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ORIGINAL ARTICLE

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# Evaluation of the self-bonding ability of sugi and application of sugi powder as a binder for plywood

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**Abstract** Binderless particleboards were manufactured from sugi (*Cryptomeria japonica* D. Don) heartwood and sapwood by hot-pressing (pressure: 5 MPa; temperatures: 180°, 200°, and 220°C; times: 10, 20, and 30 min), and the board properties [internal bonding (IB), thickness swelling (TS), water absorption (WA)] were investigated to evaluate the self-bonding ability. The IB, TS, and WA of the boards from sugi heartwood were better than those of the boards from sugi sapwood at any hot-pressing condition. Therefore, it was suggested that the self-bonding ability of sugi heartwood was superior to that of sugi sapwood. Then, sugi heartwood and sapwood powder with grain size 10 μm were used as a binder for plywoods. Four kinds of plywood were manufactured from the combination of powder and veneer, both of which were prepared from sugi heartwood and sapwood under the same hot-pressing conditions as the binderless particleboard, and the adhesive shear strength and wood failure of the plywood were investigated. As a result, the plywood composed of sugi heartwood veneer met the second grade of JAS for plywood, when either powder was used as a binder, when they were pressed at 200°C for 20–30 min and 220°C for 10 min.

**Key words** Sugi · Self-bonding ability · Binderless particleboard · Plywood

## Introduction

Much research has recently been performed on manufacturing wood-based materials without synthetic adhesives from the environmental aspect. In particular, the self-bonding ability of lignocellulosic materials is attracting a great deal of interest as one of the effective means to manufacture wood-based materials without any adhesives. However, there are few studies on manufacturing wood-based materials that consist of large elements such as plywood and laminated lumber without adhesives, because the application of the self-bonding ability of lignocellulosic materials is still limited to the manufacture of binderless board, extrusion, molding material, and vibration welding.[1–4]

Among the lignocellulosic materials, a kenaf (*Hibiscus cannabinus* L.) core is considered to be a good raw material for binderless board because kenaf core binderless board had high internal bonding (IB).[5–7] In our previous study,[8] we thought that the kenaf core had an excellent self-bonding ability and used it as a binder for plywood. The result showed that fine kenaf core powder played an effective role as a binder under appropriate manufacturing conditions. However, the plywood could not meet the requirements for the second grade of plywood by the Japanese Agricultural Standard (JAS) because of its low water resistance properties.

As for the binderless boards, it has been considered that the lignocellulosic material, which is rich in hemicellulose, would give an advantage in the mechanical and physical properties of binderless boards. However, it has been reported that the water resistance properties, thickness swelling (TS), and water absorption (WA) of kenaf core binderless boards were relatively low, whereas the IB was very high, regardless of its high hemicellulose content.[5,7] Considering results of both kenaf core binderless boards and plywood bonded with kenaf core powder, it seemed that the high hemicellulose content of raw material would not always give an advantage in the water resistance properties of binderless boards and plywood. Therefore, it was

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recommended that a wood powder that is richer in lignin but poorer in hemicellulose than kenaf core powder be used as a binder to improve the water resistance properties of plywood.

Because sugi (*Cryptomeria japonica* D. Don) is one of the most popular raw materials in the wood industry of Japan, a large amount of sugi waste wood is generated in the manufacturing process. Although most of these wastes are effectively used as raw materials for conventional particleboard and fiberboard, it is desirable to manufacture these boards without using adhesives. However, so far it has been reported that it is difficult to manufacture binderless board with good performance from wood just by hot-pressing.[9,10]

In this study, binderless particleboards were manufactured from sugi heartwood and sapwood by hot-pressing, and the self-bonding ability of the board was investigated. Then sugi heartwood and sapwood powder at particle size 10 μm were used as a binder for plywood, and the adhesive shear strength and wood failure of the plywood were investigated.

