Permanent Fixation of Radially Compressed Bamboo in Dry Condition by Heating and Its Mechanism

Bambang Subiyanto[1)], Wahyu Dwianto[1)], Takashi Higashihara[2)], Toshiro Morooka[2)], Misato Norimoto[2)]

[1)] R & D Unit for Biomaterials, Indonesian Institute of Science (LIPI), Jl. Raya Bogor Km.46, Cibinong, Bogor 16911, Indonesia
[2)] Research Institute of Sustainable Humanosphere (RISH), Kyoto University, Uji, Kyoto 611-0011, Japan

Corresponding author: subiyanto@cbn.net.id (Bambang Subiyanto)

Abstract

The stress-strain relationship and stress relaxation of oven-dried bamboo in radial compressed by heating were investigated. The effect of heating temperature and time on the weight loss, residual stress and strain recovery were also examined. The results indicated that the apparent of stress-strain curve (SS-curve) of Indonesian bamboo was different with Mousou bamboo and Sugi wood. The apparent SS-curve of Mousou bamboo was same as general SS-curve of wood under heating. The effect of heating temperature on yield stress of oven-dry bamboo had different results with the Sugi wood. The yield stress of bamboo decreased slightly up to heating temperature of 140 °C, then it was significantly decreased with increasing temperature. The decreasing yield stress of bamboo at heating temperature above 140 °C could be due to degradation or decomposition of existing extractive component and hemicelluloses in bamboo by heating. Time to achieve stress relaxation decreased with increasing heating temperature. The stress relaxation of bamboo was attained faster than that of Sugi wood. Tali bamboo had a fastest to attain stress relaxation than others type of bamboo. The residual stress and strain recovery decreased with decreasing weight loss. The most interesting finding was residual stress of Indonesian bamboo (Gombong and Tali bamboos) was attained zero and stress recovery less than 0.2 when the weight loss at about 4%.

Key words: bamboo**,** permanent fixation, stress-strain.

Introduction

The information on basic properties of bamboo for supporting higher utilization of such materials are still lacking especially those related to softening behavior, characteristic value, deformations and setting of compressed conditions is necessary. However, the softening behavior and the fixation of compressive deformation of wood have been studied and widely reported (Inoue *et al*. 1993, Inoue *et al*. 1996, Furuta *et al*. 1997, Dwianto *et al*. 1998, Takahashi *et al*. 1998, Dwianto *et al*. 1999, Dwianto *et al*. 2000, Higashihara *et al*. 2000, Higashihara *et al*. 2001). The research focusing on softening and the fixation of compressive deformation of bamboo has not been conducted yet due to the presence of high strength matrix in the cell wall of bamboo. Such matrix affected the difficulties in the measurements of softening parallel to the grain. The research on bamboo softening in radial axes with oven-dried condition was reported (Subiyanto *et al*. 2000). Subsequently, the fundamental technologies on dimensional stabilization and high technological processing of bamboo will also be discussed through combined analysis of the above mechanisms. The object of this study was to examine the mechanism and permanent fixation of compressed bamboo in oven-dry condition by heating for two species Indonesian bamboos and one species Japanese bamboo.

Materials and Methods

Preparations of specimens

Three bamboo species namely gombong (*Gigantochloa pseduarundinaceae*) and tali (*Gigantochloa apus*) from Indonesia and mousou (*Phyllostachys heterocycla*) from Japan were used as materials. As a comparison, a Japanese sugi wood (*Cryptomeria japonica* D. Don) often used as raw material on the research of softening mechanism of wood (Inoue *et al*. 1993, Inoue *et al*. 1996, Furuta *et al*. 1997, Dwianto *et al*. 1998, Takahashi *et al*. 1998, Dwianto *et al*. 1999, Dwianto *et al*. 2000, Higashihara *et al*. 2000, Higashihara *et al*. 2001). In succession, the average density of gombong, tali, mousou and sugi were 0.81, 0.83, 0.71, 0.31 g cm^{-3}, respectively. Specimens were crosscut from fresh bamboo culm in 25 mm length without node and then convert to bamboo strip in 20 mm width. For conditioning, specimens were dried in the oven at 60 °C until the moisture content reach to 12% and then cut into a size of (6 x 12) mm^2 (radial by tangential). For the specimen, two dried specimens with the similar density were bonded each other using epoxy adhesive and cut into the size of (10 x 10 x 10) mm^3.

