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ORIGINAL ARTICLE

Satoshi Fukuta · Fumihito Asada · Yasutoshi Sasaki

Manufacture of compressed wood fixed by phenolic resin impregnation through drilled holes

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Abstract An aqueous solution of phenolic resin was impregnated through drilled holes in wood, and we manufactured compressed wood with the deformation fixed by the phenolic resin. The methods of impregnation used in this study were an in-liquid platen-pressing method and a vacuum treatment. The effect of the drilled holes on solution retention was examined. Moreover, the control of solution retention was examined under the application of compression drying. The impregnation of resin into the specimens without drilled holes was insufficient, and the deformation could not be fixed. On the other hand, sufficient impregnation was possible in the specimen with drilled holes, and the deformation fixation was observed. At the stage of compression when the solution was squeezed out of the specimen, the solution retention of each specimen was accurately controlled in the specimens with drilled holes. At the stage of compressive deformation and deformation fixation using a hot press, the specimens without drilled holes could not be processed normally because swelling occurred. However, swelling did not occur in the specimens with drilled holes.

Key words Compressed wood · Phenolic resin · Deformation fixation · Impregnation · Drilled holes

S. Fukuta (✉) · F. Asada
Aichi Industrial Technology Institute, Nishishinwari, Hitotsugi-cho, Kariya 448-0003, Japan
Tel. +81-566-24-1841; Fax +81-566-22-8033
e-mail: satoshi_2_fukuta@pref.aichi.lg.jp

Y. Sasaki
Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya 464-8601, Japan

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Introduction

Research on the compressive deformation of wood was begun in Japan[1] in order to increase the usage of Japanese cedar, a domestic softwood extensively planted in reforestation programs. In the compressive deformation of wood, deformation fixation is an important technical problem. A closed heating system has been designed for fixing deformation by a comparatively simple mechanism,[2] and the compressive deformation process has begun to receive attention from industry. In previous research on the compressive deformation process using a closed heating system, we examined a new processing method characterized by drilling holes into wood to improve its productivity. Drilled holes allow the penetration and discharge of steam in wood. By examining the results of the simultaneous treatments of compression drying and deformation fixation, the effect of the drilled holes on the permeability of water in wood was shown.

Regarding the method of deformation fixation, the use of resin or other chemicals has been reported.[3–5] For the method of using phenolic resin, a particularly high fixation effect was achieved, and the improvement of mechanical properties[3,4] and biological resistance[6,7] were expected. Therefore, wider use of the material could be expected. However, homogeneous impregnation or treatment of long lumber or refractory wood is difficult, so permeability becomes a technical problem. Although research and development are advanced for Japanese cedar, the wood is not suited to resin treatment because the permeability of the heartwood of Japanese cedar is poor. Incisions are generally made for the chemical treatment of wood. However, incisions are insufficient for deformation fixation because a homogeneous treatment is needed for the whole cross section. For this reason, up to now, resin treatment has not been carried out in the manufacture of compressed wood.

In this study, we focused on the improvement of the permeability brought about by drilled holes, and the effect of drilled holes on solution retention was examined. The homogeneous resin treatment of the whole cross section was predicted because deep holes were drilled using a thin drill bit. Also, a method of controlling solution retention was examined by applying compression drying. Finally, a compressed wood with the deformation fixed using phenolic resin was manufactured by applying these techniques.

Materials and methods

Wood materials and resin

The specimens were obtained from the heartwood of Japanese cedar (*Cryptomeria japonica* D. Don) and had dimensions of 500 × 38 × 100 mm [longitudinal (L) × radial (R) × tangential (T)]. They were cut out from logs that were gathered in the same growth area of Toyota City, Aichi, Japan. The moisture content and the air-dried density were 11.5% and 0.38 g/cm^3, respectively.