## Materials and methods

### Manufacture of binderless particleboard

Sugi (*Cryptomeria japonica* D. Don) heartwood and sapwood were used as raw materials. A part of commercial veneers of sugi heartwood and sapwood that were prepared for plywood were cut into chips, then crushed into particles with a Wiley mill (WT-150; Miki Seisakusho, Japan) until the particles could pass through a 1-mm screen. Sugi heartwood and sapwood particles with moisture content of 8%–9% were manually formed into a homogeneous single-layer mat using a forming box. The mats were pre-pressed and then pressed with a hot-press machine under various hot-pressing conditions (Table 1). The dimensions of binderless particleboards were 200 × 200 × 5 mm, and the target densities were 0.8 and 1.0 g/cm$^3$. One board was manufactured under each hot-pressing condition.

Considering the application of fine sugi powder as a binder for plywoods, binderless particleboards themselves should be manufactured from fine sugi powder to evaluate the self-bonding ability of sugi precisely. Unfortunately, such fine sugi powder with an average grain size of approximately 10 μm was too small to manufacture binderless boards. However, it was considered that the mechanism of the self-bonding of sugi was not so different between particles and fine powder. Therefore, in this study, the self-bonding ability of sugi was evaluated based on the properties of binderless boards manufactured from sugi particles (<1 mm).

**Table 1.** Hot pressing condition for binderless particleboard and plywood

| Pressure (MPa) | Temperature (°C) | Time (min) |
|---|---|---|
| 5.0 | 180 | 30 |
| 5.0 | 200 | 10 |
| 5.0 | 200 | 20 |
| 5.0 | 200 | 30 |
| 5.0 | 220 | 10 |

### Evaluation of binderless particleboard properties

The properties of binderless particleboards were evaluated in accordance with the Japanese Industrial Standard (JIS) for fiberboards (JIS A 5905, 2003).[11] Four specimens of 50 × 50 × 5 mm were prepared from each board for the internal bonding (IB) test. The IB test was conducted by using a universal testing machine (Instron 4204). Four specimens of the same size were prepared from each board for thickness swelling (TS) and water absorption (WA) tests after soaking in water at 20°C for 24 h.

### Manufacture of plywood

Commercial veneers of sugi heartwood and sapwood were used. The dimensions were 240 (T) × 240 (L) × 3 (R) mm; moisture content was 6%–10%. Powder was prepared from sugi heartwood and sapwood particles that were prepared for binderless particleboard. Particles that were smaller than 1 mm were further processed into fine powder (grain size, approximately 10 μm) with a vibration ball mill for 72 h, after vacuum drying. Then, fine sugi heartwood and sapwood powder adjusted to a moisture content of 8%–9% was uniformly spread over sugi heartwood or sapwood veneers at 200 g/m$^2$ using a screen. Three veneers were laminated and hot-pressed under the same hot-pressing conditions as the binderless particleboards (Table 1). Two plywoods were manufactured from the combination of veneer and powder under each hot-pressing condition. Distance bars of 4-mm thickness were set on both sides of the laminated veneers during hot-pressing to avoid explosion of plywood caused by excessive compression of veneers.

### Tensile shear test of plywood

A total of 32 specimens of 75 × 25 × 4 mm were prepared from two plywoods manufactured under each hot-pressing condition. A tensile shear test was performed in dry and wet conditions using an universal testing machine (Autograph AG-IS 100 kN; Shimadzu, Japan); then, adhesive shear strength and wood failure were measured in accordance with the Japan agricultural standard (JAS) for plywood.[12] Half the specimens were tested in dry conditions, and the others were tested in wet conditions after soaking in 60°C water for 3 h. Thickness swelling ($TS_P$) and water absorption ($WA_P$) of the plywood were also measured after soaking in 60°C water for 3 h. $TS_P$ and $WA_P$ were calculated from the following formulas.

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

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

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.

### Scanning electron microscopy (SEM) observation of glue line of plywood

The glue line of plywood after the tensile shear test in dry and wet conditions was observed by using a SEM (Hitachi S-4000) to investigate the adhesive condition.

## Results and discussion

### Internal bonding of binderless particleboard

Figure 1 shows the relationship between board density and IB of sugi binderless particleboard pressed at 200°C for 20 min. Although IB was extremely low (<0.1 MPa) at the density of 0.8 g/cm$^3$, regardless of raw material, it increased sharply at 1.0 g/cm$^3$. In addition, IB of the boards from sugi heartwood was higher than that of boards from sugi sapwood.

