J Wood Sci (2009) 55:283–288
DOI 10.1007/s10086-009-1022-8

ORIGINAL ARTICLE

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Manufacture of plywood bonded with kenaf core powder

Received: June 20, 2008 / Accepted: January 7, 2009 / Published online: March 30, 2009

Abstract Kenaf (*Hibiscus cannabinus* L.) core powder was used as a binder to manufacture three-ply plywoods of sugi (*Cryptomeria japonica* D. Don) by conventional hot pressing under various manufacturing conditions: hot-pressing conditions (pressure, temperature, and time) and powder conditions (grain size, spread volume, and moisture content). The adhesive shear strength and wood failure of plywoods were measured in accordance with the Japanese Agricultural Standard (JAS) for plywood. The result showed that fine kenaf core powder played a role as an effective binder when plywoods were pressed at high pressure, which caused extreme compression of veneer cells. In addition, the adhesive shear strength of plywoods in dry conditions was high regardless of pressing temperature and time, but it was sensitive to pressing temperature and time in wet conditions. The highest adhesive shear strength was obtained from plywoods manufactured with kenaf core powder (grain size 10 μm, spread volume 200 g/m^2, moisture content 8.6%) under hot-pressing conditions (pressure 5.0 MPa using distance bars 4 mm thick, temperature 200°C, time 20–30 min). However, the plywood could not meet the requirement for the second grade of plywood by JAS because of its low water-resistance properties.

Key words Kenaf core · Powder · Plywood · Adhesive shear strength

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Part of this article was presented at the 58th Annual Meeting of the Japan Wood Research Society, Tsukuba, March 2008, and the 10th World Conference on Timber Engineering, Miyazaki, June 2008

Introduction

Synthetic thermosetting resins such as phenol–formaldehyde resins are generally used as adhesives to manufacture wood-based materials. However, reducing consumption of them is desirable to minimize negative impact on the environment, because formaldehyde-based adhesives are derived from petrochemicals. In addition, the increase of their production costs has promoted the improvement of alternative resins based on natural and renewable materials for wood adhesives. So far, much research has been performed on formaldehyde-free adhesives. In particular, lignin and tannin have been used as substitutes for phenol and resorcinol in synthetic thermosetting resins.[1–5] Although some of these resins are already used in industrial applications, the supply is limited.

In recent years, binderless boards have attracted great interest as environment-friendly products, because they can be manufactured from fragments of lignocellulosic materials by hot pressing, without the addition of any adhesives. This phenomenon, called self-bonding, has been explained in terms of activation of chemical components of the board constituents, mainly hydrolysis of hemicellulose and softening of lignin during hot pressing. Nonwood lignocellulosic materials have been used as the preferable raw materials for binderless boards.[6–11] Among the nonwood lignocellulosic materials, kenaf core has been reported to be one of the most suitable raw materials for binderless boards due to its high hemicellulose content. Xu et al.[12,13] developed binderless particleboards from kenaf core using steam-injection pressing. They also developed binderless fiberboard from kenaf core.[14] Okuda and Sato[15] successfully manufactured binderless boards from finely ground powder of kenaf core. Although the research on binderless boards is still in progress, these results suggested that kenaf core can be used as a binder.

Therefore, in this study, kenaf core powder was used as a binder to manufacture three-ply plywoods of sugi by hot pressing under various manufacturing conditions. The effects of hot-pressing conditions (pressure, temperature, and time) and powder conditions (grain size, spread volume, and moisture content) on the adhesive shear strength of plywoods were investigated.

Materials and methods

Powder preparation

Two kinds of powder of different grain size were prepared from kenaf (*Hibiscus cannabinus* L.) core, which was harvested in Indonesia. Kenaf core was separated from bast fiber and was dried at 70°C for 80 h (8 h/day for 10 days). Then it was crushed into powder with a flour mill (model CM-10; Hosokawa, Japan). The average grain size of the powder was approximately 53 μm (KCP-53) and moisture content was 10.4%. KCP-53 was further processed into fine powder with a vibration ball mill for 72 h after vacuum drying. The average grain size of the fine powder was approximately 10 μm (KCP-10) and moisture content was 8.6%. KCP-10 with moisture content of 0% and 30% was obtained by oven drying at 105°C and direct spraying of water, respectively.