The resin was a water-soluble, low molecular weight phenolic resin (PX-341) formulated by Aica. The solution was 51% in concentration, the pH value was 9.7, and the mean molecular weight was 400. In this study, it was diluted to a concentration of 20%. The temperature of the solution was about 20°C.

Drilling process

Holes were drilled in the LT surface at a machining center, as shown in Fig. 1. The holes were positioned to have an offset of 3 mm for each row, and were drilled regularly to a depth of 35 mm at intervals of 10 or 15 mm. The drilled holes were 1.3 mm in diameter.

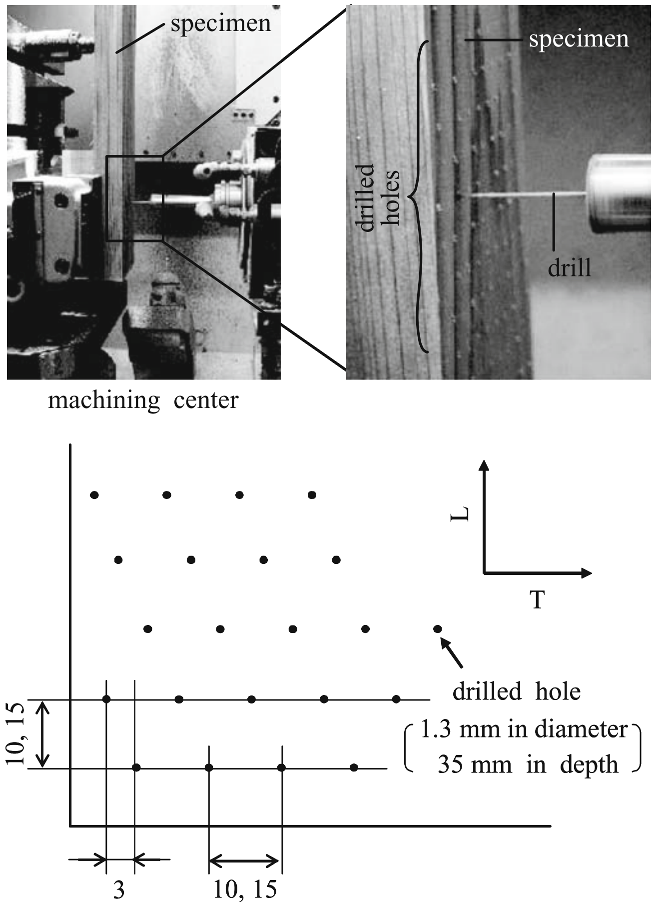

Fig. 1. Drilling process using machining center. *L*, Longitudinal; *T*, tangential

Methods of impregnation of solution

The methods of impregnation of the solution used in this study were in-liquid platen pressing[8] or vacuum treatment. In-liquid platen pressing is a technique for impregnating a solution into the specimen during the recovery of compression deformation in a container filled with solution. In methods using this principle, various mechanisms have been developed and examined in previous research.[8–15] In those reports, the improvement of liquid penetration by the fracture of closed bordered pits is reported,[11,13–16] and these methods are very interesting and effective. In this research, the effect of the drilled holes on solution retention was examined for both in-liquid platen pressing and vacuum treatment. An increase in the solution retention or a shortening of the treatment time could be expected by drilling holes, even for refractory wood.

The process of in-liquid platen pressing is as follows. Specimens were compressed for 1 min using a platen press in a container filled with solution. The compression ratio was 50% and the loading speed was 30 mm/min. Subsequently, the load was removed (unloaded), and the specimen was taken out of the container after 1 or 10 min; the solution was impregnated for 1 or 10 min into the wood during the recovery of compression deformation. A wire net of 0.5 mm in diameter was placed underneath the specimen (the drilled surface). This wire net was used to release the air in the specimen exiting horizontally from the drilled holes during the compression. The wire net was similarly used for the specimen without drilled holes. The surface of the specimen was wiped after impregnation, weighed immediately, and the solution retention was obtained. Then the external appearance of the specimen was observed. The number of specimens was seven. The specimen soaked for 10 min was quickly taken out of the solution every minute, and the thickness at the central part was immediately measured. Thus, the recovery ratio at the central part of the specimen at every minute was obtained.