In general, the IB of binderless boards tends to increase with increasing board density. Xu et al.[13] reported that low-density binderless particleboards could be manufactured from a kenaf core using steam injection pressing. They manufactured binderless particleboard with an IB of 0.1 MPa at a density of 0.2 g/cm$^3$. Okuda and Sato[7] successfully manufactured binderless board from kenaf core powder with an IB of 5.7 MPa at a density of 1.0 g/cm$^3$ by hot-pressing. Comparing the binderless boards from kenaf core and sugi, it seemed that sugi binderless particleboard with high IB could be manufactured when the board density was relatively high. This result suggests that sugi powder would play an effective role as a binder when they are

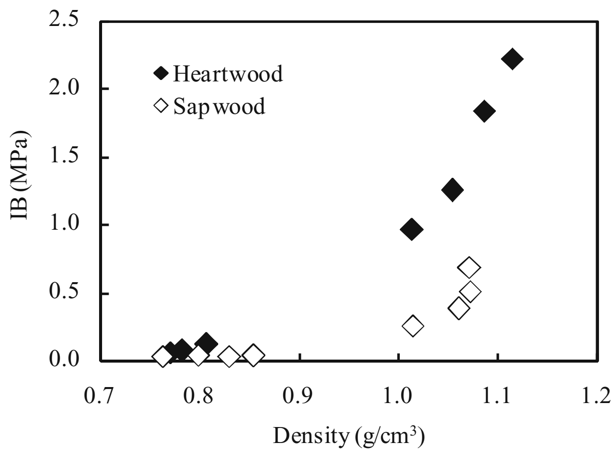

**Fig. 1.** Relationship between board density and internal bonding (IB) of sugi binderless particleboard pressed at 200°C for 20 min