Manufacture of plywood

Sugi (*Cryptomeria japonica* D. Don) heartwood veneers were used as raw materials for the plywood. The dimensions were 240 × 240 × 3 mm and the moisture content was 4%–8%. In the experiment to investigate the effect of the moisture content of the powder, veneers with moisture content of 0%, which were oven-dried at 105°C, were used. In the manufacturing of plywoods, kenaf core powder (KCP-53 and KCP-10) was used as substitute for commercial glues. First, it was uniformly spread over sugi heartwood veneers with a screen. Next, the three veneers were laminated and hot-pressed under various manufacturing conditions: hot-pressing conditions (pressures of 1.5, 3.0, 4.0, and 5.0 MPa; temperatures of 180°, 200°, and 220°C; times of 10, 20, and 30 min) and powder conditions (grain sizes of 10 and 53 μm; spread volumes of 0, 100, 200, and 300 g/m^2; moisture contents of 0%, 8.6%, and 30%). Distance bars of 4 mm in thickness were set on both sides of the laminated veneers during hot pressing, except during the experiment to investigate the effect of pressing pressure. Two plywoods were manufactured under each manufacturing condition. The details of each set of manufacturing conditions for the plywoods are shown in Table 1.

Tensile shear test of plywood

To evaluate the adhesive shear strength of plywoods, a total of 32 specimens measuring 75 × 25 × 4 mm were prepared from two plywoods manufactured under each set of manufacturing conditions. The tensile shear test of plywoods was conducted in dry and wet conditions, and then the adhesive shear strength and wood failure were measured in accordance with the Japan Agricultural Standard (JAS) for plywood.[16] Half of the number of specimens were tested in dry conditions, and the others were tested in wet conditions after soaking in water at 60°C for 3 h. Thickness swelling (TS) and water absorption (WA) of the plywoods were measured after soaking in water at 60°C for 3 h. TS and WA were calculated from the following formulas.

$$\mathrm{TS}(\%) = \frac{T_2 - T_1}{T_1} \times 100, \tag{1}$$

$$\mathrm{WA}(\%) = \frac{W_2 - W_1}{W_1} \times 100, \tag{2}$$

where T_1 and T_2 are the thickness of specimens before and after soaking in water, respectively, and W_1 and W_2 are the weight of specimens before and after soaking in water, respectively.

Table 1. Manufacturing conditions of plywoods

Hot-pressing conditions			Powder conditions			Veneer moisture content (%)
Pressure (MPa)	Temperature (°C)	Time (min)	Grain size (μm)	Spread volume (g/m^2)	Moisture content (%)	
1.5[a]	200	20	10	200	8.6	4–8
3.0[a]	200	20	10	200	8.6	4–8
4.0[a]	200	20	10	200	8.6	4–8
5.0	180	30	10	200	8.6	4–8
5.0	200	10	10	200	8.6	4–8
5.0	200	20	10	200	8.6	4–8
5.0	200	30	10	200	8.6	4–8
5.0	220	10	10	200	8.6	4–8
5.0	200	20	53	200	10.4	4–8
5.0	200	20	10	0	8.6	4–8
5.0	200	20	10	100	8.6	4–8
5.0	200	20	10	300	8.6	4–8
5.0	200	20	10	200	0	0
5.0	200	20	10	200	8.6	0
5.0	200	20	10	200	30.0	0

[a] Plywoods were hot-pressed without using distance bars

Observation of glue line and fractured surface of plywood

The glue line and fractured surface of plywoods after tensile shear testing were observed using a scanning electron microscope (SEM) to investigate the adhesive condition.

Results and discussion

Effect of pressing pressure

Figure 1 shows the relationship between density and adhesive shear strength of plywoods in dry and wet conditions at pressing pressures of 1.5 and 3.0 MPa. In this experiment, veneers could be compressed independently in the thickness direction, because distance bars were not set during hot pressing. Therefore, the average densities of plywoods pressed at 1.5 and 3.0 MPa were 0.46 and 0.80 g/cm^3, respectively, and they were directly affected by pressing pressure. Moreover, it was clear that the increase in density with increased pressing pressure caused the increase in the shear strength in both dry and wet conditions.