The process of vacuum treatment is as follows. After the specimens were left in an outgassing chamber under a vacuum of 30 mmHg for 30 min, the solution was impregnated. The specimens were taken out of the solution after soaking for 30 min under atmospheric pressure. The solution retention was obtained, and the appearance of the specimens was observed. The number of specimens was seven.

Squeezing solution

Considering the mechanism of deformation fixation using resin, reported in previous research,[1] the permeation of the resin into the cell wall greatly contributes to deformation fixation. On the other hand, it seems that excess solution remaining in the cell pores does not greatly contribute to deformation fixation. Moreover, when solution retention is excessive, the texture of the wood is ruined. It is also preferable that the amount of resin used is minimized to reduce the environmental impact and cost.

Thus, in this research, to squeeze excess solution from the cell pores by compression drying, all the specimens were compressed to 50% of their former thickness using a press at room temperature. A wire net was placed underneath the specimen. Here, the wire net was used to release the solution exiting horizontally from the drilled holes during compression. After compression, the specimens were weighed, solution retention was calculated again, and the appearance of the specimens was observed.

Deformation fixation of compressed specimen

Next, the specimens were dried to an almost air-dried state in a dryer at 50°–60°C. After drying, the specimens were compressed using a hot press at 140°C for 1 h, and deformation fixation was performed by curing the resin. The compression ratio was 50%. A wire net was placed underneath the specimen to allow the release of the steam generated in the specimen and exiting horizontally from the drilled holes. After this process, a visual observation was carried out. Also, the absolute dry mass of the specimen was determined, and the weight percent gain based on the absolute dry mass before impregnation was calculated.

Fixation recovery

The fixation efficiency of the specimens after the deformation fixation was examined by a boiling test, and the permeability of the solution could be evaluated from the fixation efficiency. The specimens were divided into ten equal pieces in the longitudinal direction, and pieces 45 mm long were formed. The boiling test was executed as follows. Water was impregnated into the pieces using a vacuum until saturation. The pieces were then placed in boiling water for 2 h, and then dried to an absolute dried state in a dryer. The recovery ratio (R) was calculated by

$$R = \frac{\text{Amount of recovery}}{\text{Amount of compression}} \times 100 = \frac{T_R - T_1}{T_0 - T_1} \times 100(\%), \quad (1)$$

where T_R is the thickness after the recovery test, T_1 is the thickness after compression, and T_0 is the thickness before compression.

The resin was cured on the surface of the specimens after deformation fixation. It was thought that the resin coated on the surface had an effect on the result of the boiling test. Thus, the edges of the specimens were removed beforehand using a saw, and 1 mm of the surface was removed by planing to remove the resin. Therefore, the value of T_1 used took into consideration the thickness after planing. The specimen without drilled holes, for which swelling occurred during deformation fixation, was subjected to the boiling test under such a condition. Therefore, the amount of recovery resulting from swelling was included in the value of the recovery ratio.

Results and discussion

Solution retention after impregnation

Figure 2 shows the solution retention after impregnation. The solution retention of the specimens with drilled holes was greater than that of the specimens without drilled holes for each method; the effect of drilling holes was clear. Also, the solution retention for a drilling interval of 10 mm was greater than that for the interval of 15 mm; thus, the effect of the drilling interval on the permeability of the wood was observed. The solution retention of the specimens with drilled holes (drilling interval of 10 mm, depth of 35 mm) was twice that of the specimens without holes for vacuum treatment, and 3.5 to 5 times that for in-liquid platen pressing. The solution retention for in-liquid platen pressing increased with soaking time after unloading. The increase in solution retention was more marked in the specimens with drilled holes than in the specimens without drilled holes, and the solution retention of the specimens with drilled holes for a soaking time of 10 min was greater than that for the specimens that had undergone the vacuum treatment.