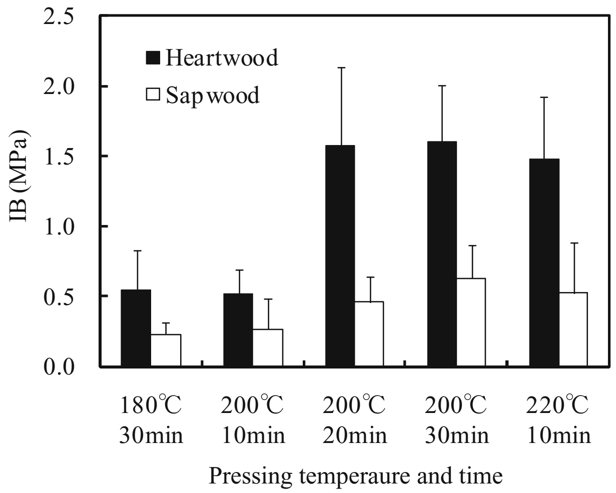

**Fig. 2.** Influence of pressing temperature and time on IB of sugi binderless particleboard at density of 1.0 g/cm$^3$

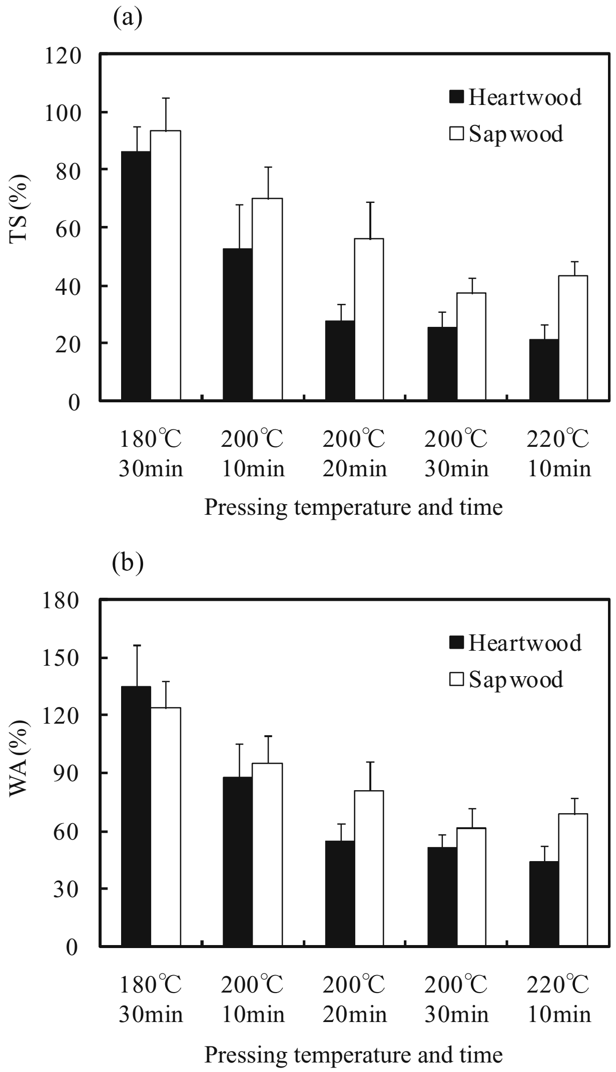

**Fig. 3.** Influence of pressing temperature and time on thickness swelling (TS) (**a**) and water absorption (WA) (**b**) after 24 h of water soaking of sugi binderless particleboard at density of 1.0 g/cm$^3$