Measurement of stress-strain relationship

A testing machine (Shinkoh TOM 5000X) equipped with hot plates was used for stress-strain relationship (SS-curve) measurement. The oven-dry specimen was compressed in the radial direction at a constant strain rate of 10 mm min^{-1}. The load and deflection of each specimen were measured at temperature of 20, 60, 100, and 140 to 240 °C with an interval of 20 °C to obtain the SS-curve. At temperature between 20 to 100 °C, the compressions were performed for specimens placed in a water bath controlled at constant temperatures by using a standard mechanical testing machine (Shimadzu AG-5000E) the yield stress was obtained from the SS-curve, which in this experiment defined as stress at crossing point between linear line of elastic and plastic area.

Measurement of stress relaxation

The oven-dried specimens was compressed in the radial direction to the strain of 25% (7.5 mm) with a constant strain rate of 10 mm min^{-1} using a testing machine (Shimadzu AG 5000E) equipped with hot plates. Stress relaxation was performed at the temperature of 140, 160, 180 and 200 °C. The weight and the thickness of specimen were measured before and immediately after the measurement of the stress relaxation. The weight loss (WL) was determined as the difference of such weights. After the measurement, specimens were soaked in water at room temperature under vacuum pressure for 2 hours, and released the pressure for 2 hours; finally the specimens were dried at temperature of 105 °C for 24 hours. For each process, the thickness and weight of specimens were measured. From the thickness measurement, the recoveries of compressive deformation (recovery of set = SRw) of the specimens were obtained (Inoue *et al.* 1993).

Results and Discussion

Figure 1 shows the effect of temperature on SS-curve of bamboo in oven-dry condition. The effect of temperature on SS-curve of gombong and tali bamboo (Indonesian bamboo) is apparently different in SS-curves from those of mousou bamboo. For both of Indonesian bamboos the linear elastic region, which is clearly visible below 100 °C, becomes less distinct above 100 °C. The slope of linear elastic region decreased more in gombong bamboo than in other type of bamboos when heating temperature more than 100 °C. The cause of differences appearing in SS-curves of Indonesian bamboos and Japanese bamboo remains unsolved. It may be due to difference in chemical component between these bamboos. The behavior of SS-curve for mousou bamboo is almost the same as that of wood. It should be noted, however, that the slope of linear-elastic line at above 180 °C decreases drastically when compared with those of wood. This may be due to differences of microstructure and chemical components of bamboo and wood.

Figure 2 shows temperature variation of normalized yield stress of bamboos in oven-dry condition. Tali had a greater yield stress than other type of bamboos in the whole temperature range examined. The yield stress of bamboos decreased slightly up to heating temperature of 140 °C, and then it significantly decreased with increasing temperature. This yield stress SS-curve of bamboos had a different with the wood when heating temperature above 160 °C. The most interesting finding is that the yield stress began to decrease drastically at around 160-180 °C for bamboos, however, no decreasing for Sugi wood. The decrease of yield stress above such region is thought to be due to degradation or decomposition of bamboos chemical component by heating.

To examine the decomposition of chemical component of bamboo, behavior of bamboo was measured using TGA (thermal gravimetric analysis). In an effort to further elucidate the significance of this observation, TGA measurements were made for powdered samples of bamboo after boiling for 2 hours to eliminate extractive components. Table 1 shows the beginning temperatures of the decomposition for untreated and treated bamboo determined from TGA measurements.