Figure 2 shows the SEM images of plywoods pressed at 1.5 and 3.0 MPa in the thickness direction. Although the cells in veneers of plywoods pressed at 1.5 MPa were hardly compressed, most of those in the plywoods pressed at 3.0 MPa were severely compressed in the thickness direction. This effect was more pronounced in the earlywood of veneers, which was compressed more easily than latewood. In addition, it was observed that the color of KCP-10 changed from its original color to dark brown on the fractured surface of plywoods pressed at 3.0 MPa. The internal temperature of plywoods pressed at 3.0 MPa increased immediately and reached the target temperature soon after hot pressing began. In contrast, the internal temperature of plywoods pressed at 1.5 MPa gradually increased and it took more than 5 min more for the target temperature to be reached than for the plywoods pressed at 3.0 MPa. It was considered that the cells of compressed veneers pressed at 3.0 MPa contributed to the good heat conductivity, and caused the color change of KCP-10.

These results suggest that the pressing pressure should be as high as possible in the manufacture of plywoods with high adhesive shear strength if KCP-10 is used as a binder. However, when plywoods were pressed at 4.0 MPa, they exploded after the pressing pressure was released, because the veneer cells were compressed so hard that steam could not escape. Therefore, it was considered that distance bars should be used to manufacture plywoods as simply as possible. Considering that the average density of the intact part of exploded plywoods was around 0.84 g/cm^3, distance bars of 4 mm in thickness were used to manufacture plywoods.

Effect of pressing temperature and time

Figure 3 shows the adhesive shear strength and wood failure of plywoods pressed at various temperatures and for various times. Although most plywoods showed high adhesive shear strength in dry conditions, the adhesive shear strength of

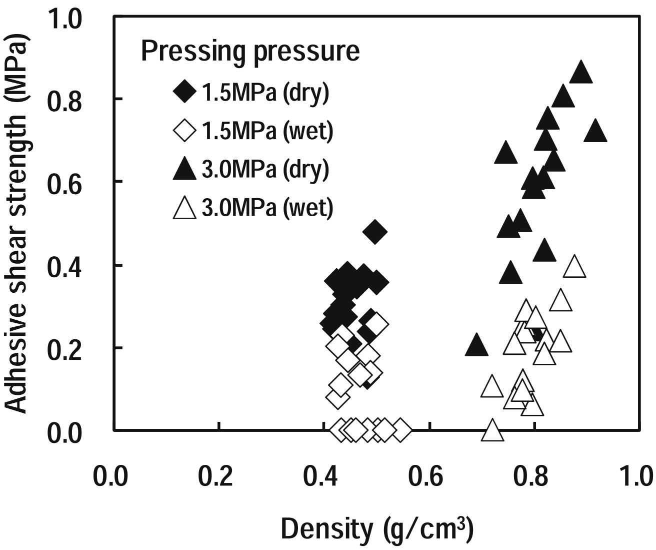

Fig. 1. Relationship between density and adhesive shear strength of plywoods in dry and wet conditions at pressing pressure of 1.5 and 3.0 MPa