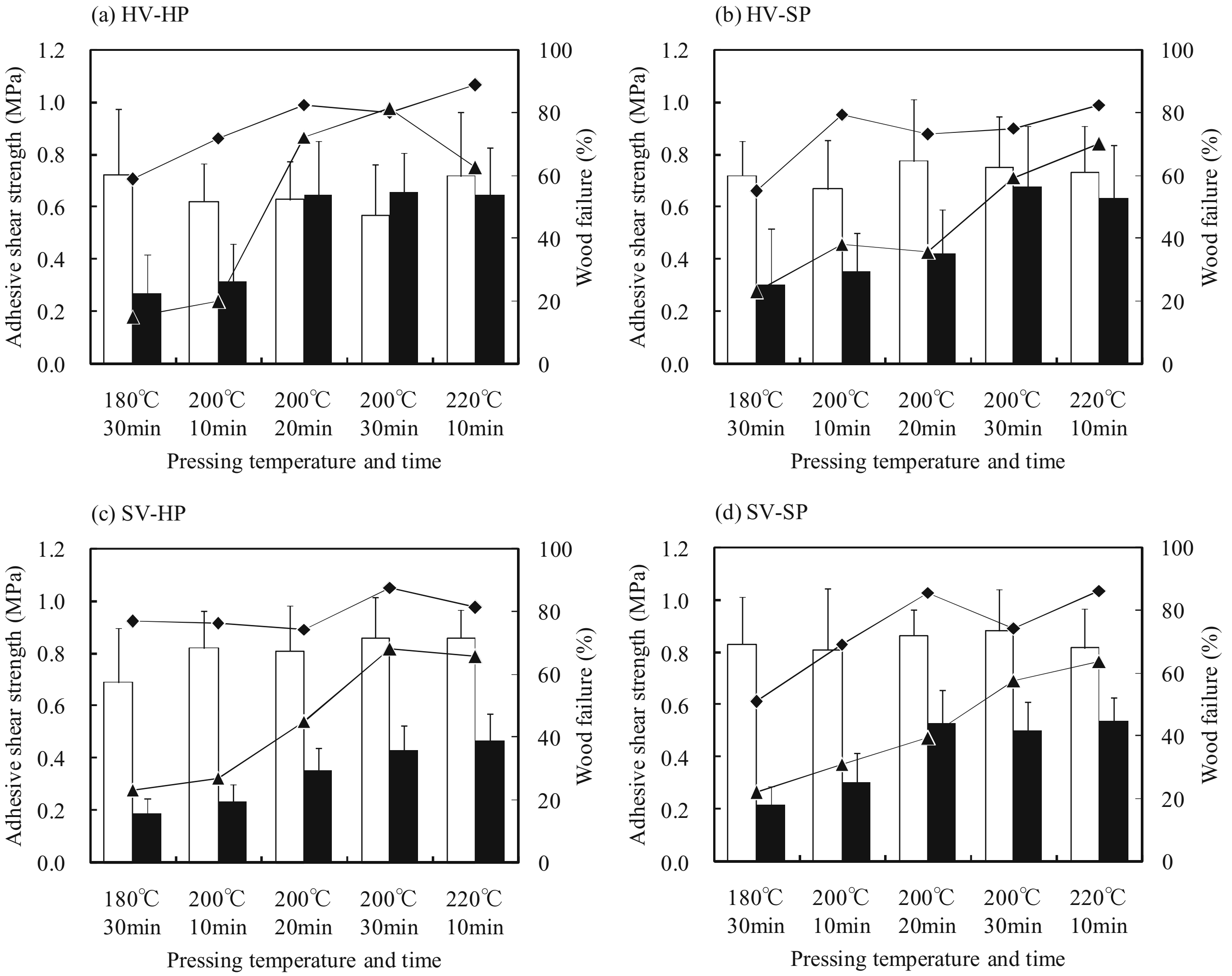

**Fig. 4.** Influence of pressing temperature and time on adhesive shear strength (*blocks*) and wood failure (*symbols*) of plywood manufactured from the combination of veneer and powder. *Open blocks*, dry conditions; *filled blocks*, wet conditions; *diamonds*, dry conditions; *triangles*, wet conditions; *HV*, heartwood veneer, *SV*, sapwood veneer; *HP*, heartwood powder; *SP*, sapwood powder

compressed severely. The difference in the self-bonding ability between kenaf core and sugi might be caused by the difference of the chemical components.

Figure 2 shows the influence of pressing temperature and time on the IB of sugi binderless particleboard at 1.0 g/cm$^3$. Regardless of raw material, IB increased when the boards were pressed at 200°C for 20 min. In addition, IB of boards from sugi heartwood was more than twice that of the boards from sugi sapwood at any pressing temperature and time. The IB values of the boards from sugi heartwood and sapwood pressed at 200°C for 20 min were 1.57 and 0.46 MPa, respectively, at a density of 1.0 g/cm$^3$.

## Water resistance properties of binderless particleboard

Figure 3 shows the influence of pressing temperature and time on the TS and WA of sugi binderless particleboard at a density of 1.0 g/cm$^3$. Regardless of raw material, TS and WA tended to decrease with increasing pressing temperature and time. However, the TS and WA of boards from sugi heartwood were lower than those of boards from sugi sapwood because they were affected by the IB of the boards. When the binderless particleboards were pressed at 200°C for 20 min, the TS and WA values of the boards from sugi heartwood were 27.6% and 54.6%, respectively, whereas those of the boards from sugi sapwood were 56.2% and 81.4%, respectively.

In contrast, TS and WA of boards at 0.8 g/cm$^3$ were higher than those of boards at 1.0 g/cm$^3$. Especially, the TS and WA of the boards pressed at 180°C for 30 min and at 200°C for 10 min were so low that most of the test specimens broke into pieces during soaking in water.

## Adhesive shear strength and wood failure of plywood

Figure 4 shows the influence of pressing temperature and time on the adhesive shear strength and wood failure of plywood. Regardless of the combination of veneer and powder, the adhesive shear strength and wood failure of plywood in dry conditions were high at any pressing temperature and time, but the adhesive shear strength and wood failure of plywood decreased after soaking in water at most pressing temperatures and times. The adhesive shear strength and wood failure of plywood in wet conditions tended to increase with increasing pressing temperature and time. In addition, it was observed on the fractured surface of the test specimens that the color of powder darkened with increasing pressing temperature and time. These tendencies, which were observed for plywood bonded with sugi powder, were the same as those of plywood bonded with kenaf core powder.[8] As shown in Figs. 2 and 3, the self-bonding ability was significantly different between sugi heartwood and sapwood. However, there was not a significant difference in adhesive shear strength and wood failure between plywood bonded with sugi heartwood powder and that bonded with sapwood powder.

In contrast, there was a significant difference in the adhesive shear strength and wood failure between the plywood composed of sugi heartwood veneer and that composed of sapwood veneer. Unfortunately, plywood composed of sugi sapwood veneer could not meet the second grade of JAS for plywood at any pressing temperature and time, whichever powder was used as a binder. Among the plywoods composed of sugi heartwood veneer, plywood bonded with sugi heartwood powder met the second grade of JAS for plywood when pressed at 200°C for 20 or 30 min and at 220°C for 10 min. Plywood bonded with sugi sapwood powder also met the second grade of JAS for plywood when pressed at 200°C for 30 min and 220°C for 10 min. From these results it was suggested that adhesive shear strength and wood failure of plywood were affected more by the origin of the veneer than by the origin of the powder.