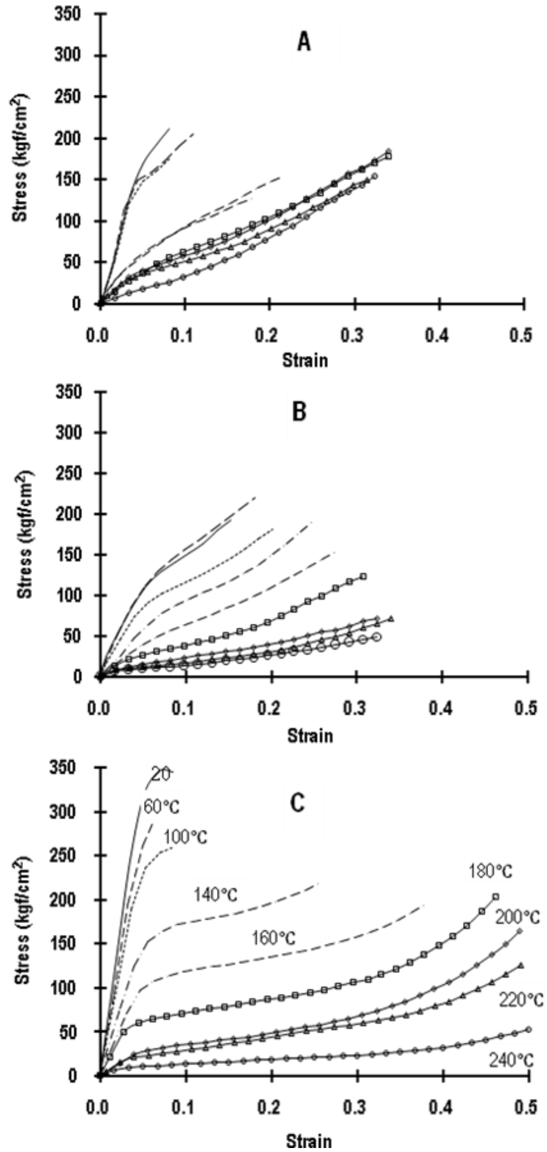

Figure 1 The effect of temperature on stress-strain curve of bamboo. A: Gombong bamboo; B: Tali bamboo; C: Mousou bamboo.

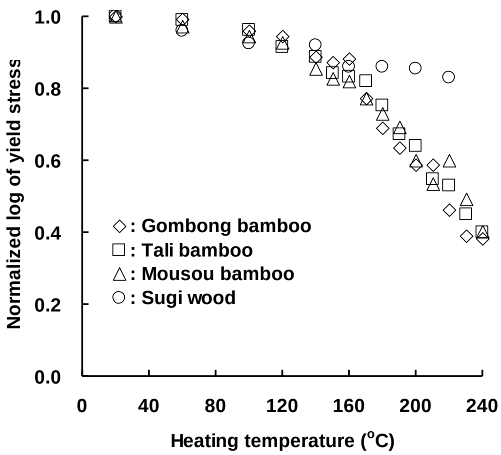

Figure 2 Effect of heating temperature on normalized yield stress for bamboos in oven-dry condition.

Table 1 Temperature on the beginning decomposition of untreated and treated bamboo based on TGA measurement

Type of material	Untreated (°C)	Treated (°C)
Mousou bamboo	151.50	225.60
Gombong bamboo	168.53	228.90
Tali bamboo	152.01	231.08

The beginning of the decomposition of chemical component in bamboo occurred at temperature above 150 °C. As shown in Table 1, the beginning temperatures of the decomposition treated bamboo are significantly higher than those of untreated one. This means that existing of extractive in the bamboo play a more significant role in the softening of oven-dry bamboo in relation with SS-curve of bamboo. It was found that temperature on the beginning decomposition of untreated bamboo was occurred at heating temperature around 150 °C for tali and mousou bamboo, and at 168 °C for gombong bamboo. Then temperature on the beginning decomposition increased to more than 225 °C when the extractive removed from the bamboo. This means that the significantly decreasing of yield stress of bamboo at around heat temperature of 140 °C to 160 °C caused existing of extractive in the bamboo.

