COMPRESSIVE DEFORMATION PROCESS OF JAPANESE CEDAR (*CRYPTOMERIA JAPONICA*)

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ABSTRACT

We examined the compressive deformation behavior, and methods of compression fixation were considered. Furthermore, we examined the mechanical characteristics of compressed wood for each method of fixation and each compression ratio. As a result of the examination, the deformation behavior was found to differ depending on the direction of compression. The deformation progressed without causing destruction in compression into the tangential surface, but compression into the radial surface caused partial buckling of the cell walls in the process of deformation. The compression stress showed the tendency to decrease as the temperature and moisture content increased. Steam treatment by the closed heating method was compared with heat treatment by the open heating method as methods of fixation. The closed heating method was found to be effective for deformation fixation in a short time. As the result of the mechanical properties of compressed wood, the moduli of rupture (MOR) and elasticity (MOE) increased as the compression ratio increased, and they showed the tendency to be roughly proportional to the increase in density. However, hardness increased only nominally up to 40 % compression and then increased rapidly from 40 %. Moreover, in 480-min heat treatment by open heating, the influence of heat deterioration on impact-absorbed energy was found.

Keywords: Compressive deformation, compressed wood, compression fixation, mechanical properties, Japanese cedar.

INTRODUCTION

The accumulation of forest resources such as cedar timber is increasing in the forested areas of Japan. Therefore, the positive use of such resources is greatly desired. Moreover, the development of new technology and new products is required in wood manufacturing. In such a background, we have investigated the compressive deformation process of cedar, which has low density and inferior mechanical properties in general. Compressive deformation is a technology by which the shape of a material is deformed and fixed. By this method, mechanical properties, such as surface hardness and bending strength, can be improved because of an increase in the density owing to a decrease in the size of the cell pores in the case of wood, as has been reported by Norimoto (1993, 1994) and Ito et al. (1995). In the past several years, interest in the compressive deformation process for domestic softwood such as Japanese cedar has been rising.

Regarding the behavior of deformation, systematic measurement of the stress and strain in the radial direction and the recovery behavior have been examined using various types of wood (Norimoto 1993, 1994; Liu et al. 1993, 1995). However, reports on deformation in the tangential direction are few. In this study, we examined the behavior of deformation in the tangential and radial directions. Moreover, we examined the change in mechanical properties with temperature and moisture content. We also investigated the relationships among the method of compression fixation, the fixation conditions, and the physical properties. Up to now, the heat treatment method (Inoue and Norimoto 1991a; Inoue et al. 1993a; Dwianto et al. 1997; Udaka and Furuno 1998), the steam treatment method (Inoue et al. 1993a, 1993b), and resination and chemical treatment (Inoue et al. 1991b; Inoue et al. 1993c; Inoue et al. 1994; Ito and Ishihara 1997; Takasu et al. 1997; Inoue et al. 2000) have been developed as methods of compression fixation. However, the impregnability of the wood presents a problem. Consequently, experimental research on the heat and steam treatment methods has been progressing in recent years (Hayashi et al. 1995; Inoue et al. 1998). Therefore, heat and steam treatment methods were adopted as the fixation methods in this study. The changes in various physical properties for each fixing method and processing conditions have also been examined (Inoue et al. 1998), but changes in mechanical properties with the compression ratio have not, and there is no example of a detailed report to date. In the compressive deformation process, in which strength improves markedly because of a decrease in the size of cell pores, the changes in mechanical properties with the compression ratio are of high interest. Therefore, in this study, we examined the influence of the compression ratio and processing conditions on the mechanical properties.

MATERIALS AND METHODS

Compression test

Specimens of Japanese cedar (*Cryptomeria japonica* D. Don) were cut from one long log. All the specimens were sapwood and they were 25 by 25 by 25 mm (longitudinal by radial by tangential). The specific gravity of the wood was 0.34 (oven-dried gravity). Moisture content was adjusted to wet (over 100%), high (MC 20 ~ 22%), air-dried (MC 10 ~ 12%), and oven-dried (0%) states for each test temperature.

Compression tests were carried out at specified temperatures. Compression was applied in the radial direction with the restriction of tangential deformation and in the tangential direction with the restriction of radial deformation. The restriction was to an extent that did not influence the compressive stress. Compression ratio was 60%; specimens were compressed to 40% of their original thickness. The stress-strain diagram was examined at the loading speed of 5 mm/min. In addition, the stress at 50% compression was determined. The number of specimens was five.