During in-liquid platen pressing, the thickness of the center of the specimens was measured every 1 min, and the

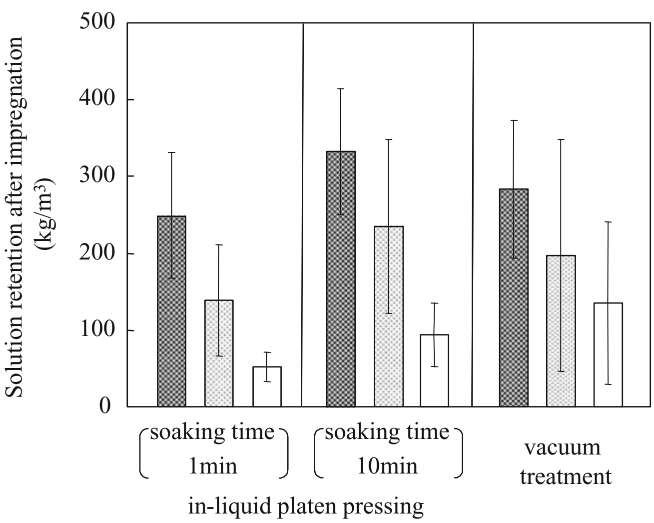

Fig. 2. Effect of drilled holes on solution retention after impregnation with an aqueous solution of low molecular weight phenolic resin. *Dark shading*, with drilled holes (drilling interval, 10 mm; depth, 35 mm); *light shading*, with drilled holes (drilling interval, 15 mm; depth, 35 mm); *no shading*, without drilled holes

recovery ratio was determined every 1 min to examine the effect of the soaking time. Figure 3 shows the relationship between the soaking time after unloading and the recovery ratio. The deformation of the specimens without drilled holes had a recovery ratio of about 35% immediately after unloading. However, no significant increase in the recovery ratio was observed with time, and the recovery ratio after 10 min was about 40%. According to the visual observation, the deformation near the end grain recovered slightly at first, and the deformation recovered gradually from inside the end grains. However, the deformation did not recover fully over the entire length. This is because the specimen (the heartwood of Japanese cedar) is a refractory wood, and its permeability is poor; some of the air in the cell pores seemed to be compressed and remained in the cell pores without being exhausted during the compression. This air returned to its former volume during the recovery of deformation after unloading. Therefore, the liquid suction force was thought to decrease. In addition, the specimens without drilled holes draw the solution from the end grains. The penetration of the solution from the end grains to the inside is thought to be considerably delayed because the solution is inferior to air in terms of permeability. On the other hand, the air and liquid easily penetrate the specimen with drilled holes.[3] Therefore, exhaustion of the air in the cell pores and the drawing of the solution occur through the drilled holes. As a result, the deformation recovered gradually with time; the recovery ratio after 10 min was about 80% for a drilling interval of 15 mm and 90% for a drilling interval of 10 mm. It is surmised that the increase in solution retention with soaking time is owing to the increase in the recovery ratio with time. In the specimens with a drilling interval of 10 mm, each part of the longitudinal direction was the same thickness at the recovery stage, and each part was observed to recover almost equally.

Then, on the basis of the result for the specimens with a drilling interval of 10 mm, we considered solution retention. According to the volume decrease at the compression ratio of 50%, the theoretical solution retention after suction is 500 kg/m^3 at the recovery ratio of 100%. Solution retention at the soaking time of 1 min in Fig. 2 (249 kg/m^3) was 86% of the theoretical solution retention (290 kg/m^3), which corresponded to the recovery ratio of 58% in Fig. 3. Solution retention at the soaking time of 10 min in Fig. 2 (333 kg/m^3) was 75% of the theoretical solution retention (445 kg/m^3), corresponding to the recovery ratio of 89% in Fig. 3. The filling ratios for soaking times of 1 and 10 min were 86% and 75%, respectively. The value for the soaking time of 10 min (75%) was less than that for 1 min (86%), because the specimens had been taken out from the solution to measure their thickness every 1 min. However, these values were much greater than those reported in previous research using the same method.[10] This demonstrates that the liquid penetration is improved by drilling holes. Solution retention did not reach the theoretical value probably because of the influence of the compressed air that remained in the cell pores without being exhausted or the influence of the lateral strain that occurred with the deformation.