Figures 3 and 4 shows the stress relaxation and its normalized curves of oven-dry bamboos in compression under heating temperature of 140 °C and 160 °C, respectively. The density of bamboos had higher than those of sugi wood causing the initial stress for bamboos shows higher than sugi wood. The curve of all type of bamboos shows different with sugi wood. The stress relaxation of all type of bamboos showed faster than that of sugi wood. The heating temperature of 140 °C, the stress relaxation zero could not attain even though the heating time up to 24 hours. In the heating temperature of 160 °C, the result shows that the heating time to attained stress relaxation zero for gombong, Tali and mousou of 13.40, 13.16, and 19.06 hours, respectively.

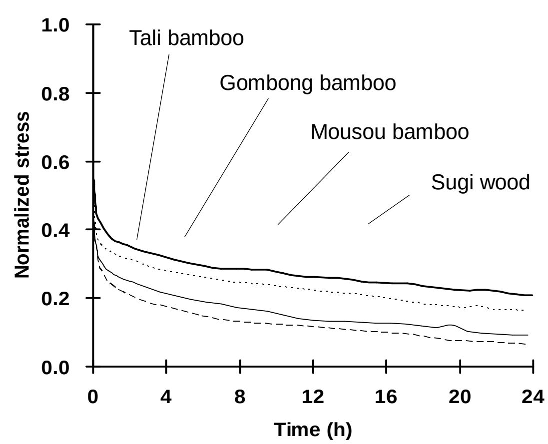

Figure 3 Normalized of stress relaxation curves of oven-dry bamboo in compression under heating temperature of 140 °C.

The stress relaxation showed faster in tali bamboo than in the others type of bamboos. In the other hand, the stress relaxation for sugi wood could not attain zero even though the specimens pressed for 24 h. The differences trend of stress relaxation between bamboo and sugi may be causing existing higher content of extractive in the bamboo than that of in sugi wood. Previous study (Subiyanto *et al*. 2000) reported that difference in the beginning temperature of the decomposition between bamboo and wood had a difference in extractives.

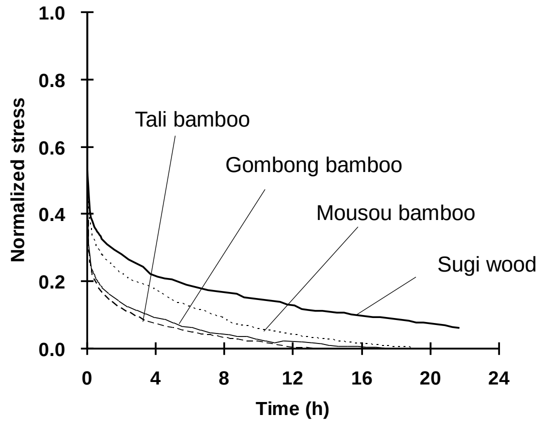

Figure 4 Normalized of stress relaxation curves of oven-dry bamboo in compression under heating temperature of 160 °C.

The curves of stress relaxation for all type of oven-dry bamboos in compression under heating temperature of 180 and 200 °C shows same trend with the heating temperature of 160 °C (Figure 5 and 6). However, the stress relaxation zero was occurring faster at higher than low temperature. The stress relaxations under heating temperature of 180 °C were occurred within 3.38, 2.80, 3.85 and 13.45 hours, for gombong, tali, mousou bamboos, and sugi wood, respectively. The stress relaxations under heating temperature of 200 °C were occurred within 0.85, 0.76, 1.72 and 4.05 hours, for gombong, tali, mousou bamboos and sugi wood, respectively. In the range of heating temperature, the bamboo had a faster to attained stress relaxation zero than that in wood. In addition, tali bamboo had a fastest attained stress relaxation zero than others type of bamboos, because the temperature on the beginning decomposition of tali bamboo was occurred in the lower temperature than in the gombong bamboo.