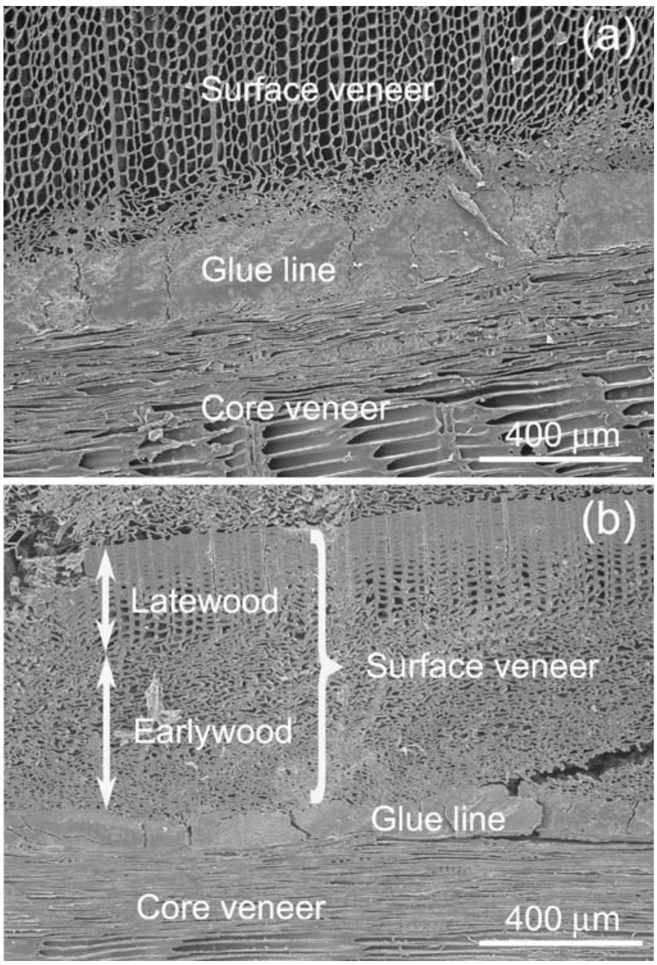

Fig. 2a,b. Scanning electron microscopy (SEM) images of plywoods pressed at **a** 1.5 MPa and **b** 3.0 MPa in the thickness direction

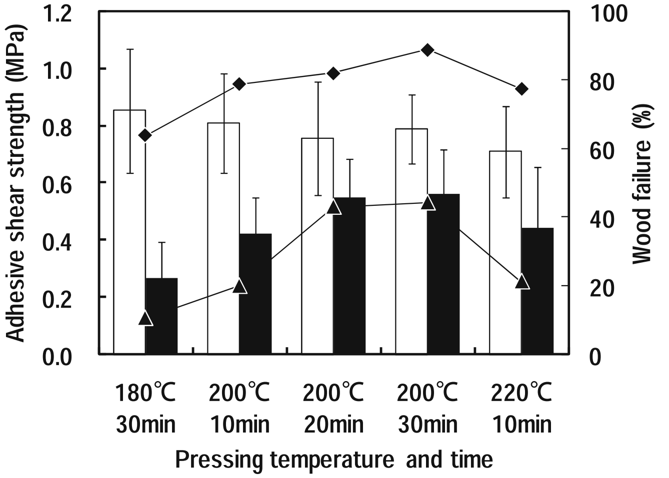

Fig. 3. Adhesive shear strength (*blocks*) and wood failure (*symbols*) of plywoods pressed at various pressing temperatures and times. *Open blocks*, dry conditions; *filled blocks*, wet conditions; *diamonds*, dry conditions; *triangles*, wet conditions

plywoods in wet conditions increased with time and with increased pressing temperature up to 200°C. However, considering that binderless boards manufactured from kenaf core powder at a pressing temperature of 180°C for 10 min showed good properties,[15] it seemed that the higher pressing temperature and the longer pressing time should be applied to manufacture plywoods with high adhesive shear strength.

Figure 4 shows the TS and WA of plywoods pressed at various temperatures and for various times. It is well known that the mechanical properties (modulus of rupture, modulus of elasticity, internal bonding strength) and the water-resistance properties (TS, WA) of binderless boards improve with increased pressing temperature and time. Although the TS and WA of plywoods were also improved with increased pressing temperature and time, it was suggested that the TS and WA of plywoods pressed at 180°C for 10 min would be extremely low. Therefore, it was considered that the optimum pressing temperature and time were very different between binderless boards and plywoods.

In addition, it was observed that KCP-10 changed from its original color to dark brown on the fractured surface of plywoods, and it darkened with increased pressing temperature and time. Therefore, it was suggested that there might be a relationship between the color change of KCP-10 and the adhesive shear strength of plywoods in wet conditions. However, when plywoods were pressed at 220°C for 10 min, the adhesive shear strength of the plywoods was decreased, because KCP-10 was partially burned during hot pressing.