Compression fixation

Specimens of Japanese cedar (*Cryptomeria japonica* D. Don) were cut from one long log. All the specimens were sapwood, air-dried and 300 by 40 mm (longitudinal by tangential). The specific gravity of the wood was 0.36 (oven-dried gravity). The thickness of specimens (radial direction) was made to become 10 mm when compressed according to the compression ratio described in Table 1; the thickness of the specimens for compression ratios of 0, 20, 30,

TABLE 1. *Processing conditions.*

Fixation method	Treatment time (min)	Temperature (°C)	(Saturated steam pressure) (MPa)	Compression ratio (%)
Open				0
heating	120	100		20
		120		30
		140		40
	480	160		50
		180		60
Closed				0
heating	15	100		20
		120	(0.2)	30
		140	(0.4)	40
		160	(0.6)	50
		180	(1.0)	60

40, 50 and 60% were 10.0, 12.5, 14.3, 16.7, 20.0, and 25.0 mm, respectively.

Compression fixation was executed by two methods using a hot-press. Figure 1 shows schematics of the two methods. Figure 1 (a) shows the heat treatment method. It is an open heating method. Specimens are compressed to the prescribed thickness (10 mm) and maintained. Figure 1 (b) shows the closed heating method in which the specimen is sealed in a gasket on the edge of the device simultaneously with the completion of compression (Inoue et al. 1993b). This method makes use of the heat and steam generated from the water that exists in wood. To prevent moisture in the specimen from evaporating, a sufficient amount of steam was fed into

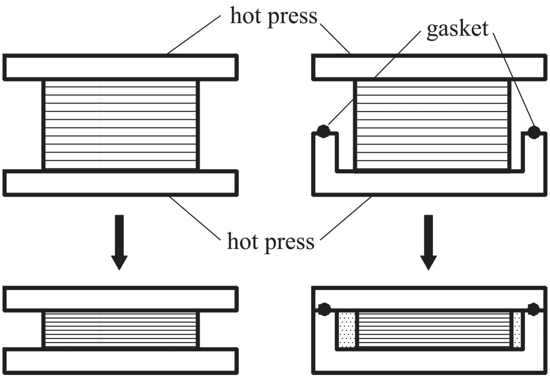

FIG. 1. Heat or steam fixation method. (a) open heating method (b) closed heating method

the device. The internal steam pressure was measured with a pressure gauge, and represents the saturated steam pressure that depends on the temperature because sufficient water is present in this device.

Table 1 shows the processing conditions. A compression ratio of 0% corresponds to the situation that the specimen is not compressed and is in contact with the press side. Heating time is measured starting from the time the center of the specimen reaches a prescribed temperature. The specimen was removed after sufficient cooling by dousing the device with water during pressing.

Specimens of 20- by 40-mm (longitudinal by tangential) dimensions were taken from the compressed wood. Recovery from compression was determined by the following test. The thickness (radial direction) of the specimen was first measured. Then the specimen was soaked in water (25°C) until saturation, placed in boiling water for 1 hour, and then measured for final thickness after oven-drying.

Percentage of recovery (R) was calculated by

$$R = \frac{T_R - T_1}{T_0 - T_1} \times 100(\%), \qquad (1)$$

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

Color test

Color differences were determined using the L-a-b color system on a color difference meter (Nihon Denshoku Co. Ltd. Σ80). The measurement point was 6 mm in diameter in earlywood of the specimen, and the values measured at 6 points were averaged.

Bending test

The specimens used as described below have sufficiently adjusted moisture content at 20°C and 65% relative humidity. All tests were conducted under the same conditions. Specimens of 10 by 10 mm (radial by tangential) were taken from the compressed wood. A single-point bending test was conducted according to JIS Z

2101 (1994). The span of the fulcrum was 140 mm with a loading speed of 10 mm/min. Load was applied to the radial surface. MOR and MOE were calculated. Three specimens were tested under each set of test conditions.

Hardness test

The Brinell hardness test was conducted according to JIS Z 2101 (1994). A 10-mm diameter steel ball was imbedded into the tangential surface at a loading speed of 0.5 mm/min to a depth of 0.32 mm. Hardness was measured at 6 locations in the earlywood at the surface, and the results were averaged.