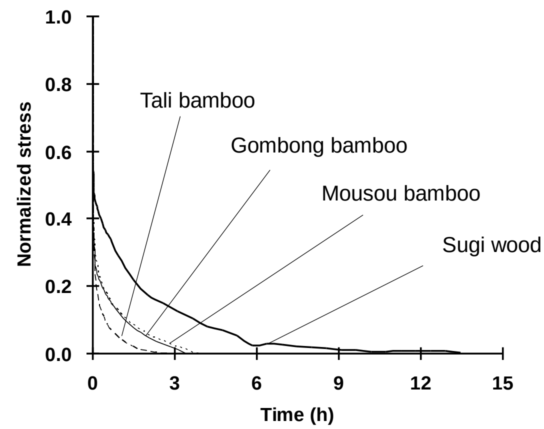

Figure 5 Normalized of stress relaxation curves of oven-dry bamboo in compression under heating temperature of 180 °C.

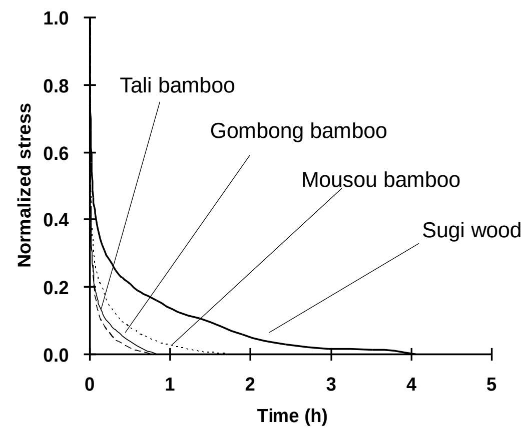

Figure 6 Normalized of stress relaxation curves of oven-dry bamboo in compression under heating temperature of 200 °C.

Figure 7 to 10 show relationship between weight loss and heating time of tali, gombong, mousou bamboos, and sugi wood under various heating temperature. The relationship between weight loss and heating time of gombong and mousou bamboos under various heating temperature was almost the same in tali bamboo. The effect of heating condition on the weight loss of tali bamboo shows that the weight loss increased with increasing temperature and heating time. When the heating temperature less than 160 °C, there was a relatively slow escalating trend of the weight loss.

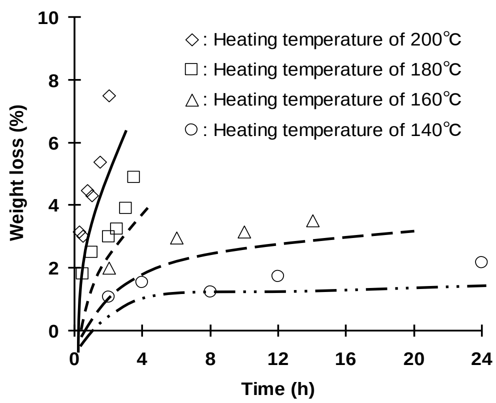

Figure 7 Relationship between weight loss and heating time of Tali bamboo under various heating temperature.

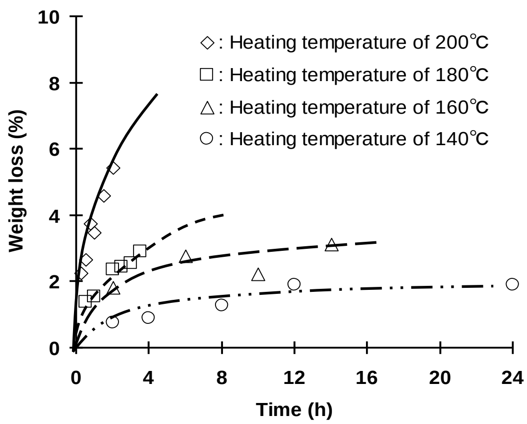

Figure 8 Relationship between weight loss and heating time of Gombong bamboo under various heating temperature.