Effect of grain size of powder

Figure 5 shows the adhesive shear strength and wood failure of plywoods bonded with KCP-10 and KCP-53. It was clear that the adhesive shear strength of plywoods bonded with KCP-53 were much lower than those of plywoods bonded with KCP-10. It has been reported that although KCP-53 is suitable as raw materials for binderless boards, it cannot achieve good contact with veneers of plywoods. On the other hand, KCP-10 played an effective role as a binder to manufacture plywoods, because the grain size of KCP-10 was small enough to mold into the uneven surface of the veneer, which consisted mainly of tracheids with widths of 20–30 μm.[17]

Figure 6 shows the SEM image of the fractured surfaces of plywoods bonded with KCP-10 or KCP-53 after the tensile shear test. It was observed that KCP-10 was compressed more smoothly to the uneven veneer surface than KCP-53, and tracheid shapes were replicated in the KCP-10 glue line. These results suggest that there may be an anchor effect between KCP-10 and the veneers.

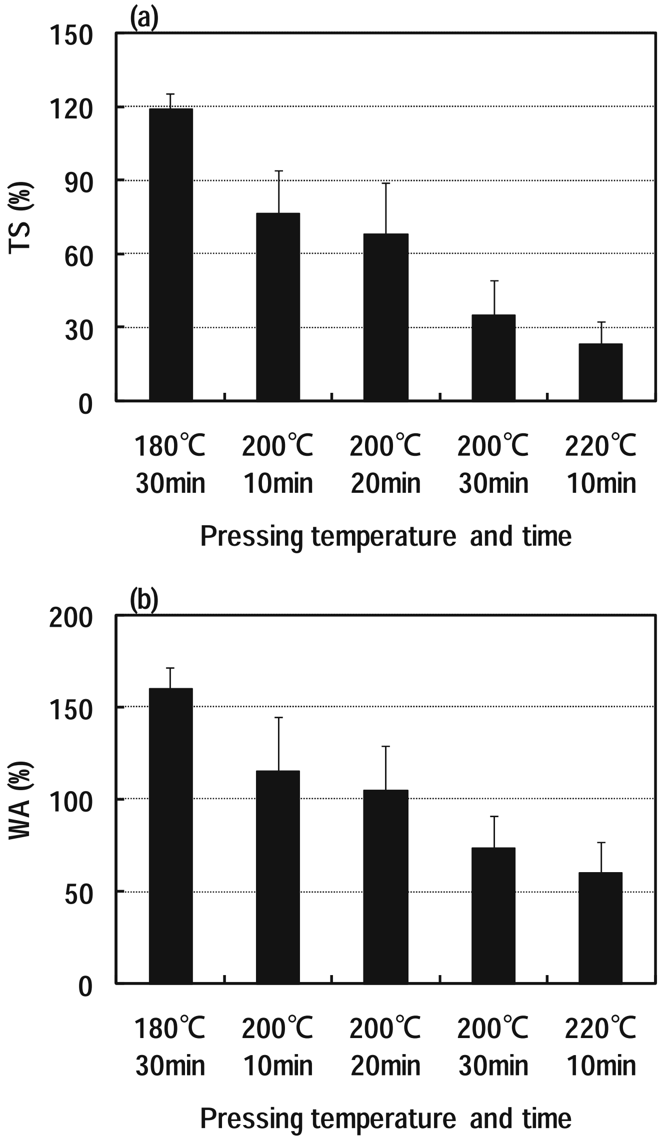

Fig. 4. **a** Thickness swelling (*TS*) and **b** water absorption (*WA*) of plywoods pressed at various pressing temperatures and times

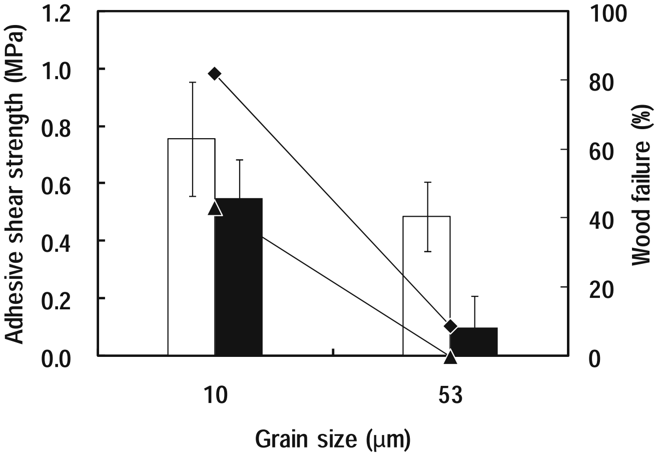

Fig. 5. Adhesive shear strength (*blocks*) and wood failure (*symbols*) of plywoods bonded with KCP-10 and KCP-53. *Open blocks*, dry conditions; *filled blocks*, wet conditions; *diamonds*, dry conditions; *triangles*, wet conditions

