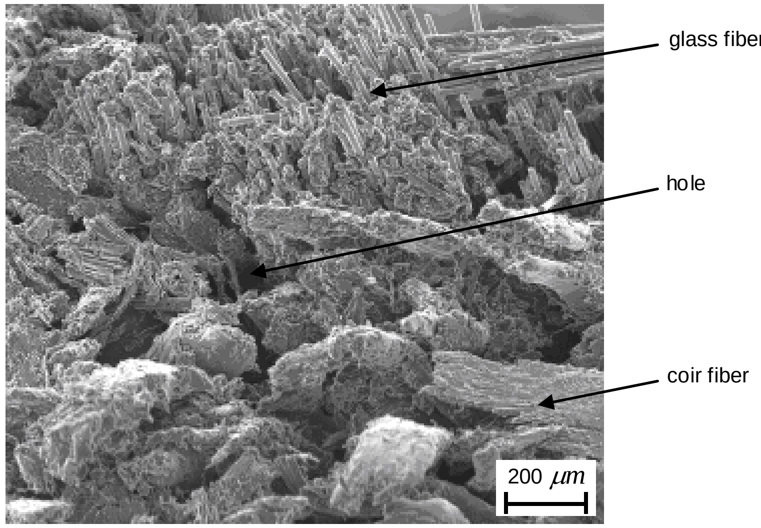


Fig. 4. SEM image of sample 4 after impact test

Analysis of Buffering Capacity

The curve in Fig. 5 was a force-displacement curve of sample 4 obtained by the three-point bending test. The force-displacement curves for all the samples exhibited the same tendency as sample 4. Thus one can better understand the total process of change through interpretation of the results for sample 4.

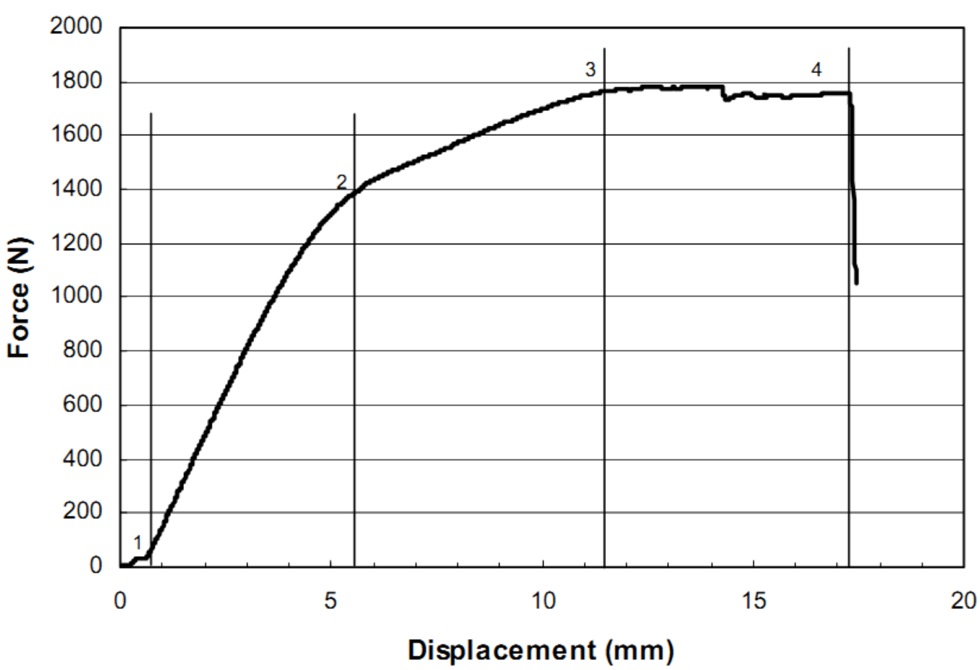


Fig. 5. Typical force-displacement curve for sample 4

The curves can be explained as four parts from point 0 to point 4. From point 0 to point 1, as shown in Fig. 5, the force increased first, and then stayed constant for a small range until the displacement was near 0.7 mm. This is mostly because of creep of the poplar veneer and the compaction of coir fibers mats.