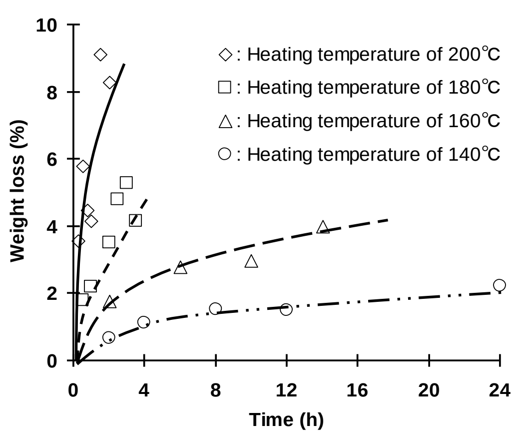

Figure 9 Relationship between weight loss and heating time of Mousou bamboo under various heating temperature.

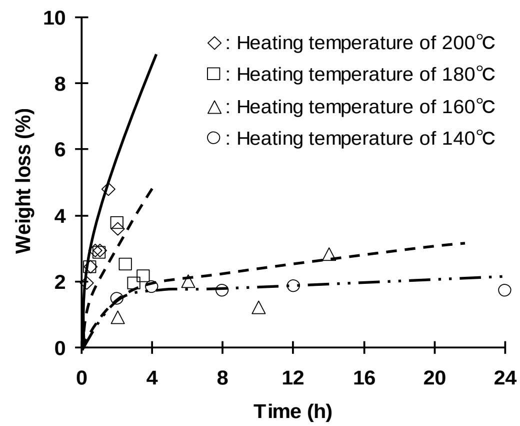

Figure 10 Relationship between weight loss and heating time of Sugi wood under various heating temperature.

The weight loss increased significantly at above 160 °C heating temperature. The heating temperature had a much greater effect on weight loss than did the heating time. At the same heating time, a higher heating temperature resulted more weight loss, especially when heating temperature was above 160 °C. In addition, the weight loss increased more in tali and mousou bamboos than in gombong bamboo. This means that much more of the extractive was removed tali and mousou bamboos due to the lower the temperature on the beginning decomposition of tali and mousou bamboo than that in gombong bamboo. The weight loss of sugi wood significantly increased below 180 °C heating temperature.

Figure 11 to 14 show relationship between recovery of set (SRw) and heating time of tali, gombong, mousou bamboos, and sugi wood under various heating temperature. The SRw is one of indication to describe of fixation of compressed materials. The trends of relationship between SRw and heating time of tali bamboo under various heating temperature for other type of bamboos was almost the same in tali bamboo. The effect of heating condition on the SRw of the tali bamboo shows that the

SRw decreased with increasing temperature and heating time. When the heating temperature less than 160 ^{o}C, there was a relatively slow declining trend of the SRw. The SRw decreased significantly at above 160 ^{o}C heating temperature. The heating temperature had a much greater effect on SRw than did the heating time. At the same heating time, a higher heating temperature resulting lower SRw, especially when heating temperature was above 160 ^{o}C as shown in Figure 10. In addition, the SRw decreased more in tali bamboo when heating temperature above 140 ^{o}C than in gombong and mousou bamboos. At heating temperature of 140 ^{o}C, the SRw of tali bamboo significantly decreased when heating temperature more than 12 h. This may due to the decomposition of chemical component of bamboo in inner part as reported in the previous report.

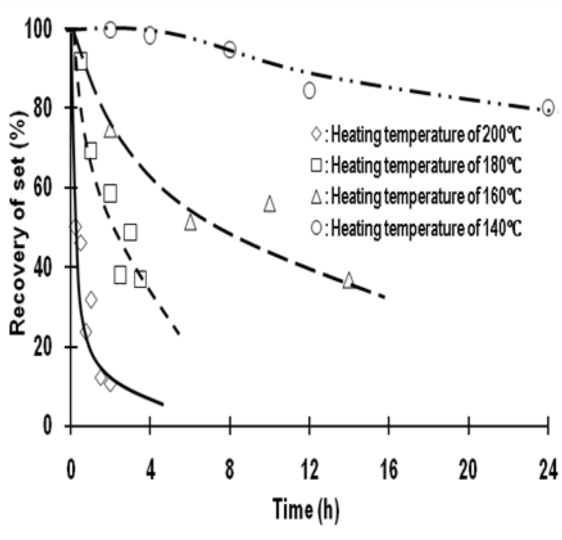

Figure 11 Relationships between recovery of set and time for gombong bamboo in various heating temperature.