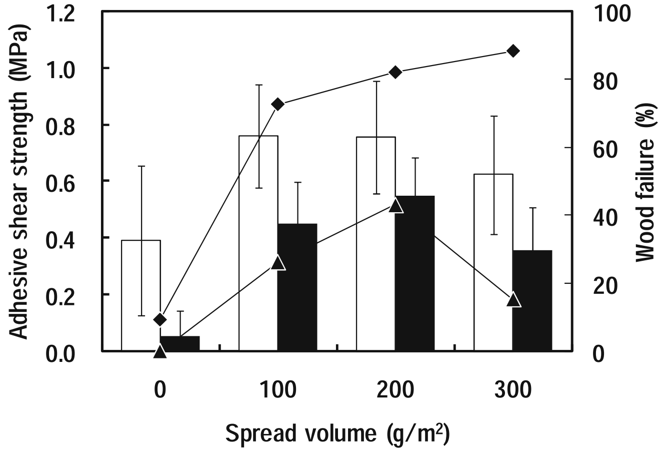

Fig. 7. Adhesive shear strength (*blocks*) and wood failure (*symbols*) of plywoods bonded with KCP-10 at various spread volumes. *Open blocks*, dry conditions; *filled blocks*, wet conditions; *diamonds*, dry conditions; *triangles*, wet conditions

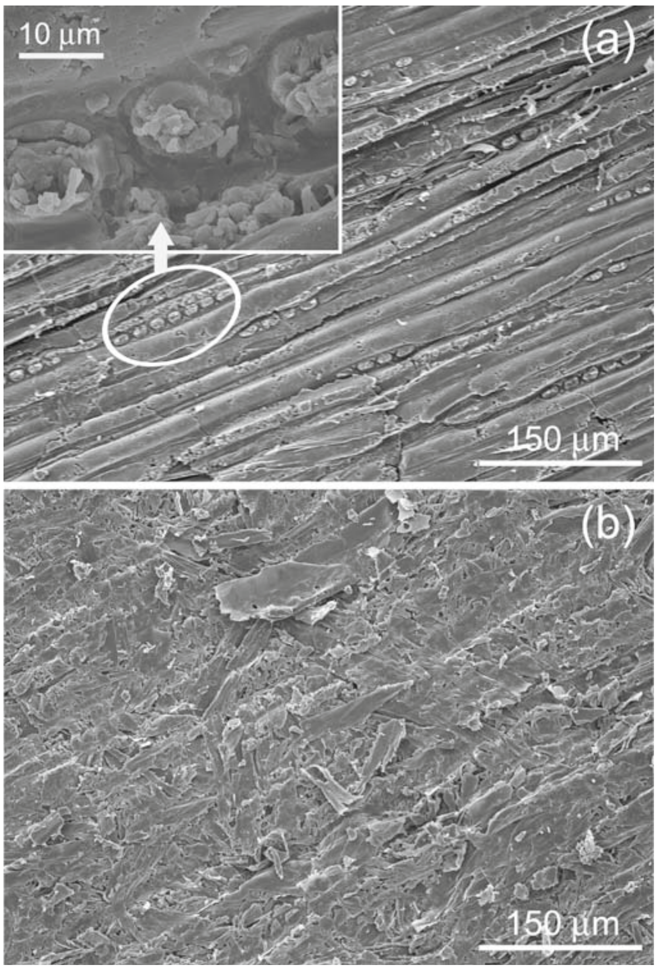

Fig. 6a,b. SEM images of the fractured surface of plywoods bonded with **a** KCP-10 and **b** KCP-53 after the tensile shear test

In addition, it was also observed that the color of KCP-10 changed from its original to dark brown, whereas that of KCP-53 hardly changed. Because KCP-10 was processed by intensive milling to obtain the wood meal, it is likely that the microstructure of the cell walls was severely damaged, and hemicellulose and lignin could be easily available on the surface of KCP-10. Therefore, it was considered that chemical reaction occurred more easily in KCP-10 than in KCP-53, and it might contribute to improved adhesive shear strength of plywoods.