Squeezing solution

Compressive deformation was applied to the impregnated specimens, and we squeezed the solution from the specimens. Figure 4 shows solution retention after compression. The solution retention of the specimens with drilled holes was half that shown in Fig. 2, and it was possible to squeeze the solution from the specimens. The solution, once impreg-

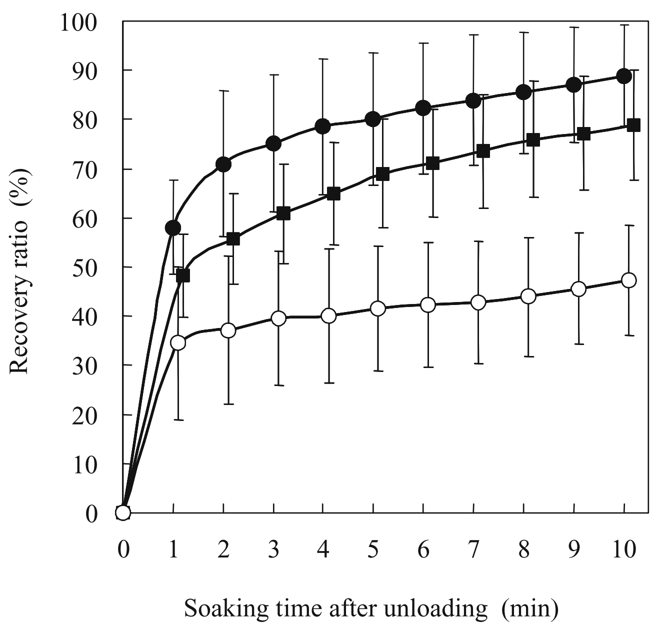

Fig. 3. Relationship between soaking time after unloading in solution and recovery ratio. *Filled circles*, drilling interval 10 mm, depth 35 mm; *squares*, drilling interval 15 mm, depth 35 mm; *open circles*, without drilled holes

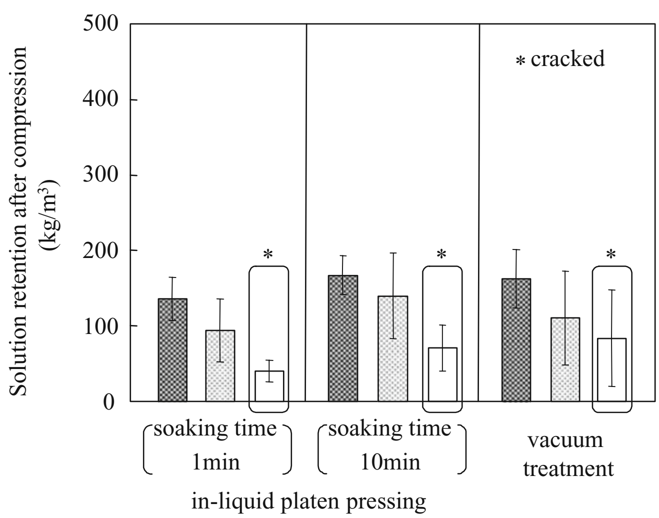

Fig. 4. Solution retention after compression to squeeze the solution from the specimen. *Dark shading*, with drilled holes (drilling interval, 10 mm; depth, 35 mm); *light shading*, with drilled holes (drilling interval, 15 mm; depth, 35 mm); *no shading*, without drilled holes