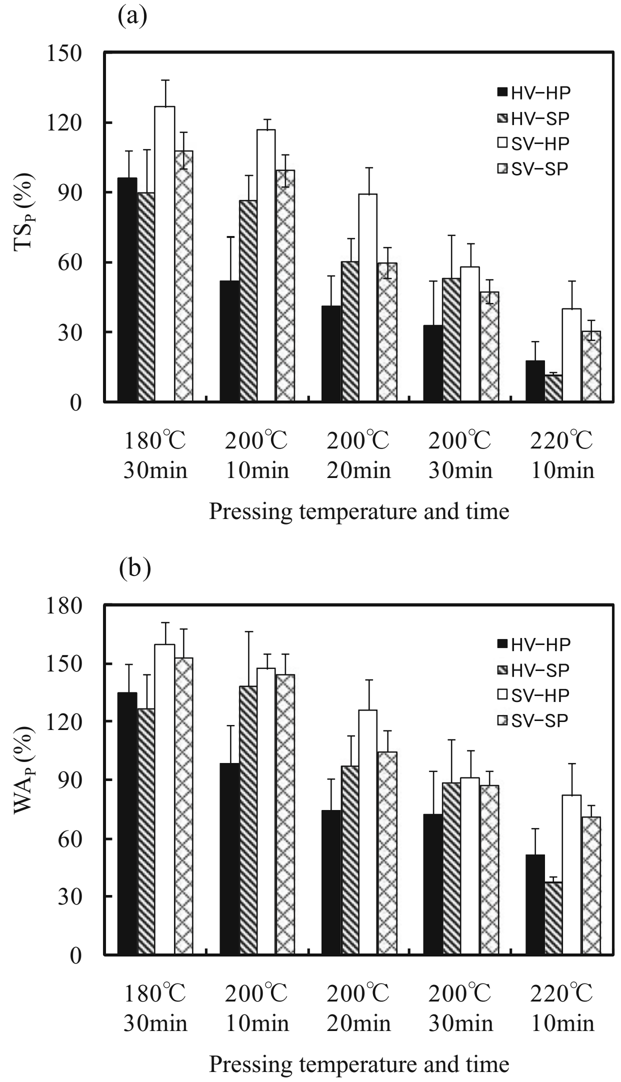

**Fig. 5.** Influence of pressing temperature and time on thickness swelling ($TS_P$) (**a**) and water absorption ($WA_P$) (**b**) after 3 h hot water soaking of plywood manufactured from the combination of veneer and powder. *HV*, heartwood veneer; *SV*, sapwood veneer; *HP*, heartwood powder; *SP*, sapwood powder

## Water resistance properties of plywood

Figure 5 shows the influence of pressing temperature and time on the $TS_P$ and $WA_P$ of plywoods. Regardless of the combination of veneer and powder, $TS_P$ and $WA_P$ tended to decrease with increasing pressing temperature and time. However, $TS_P$ and $WA_P$ of plywood composed of sugi heartwood veneer were lower than that of plywood composed of sugi sapwood veneer on the whole.

Figure 6 shows an SEM image of the glue line of plywood manufactured from the combination of sugi heartwood veneer and sugi heartwood powder when pressed at 180°C for 30 min and 220°C for 10 min. In our previous study,[8] we reported that high pressure during the hot-pressing was needed to manufacture plywood with high adhesive shear strength and wood failure, but that such an extreme hot-pressing condition caused great compression of the cells in plywood veneers. In this experiment, the compression set of plywood was estimated at approximately 60%. Therefore, cells in veneers of plywood after the tensile shear test in dry conditions were extremely compressed at any pressing temperature and time, regardless of the combination of veneer and powder (Fig. 6). In contrast, the cells in veneers of plywood after the shear test in wet conditions seemed to recover by soaking in water.