Effect of spread volume of powder

Figure 7 shows the adhesive shear strength and wood failure of plywoods bonded with KCP-10 at various spread volumes. Although it was possible to manufacture plywoods without KCP-10, the adhesive shear strength of plywoods without KCP-10 was much lower than that of plywoods bonded with KCP-10. In particular, the adhesive shear strength of plywoods without KCP-10 was extremely low in wet conditions, because more than half of the number of specimens separated into pieces after soaking in water. However, the adhesive shear strength of plywoods bonded with KCP-10 was not always increased with increased spread volume of powder. These results corresponded with the fact that high adhesive shear strength usually can be obtained from wood-based materials bonded with adhesives at a proper spread volume.

Effect of moisture content of powder

Figure 8 shows the adhesive shear strength and wood failure of plywoods bonded with KCP-10 of various moisture contents. It is well known that the properties of binderless boards are improved with increased moisture content of raw materials, because chemical components of the board materials are activated. In this experiment, compared with the adhesive shear strength of plywoods bonded with KCP-10 with moisture content of 0%, the adhesive shear strength of plywoods bonded with KCP-10 with moisture content of 8.6% and 30% were slightly increased in dry conditions. However, the adhesive shear strength of plywoods in wet

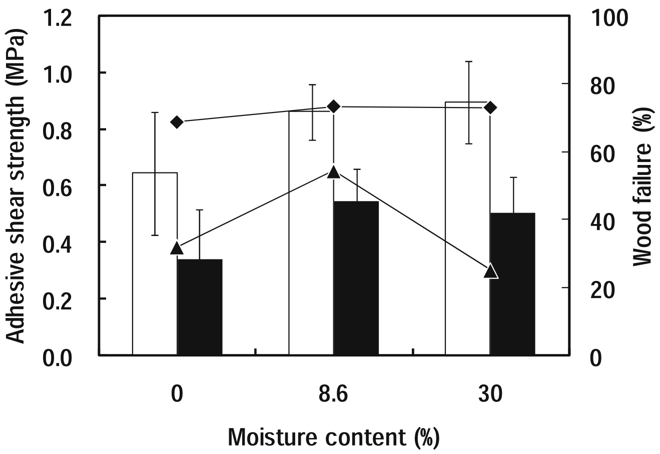

Fig. 8. Adhesive shear strength (*blocks*) and wood failure (*symbols*) of plywoods bonded with KCP-10 of various moisture contents. *Open blocks*, dry conditions; *filled blocks*, wet conditions; *diamonds*, dry conditions; *triangles*, wet conditions

conditions could not always be improved with an increase in the moisture content of KCP-10. Some cracks were observed on the surface of plywoods bonded with KCP-10 with a moisture content of 30% after the pressing pressure was released, because steam was unable to escape during hot pressing. Therefore, it was considered that other means should be applied to improve the adhesive shear strength of plywoods.

Conclusions

Kenaf core powder was used as a binder to manufacture three-ply plywoods of sugi by conventional hot-pressing. The effects of hot-pressing conditions (pressure, temperature, and time) and powder conditions (grain size, spread volume, and moisture content) on the adhesive shear strength of plywoods were investigated. The results can be summarized as follows.

1. The adhesive shear strength of plywoods increased linearly with increasing pressing pressure, and the water-resistance properties were improved with increasing pressing temperature and time. The best hot-pressing conditions were considered to be pressure 5.0 MPa using distance bars 4 mm thick, temperature 200°C, and time 20–30 min.
2. The grain size of kenaf core powder was the most important requirement in powder conditions, which greatly affected the adhesive shear strength of plywoods. The highest adhesive shear strength was obtained from plywoods bonded with kenaf core powder (grain size 10 μm, spread volume 200 g/m^2, moisture content 8.6%).
3. It was possible to manufacture plywoods bonded with fine kenaf core powder under proper manufacturing conditions. However, they could not meet the requirement for the second grade of plywood by JAS because of their low water-resistance properties.

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