nated into the cell pores, was exhausted out through the drilled holes by compressive deformation. On the other hand, the amount of exhausted solution was low for the specimens without drilled holes. Moreover, in the specimens without drilled holes, a crack along the longitudinal direction occurred in the specimens with comparatively high solution retention. This crack seems to be caused by the hydraulic pressure that originates from deformation. The hydraulic pressure increases because the impregnated solution cannot move or be exhausted during deformation. This crack did not occur in the specimens with drilled holes, although the solution retention of these specimens was greater than that of the specimens without drilled holes. We have reported cracking during the compression drying of green wood. A similar tendency was observed in these impregnated specimens.

Next, Fig. 5 shows the relationship between solution retention before compression and solution retention after compression for each specimen. The solution retention of each specimen was accurately controlled by squeezing out the solution during compressive deformation (compression drying), and solution retention after compression asymptotically approached a constant value. This constant value seems to be the total amount of solution corresponding to the sum of the volume of solution in the cell pores at the compression ratio of 50% and the volume of solution permeated into the cell walls. Considering a previous report, it seems that solution retention can be arbitrarily controlled by varying the compression ratio.

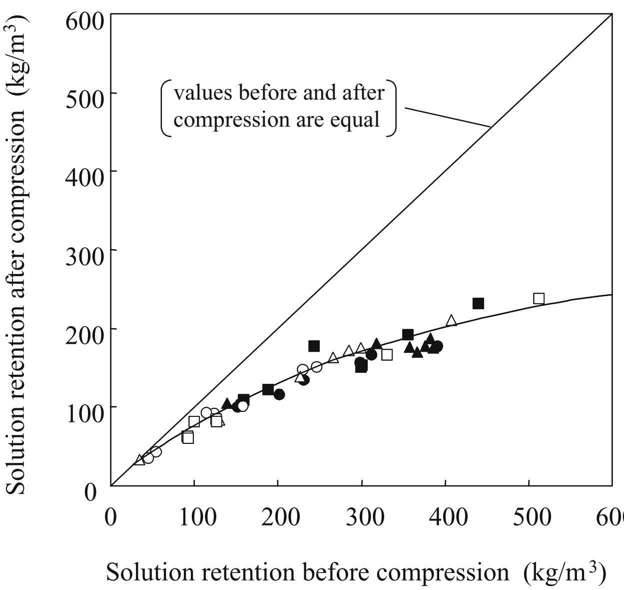

Fig. 5. Relationship between solution retention before compression to squeeze the solution from the specimen and solution retention after compression. *Open symbols*, with drilled holes (drilling interval, 15 mm; depth, 35 mm); *filled symbols*, with drilled holes (drilling interval, 10 mm; depth, 35 mm); *circles*, in-liquid platen pressing (soaking time, 1 min); *triangles*, in-liquid platen pressing (soaking time, 10 min); *squares*, vacuum treatment

Compressive deformation and fixation

Compressive deformation and deformation fixation were executed using a hot press. Figure 6 shows the weight percent gain after deformation fixation. The weight percent gain corresponded approximately to the concentration of the solution. Figure 7 shows the specimens after deformation fixation. Figure 7a shows the central cross section of a specimen without drilled holes. Almost all the specimens without drilled holes swelled convexly from the end grain to the center part; the swelling of the center part was larger than that of the end grain. The permeation of the resin was not observed at the cross section. This swelling occurred because the solution could not be impregnated into the center part of the specimen, and the deformation was not fixed. In addition, the steam generated by the moisture in the specimen during hot pressing could not be exhausted because the cured resin around the end grain blocked its release. Therefore, marked swelling occurred when the hot press was opened. It seems that the amount of solution retained by specimens without drilled holes, indicated in Fig. 6, is the amount of solution impregnated around the end grain, and the solution did not contribute to deformation fixation of the whole specimen. On the other hand, swelling did not occur in the specimen with drilled holes (Fig. 7b), which was processed normally. It seems that the steam in the specimen was exhausted through the drilled holes.