Impact bending test

Specimens of 10 by 10 by 60 mm (radial by tangential by longitudinal) were taken from the compressed wood. Impact-absorbed energy was determined using a Charpy impact testing machine (Shimadzu Co. Ltd. 50J Impact Testing Machine). The span of the fulcrum was 40 mm. Load was applied to the radial surface. Five specimens were tested under each set of test conditions.

RESULTS AND DISCUSSION

Compressive deformation behavior

Figure 2 shows the compressive stress-strain diagram at 20°C. When the tangential surface was compressed (○), the stress increased linearly with the increase of strain. The deformation progressed almost constantly stress increase after yielding. Then the stress increased rapidly from a compression ratio of about 50%. Deformation up to 40 ~ 50% is a result of the reduction of the size of cell pores owing to the deformation of the cell wall, as determined by fractography. The rapid increase of the stress from about 50% depends on the contact between deformed cell walls. Next, when a radial surface was compressed (□), the stress at the yielding point was considerably large compared with that in the compression of the tangential surface.

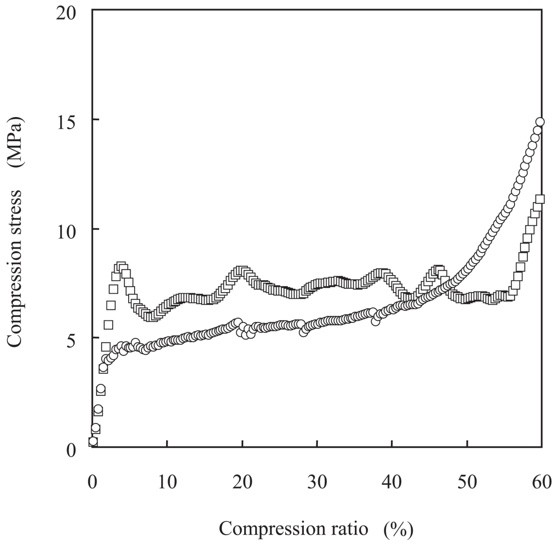

FIG. 2. The stress-strain diagram with lateral restriction at 20°C. Legend: ○ compressed into the tangential surface □ compressed into the radial surface

However, partial buckling occurred in the process of deformation. When the buckling occurred repeatedly, the stress temporarily declined.

Compression stress

Figure 3 shows the relationship between temperature and stress at 50% compression. Hereafter, the error bar in the figure indicates the range between the maximum and the minimum value. With the rise of temperature, mechanical properties may decrease because of the decrease of the cohesive force. Therefore, the compression stress decreased under all conditions as the temperature rose. For lignin and hemicellulose in wood, plasticity increases dramatically for 77 ~ 128°C and 54 ~ 142°C, respectively, in the state of high moisture content (Goring 1963). Therefore, the decrease in stress is more marked at a high moisture content.

Effect of fixation

Figure 4 shows the relationship between treatment temperature and recovery rate. The com-

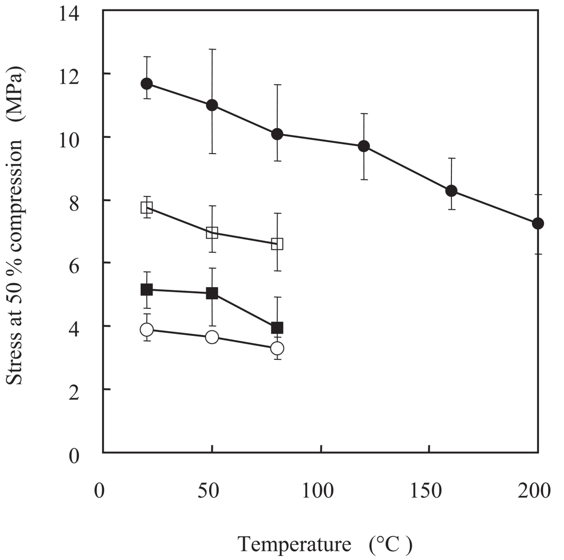

FIG. 3. Relationship between temperature and stress at 50% compression. Legend: ● oven-dried □ air-dried (MC 10 ~ 12%) ■ high moisture content (MC 20 ~ 22%) ○ wet (MC over 100%) Note: Stress was applied in the radial direction with the restriction of tangential deformation.