The next two parts are essentially two lines of different slopes. The lines can be described as,

$$F = kx \tag{1}$$

where F is the bending load (N), x is the vertical displacement of the sample (mm), and k is the slope of the line. The modulus of elasticity E (MOE) is a physical quantity used to describe the deformation of a material under an external force. It is also an important measure of the buffering capacity of the material. The relationship of k and E is as follows (Shen and Hu. 2006):

$$E \propto k \tag{2}$$

According to the basic mixtures rule of MOE of composites (Hull and Clyne. 1996), E_{total} of composites can be expressed by Eq. 3,

$$E_{total} = \sum_{i=1}^{n} V_i E_i / V = \sum_{i=1}^{n} St_i E_i / ST = \sum_{i=1}^{n} t_i E_i / T \tag{3}$$

where E_{total} is the total E of the composites, and the subscripts i refer to the different components of the composites. From Eq. 2 and Eq. 3, k_{total} of the two lines can be described as,

$$k_{total} = \sum_{i=1}^{n} t_i k_i / T \tag{4}$$

where k_{total} is the total k of the composites, t_i and k_i are the thickness and the slope of the different components of the composites, and T is the total thickness of the composites.

The first straight line is from point 1 to point 2 with the horizontal ordinates changed from 0.7 mm to 5.5 mm. Two layers polar veneers and the core layer consisting of coir fiber mats and fiberglass bore loads together. k_{total} can be calculated from Eq. 4,

$$k_{total}^{1-2} = \frac{2t_v k_v}{2t_v + t_c} + \frac{t_c k_c}{2t_v + t_c} \tag{5}$$

where k_{total}^{1-2} is the line slope from point 1 to point 2, k_v is the elastic coefficient of the single poplar veneer, k_c is the elastic coefficient of coir fiber mats, and k_g is the elastic coefficient of the fiberglass mesh. Because the thickness of the fiberglass mesh can be neglected from Eq. 4, the effect of k_g can be neglected.

When point 2 was reached, the poplar veneer in the lower surface first was damaged first in the experiment. Then the force was borne by the upper veneer and the core layer. The slope k_{total}^{2-3} from point 2 to point 3 decreased.

$$k_{total}^{2-3} = \frac{t_v k_v}{t_v + t_c} + \frac{t_c k_c}{t_v + t_c} \quad (6)$$

From the above analysis and the relationship between k and E, as in Eq. 2, it can be deduced that $E_v > E_{total}^{1-2} > E_{total}^{2-3} > E_c$. Thus, the total MOE will be less than the polar veneer but the displacement under the external force will be lager. The sandwich structure avoids brittle fracture during the application of a three-point bending test.

Near the maximum load point, the internal weaving structure of the coir fibers still had some buffering functions, and so the damage energy can be further absorbed by crack propagation along the weak weaving of the fiber mats and the weakly bonded interfaces of fiberglass mesh and coir fiber mats. The sample can still bear higher levels of load for some time, but these values were slightly less than the maximum load. This can be seen from the region between point 3 and point 4 in Fig. 5, which reflected the delay in failure because of the buffering action of the coir fibers. This shows that the unique buffering characteristics of the coir fiber mats can be exploited by the sandwich structure.

CONCLUSIONS

1. Plywood using coir fiber as reinforcement has been designed. The sandwich structure is: peeled poplar veneer as the surfaces, non-woven needle mats of coir fiber as a part of the core layer to endow the plywood with the required buffering and toughening functions, and fiberglass mesh as the other part of the core layer to ensure the strength of the plywood.
2. According to the results of intuitive analysis of the orthogonal experiments, the optimum combination of the parameters is: 10 mm sample thickness, isocyanate as adhesive for the fiberglass mesh, 50 wt% of coir fiber mats, and with the glass fiber mesh positioned between coir fiber mats.
3. The force-displacement curves of the three point bending tests can explain the buffering effect of the coir fiber mats in the sandwich structure of plywood. Once the maximum force is reached, fracture does not occur immediately; the coir fiber mats significantly delay the destruction of plywood by the external force.
4. The values of IT and MOR for natural cathay poplar are 77 kJ/m^2 and 75 MPa. In the optimized plan, the performance indices of samples 3, 4, and 7 all exceeded these values. Therefore, these composites can be used as wood replacement materials in practical applications. The suggested applications include packaging materials and platform floors of vehicles to resist the impact force.

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