The surface of the specimens after deformation fixation was smoothly covered with resin because the solution infiltrated the surface. Then, the back and face of the specimen were removed by planing (Fig. 7c). The surface after planing had the texture of wood, and no significant discoloration was observed compared with the specimen before impregnation.

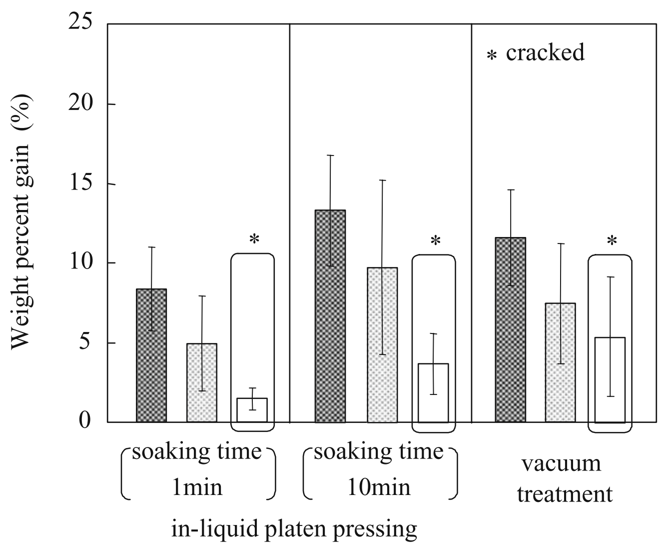

Fig. 6. Weight percent gain (oven-dry basis) after deformation fixation. *Dark shading*, with drilled holes (drilling interval, 10 mm; depth, 35 mm); *light shading*, with drilled holes (drilling interval, 15 mm; depth, 35 mm); *no shading*, without drilled holes

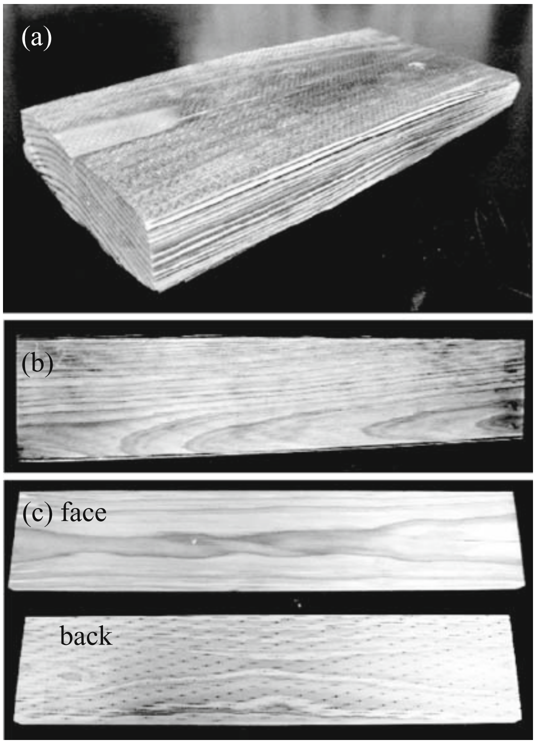

Fig. 7a–c. Specimens after deformation fixation. **a** Specimen without drilled holes (cross cut at the center), **b** specimen with drilled holes, **c** specimens after planing (face and back)