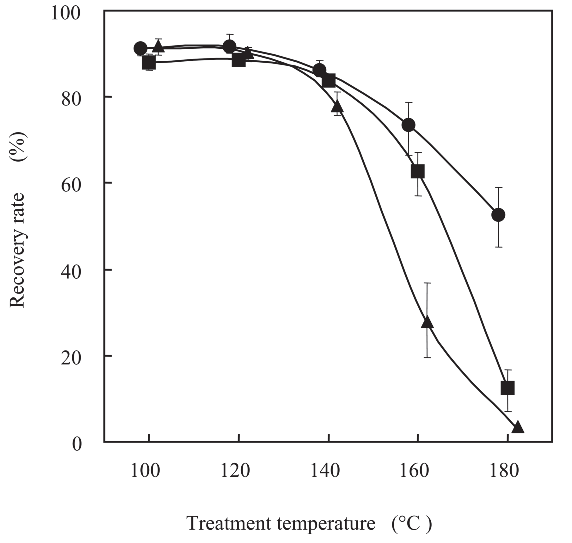

FIG. 4. Relationship between treatment temperature and recovery rate. Legend: ● open heating 120 min ■ open heating 480 min ▲ closed heating 15 min Note: compression ratio, 50%

pression ratio was 50%. Similar tendencies could be seen at other compression ratios, and the recovery rate was independent of the compression ratio. The effect of fixation became visible at 160°C or higher. In particular, the recovery decreased greatly in the closed heating method (▲), and approached almost 0% at 180°C. In contrast, a sufficient effect of fixation could not be achieved after 2 hours of treatment by the open heating method (●). The recovery rate became almost 0% when the specimen was treated for 8 hours (■) by the open heating method at 180°C. In steam treatment by the closed heating method, fixation was achieved in a short time compared with the open heating method.

Change in color

Specimens became discolored brown by the fixation process. The relationship between treatment temperature and color difference is shown in Fig. 5. The compression ratio was 50%. Similar results were obtained with other compression ratios, and the color difference was independent of the compression ratio. The color difference increased as the heating temperature rose, or as heating time lengthened. However, the color only nominally changed below 140°C. Regard-

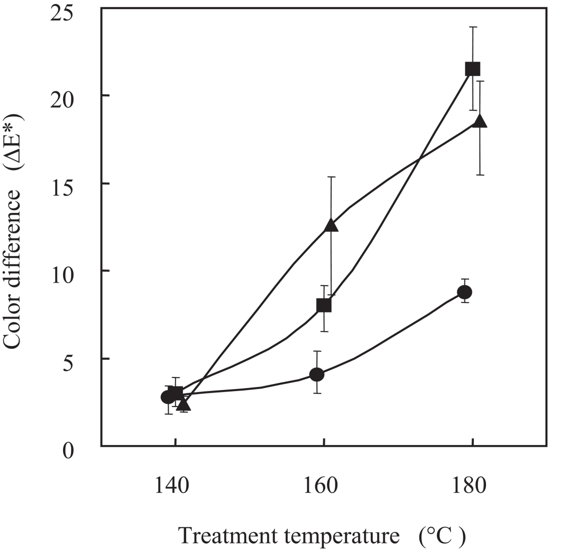

FIG. 5. Relationship between treatment temperature and color difference. Legend and Note: (same as FIG. 4)

ing the heating time, it has been revealed that the closed heating method caused extreme discoloration in a short time.

Mechanical properties of compressed wood

Generally, the strength of wood tends to increase as the density increases. Therefore, it is expected that the strength of compressed wood will increase in proportion to the compression ratio. The relationships of compression ratio with MOR and MOE are shown in Figs. 6 and 7, respectively. Both MOR and MOE increased as the compression ratio increased, and showed the tendency to be roughly proportional to the density under each set of fixation conditions. Figure 8 shows the relationships between compression ratio and hardness. Hardness showed almost the same tendency as MOR and MOE under all fixation conditions. However, the hardness increased negligibly up to 40% compression and rapidly above 40% compression; hardness was not exactly proportional to density. In Fig. 2, the deformation up to 40 ~ 50% compression was considered to be due to the reduction in the size of cell pores, and the rapid increase from about