Unfortunately, it was difficult to observe the influence of pressing temperature and time on the thickness recovery of the cells in veneers from the SEM images because of the compression of plywood sensitively affected by the density fluctuation in each veneer and fluctuation of powder spread over the veneer. However, it could be observed that there was no significant difference in the thickness of the powder layer (approximately 100–200 μm) between the plywoods after the tensile shear test in dry and wet conditions, regardless of not only pressing temperature and time but also the combination of veneer and powder. Considering $TS_P$ and $WA_P$ values, it was suggested that the increase of the thickness and weight of plywood after soaking in water would be caused mainly by thickness recovery and water absorption of the veneers. This result also supports that the adhe-

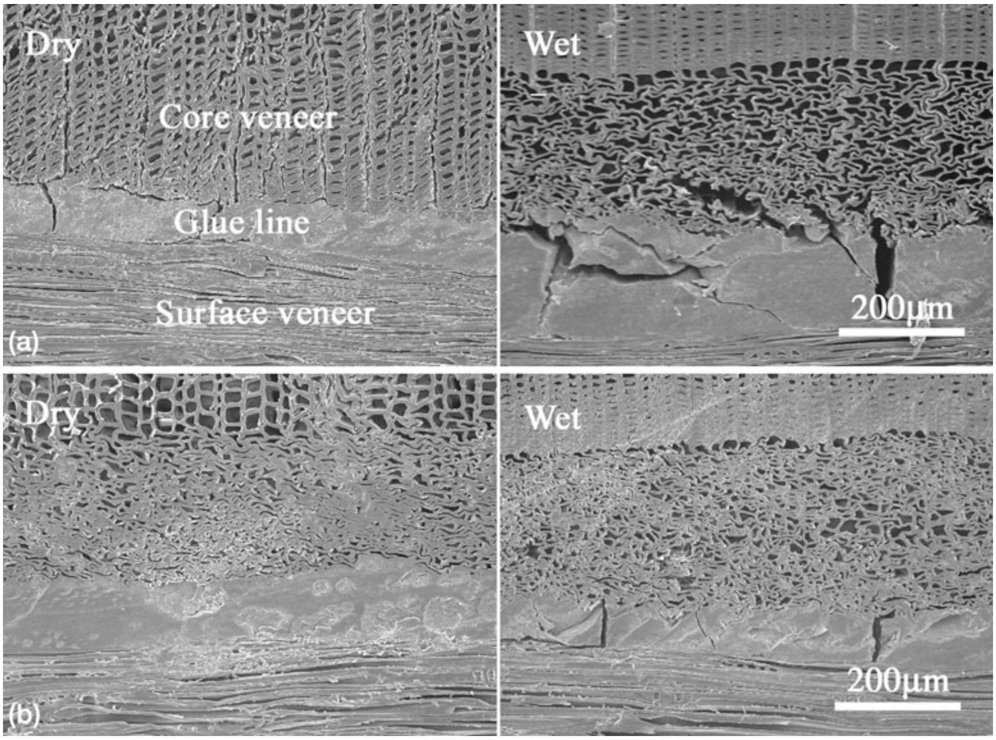

**Fig. 6.** Scanning electron microscopy (SEM) image of the glue line of plywood manufactured from the combination of sugi heartwood veneer and sugi heartwood powder when the boards were pressed at 180°C for 30 min (**a**) and 220°C for 10 min (**b**)

sive shear strength and wood failure of plywood were more affected by origin of veneer than origin of powder (see Fig. 4).

In addition, from these results, it was considered that the pressing temperature and time were important factors not only to compact wood powder sufficiently but also to reduce the thickness recovery and water absorption of the veneers.

## Conclusions

The results obtained in this study can be summarized as follows.

1. The IB, TS, and WA of binderless particleboard manufactured from sugi heartwood were better than those of binderless particleboard manufactured form sugi sapwood. Therefore, it was suggested that the self-bonding ability of sugi heartwood was superior to that of sapwood.
2. The adhesive shear strength and wood failure were not significantly different between plywood bonded with sugi heartwood powder and that with sapwood powder, although the self-bonding ability of sugi heartwood was superior to that of sapwood. However, the adhesive shear strength and wood failure of plywood composed of sugi heartwood veneer were better than those of plywood composed of sugi sapwood veneer. As a result, plywood composed of sugi heartwood veneer met the second grade of JAS for plywood, whichever powder was used as a binder, when the boards were pressed at 200°C for 20–30 min and 220°C for 10 min.
3. It was considered that the pressing temperature and time were important factors to manufacture sugi plywood bonded with sugi powder, because these factors contributed not only to compacting powder but also to reducing the thickness recovery and water absorption of veneers.

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