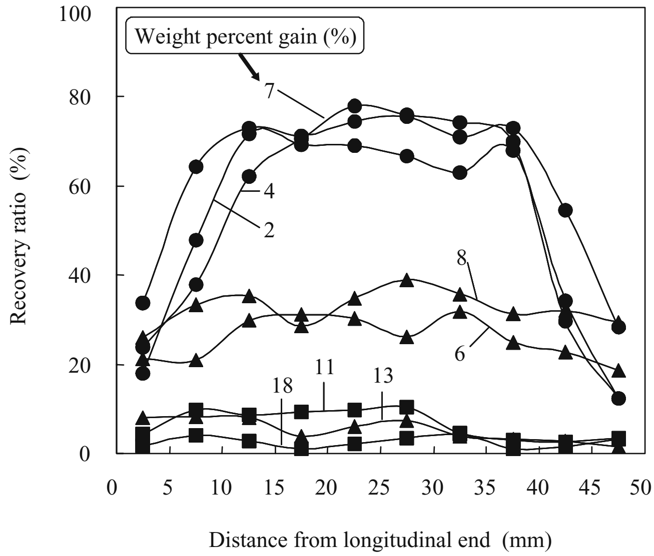

Fig. 8. Examples of the recovery ratio along the longitudinal direction. *Circles*, without drilled holes; *triangles*, with drilled holes (drilling interval, 15 mm; depth, 35 mm); *squares*, with drilled holes (drilling interval, 10 mm; depth, 35 mm). *Numbers* on the figure indicate weight percent gain (%)

Fixation recovery

Figure 8 shows examples of the recovery ratio along the longitudinal direction. The numbers in the figure indicate the weight percent gain. The recovery ratio of specimens with drilled holes and a weight percent gain of 10% or more was suppressed to 10% or less at all parts of the specimens, and the effect of deformation fixation was observed. In the specimens for which the weight percent gain was 10% or less, the deformation recovered to about 30%. However, no difference in the recovery ratio at each part in the specimens with drilled holes was observed; it is judged that the whole of the specimen was treated homogeneously by the resin. On the other hand, the recovery ratio of the specimens without drilled holes was about 80% excluding the area of the end grain. Although this value for the recovery ratio includes the recovery due to swelling after deformation fixation, the recovery was increased further by the boiling test. This result indicates that in the specimens without drilled holes, it is difficult to treat the whole of the specimen with resin homogeneously by both in-liquid platen pressing and vacuum treatment, and deformation fixation of the specimens without drilled holes was not possible.

Conclusions

An aqueous solution of phenolic resin was impregnated through drilled holes, and we manufactured compressed wood with the deformation fixed by the phenolic resin. The methods of impregnation used were in-liquid platen pressing and vacuum treatment. The effect of the drilled holes on solution retention was examined for both methods. The impregnation of resin into the specimens without drilled holes was insufficient for both methods; only part of the specimen was treated by the solution, and the deformation could not be fixed. On the other hand, the impregnation into the specimen with drilled holes was sufficient owing to the improvement of permeability through the drilled holes. A maximum solution retention of 300 kg/m^3 or more was observed in this research, and deformation fixation was observed at all parts of the specimen. The narrower the drilling interval, the greater the solution retention. For in-liquid platen pressing, the longer the soaking time after unloading, the greater the solution retention, because the amount of recovery affected solution retention. Also, solution retention at the soaking time of 10 min was greater than that for vacuum treatment. At the stage of compression to squeeze out the solution from the specimens, the expulsion of the solution through the drilled holes was possible, and the solution retention of each specimen was accurately controlled during compressive deformation. In the specimens without drilled holes, a crack was caused by the hydraulic pressure, which increased with deformation, and the expulsion of the solution was impossible. At the stage of compressive deformation and deformation fixation using a hot press, the specimens without drilled holes could not be processed normally because swelling occurred. However, swelling did not occur in the specimens with drilled holes, and the normal process could be executed because a sufficient amount of resin could be impregnated and the steam could be exhausted through the drilled holes. The specimens after manufacturing had the texture of wood, and no significant discoloration was observed compared with the specimens before impregnation.

The manufactured material can be expected to be of use for exterior wood such as decks making the best use of its characteristics of abrasion resistance, hardness, and weatherability. However, it is feared that the drilled holes influence the mechanical properties. It is necessary to clarify the influence to ensure the reliability of the products. As for the bending strength, the results are to be summarized and reported in the near future.

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