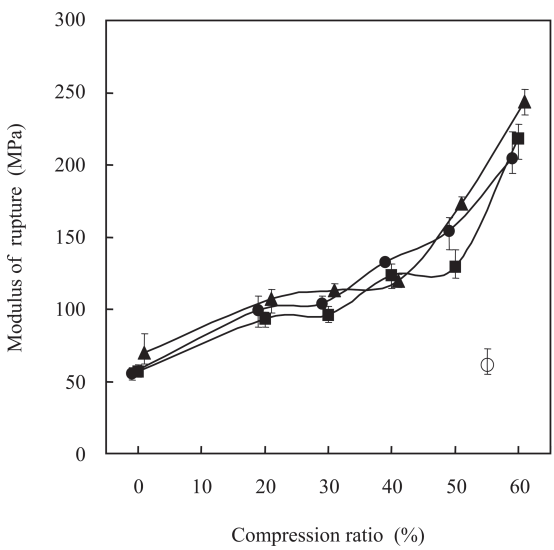

FIG. 6. Relationship between compression ratio and modulus of rupture. Legend: ● open heating 120 min ■ open heating 480 min ▲ closed heating 15 min ○ control (compression ratio, 0%) Note: treatment, 180°C

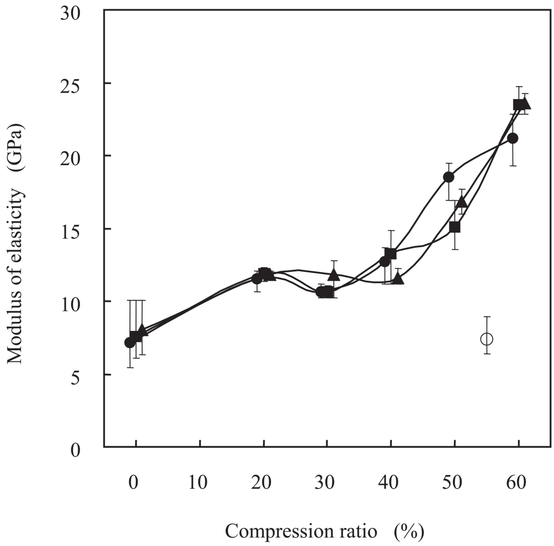

FIG. 7. Relationship between compression ratio and modulus of elasticity. Legend and Note: (same as FIG. 6)

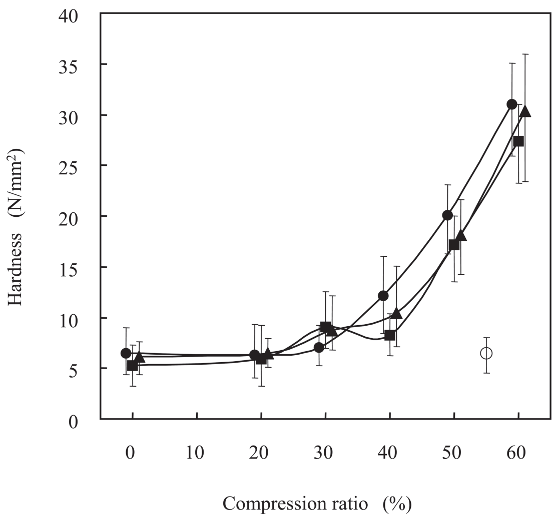

FIG. 8. Relationship between compression ratio and hardness. Legend and Note: (same as FIG. 6)

50% compression depended on the contact state of the cell wall. Generally, it is thought that the hardness increases proportionally to the rigidity of the cell wall. In this experiment, the range up to 40% compression is thought to be the reduction stage of cell pore size, and the hardness depends on the rigidity of the cell wall. Therefore, it is thought that an increase with density would not be seen. On the other hand, in the range above 40% compression, cell walls are in mutual contact or extremely close to each other. Therefore, the hardness increases rapidly above 40% compression.

Next, the relationship between compression ratio and impact-absorbed energy is shown in Fig. 9. Impact-absorbed energy increased as the compression ratio increased, excluding the case of the 480 min open heating method. The impact-absorbed energy at 0% compression in the 480 min open heating process was lower than the control value (○), and the increase in impact-absorbed energy with increasing compression ratio was less than those under the other two sets of conditions. Then, the impact-absorbed energy at each temperature was examined because the heat deterioration should be considered in these results. Figure 10 shows the relationship between treatment temperature and impact-absorbed energy. The impact-absorbed energy in the 480-min open heating process decreased greatly compared with those in the other two processes as the temperature rose, and it became about half the control value (○) at the 0% compression ratio (□) at 180°C. The heat deterioration is considered as the factor that the impact-absorbed energy decreased with increasing temperature in the 480-min open heating process.

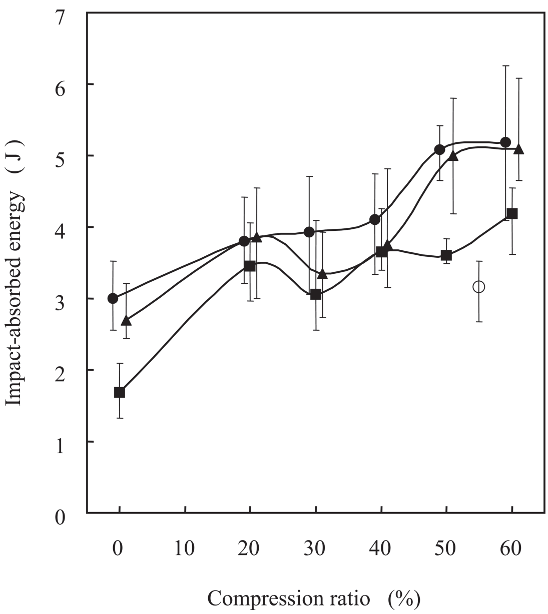

Fig. 9. Relationship between compression ratio and impact-absorbed energy. Legend and Note: (same as Fig. 6)

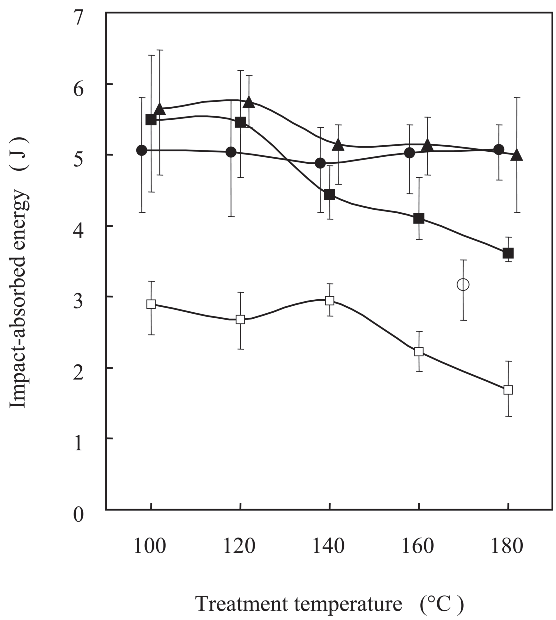

Fig. 10. Relationship between treatment temperature and impact-absorbed energy. Legend: ● open heating 120 min ■ open heating 480 min □ open heating 480 min (compression ratio, 0%) ▲ closed heating 15 min ○ control (compression ratio, 0%) Note: compression ratio, 50%

CONCLUSIONS

In this study, the compressive deformation behavior of Japanese cedar was examined for the purpose of manufacturing compressed wood, and the methods of compression fixation were examined. Furthermore, some mechanical properties of compressed wood were examined.

Deformation behavior differed according to the compressed direction. The deformation progressed without causing destruction in compression into the tangential surface. In contrast, compression into the radial surface caused partial buckling in the process of deformation. The compression stress showed a tendency to decrease as the temperature and moisture content rose.

Next, the methods of compression fixation were examined. The closed heating method was found to fix the deformation well in a short time. The specimen became discolored brown by heat or steam treatment in the fixing process, and the color difference increased above 140°C. In particular, it was revealed that discoloration advances in a shorter time in the closed heating process compared with the open heating process.

The moduli of rupture and elasticity increased as the compression ratio increased, and they showed the tendency to be roughly proportional to density. However, the hardness only slightly increased up to the 40% compression ratio, and then subsequently increased suddenly. The impact-absorbed energy did not increase proportionally to the compression ratio for 480-min open heating, unlike in the other processes. In short, the impact-absorbed energy decreased because of heat deterioration in 480-min open heating.

This work clarified the features of compressive deformation of Japanese cedar, and useful findings on the processing conditions necessary to achieve the desired mechanical properties were obtained.

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