Figure 11 and 12 shows the relationship between strain recovery in dipping water (SRw) and weight loss of gombong and mousou bamboos in oven-dry condition, respectively. The trends of relationship between SRw and weight loss of tali bamboo under various heating temperature was almost the same in gombong bamboo. The SRw of bamboo decreased with increasing weight loss. When weight loss was up to 4%, there was a drastically declining, and then weight loss more than 3%, there was a relatively slow declining of SRw for gombong and tali bamboos. This tendency was little difference with the mousou bamboo and sugi wood, the SRw of gombong and tali bamboos were more significantly decreased than those of mousou bamboo and sugi wood. The heating temperature had a much effect on the weight loss and strain recovery. The weight loss and strain recovery decreased with increasing heating temperature. This means that much more extractives were decomposed and removed during heating treatment. The extractive component of bamboo play a more significant role in decomposition of it chemical component during heating.

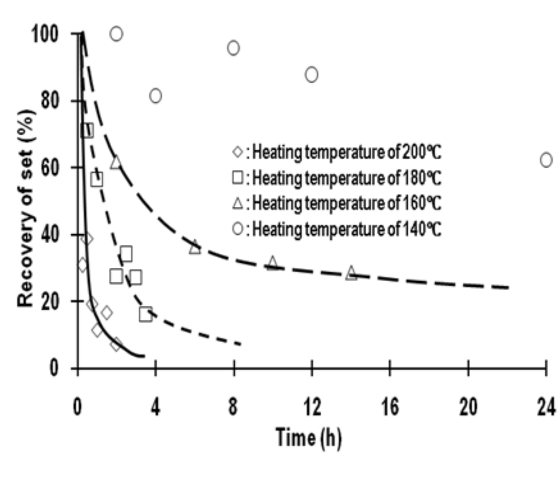

Figure 12 Relationships between recovery of set and time for tali bamboo in various heating temperature.

Figures 13 and 14 shows the relationship between residual stress and weight loss of oven-dry gombong, and mousou bamboos, respectively. The trends of relationship between residual stress and weight loss of tali bamboo under various heating temperature was almost the same in gombong bamboo. The residual stress was reduced with increasing weight loss. When weight loss was up to 3%, there was a drastically declining, then, weight loss more than 3%, there was a relatively slow declining of residual stress for gombong and tali bamboos. This tendency was little difference with the mousou bamboo and sugi wood, in the gombong and tali bamboos were lower of weight loss to attained zero of residual than those of mousou bamboo and sugi wood. The effect of heating condition on the residual stress of all type of bamboos shows that the residual stress decreased with increasing heating temperature.

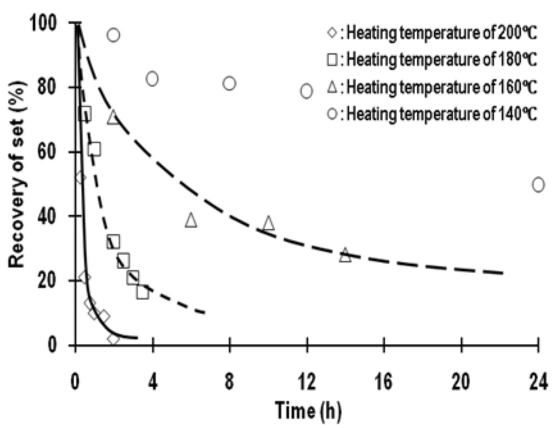

Figure 13 Relationships between recovery of set and time for mousou bamboo in various heating temperature.

From the figures of relationship between weight loss and residual stress, and SRw, it was found that the range of weight loss more than 3 % were significantly reduced residual stress and SRw of oven-dry gombong and tali bamboos. The stress relaxation attained zero and SRw less than 0.2 was observed when weight loss more than 4% for gombong and tali bamboo.

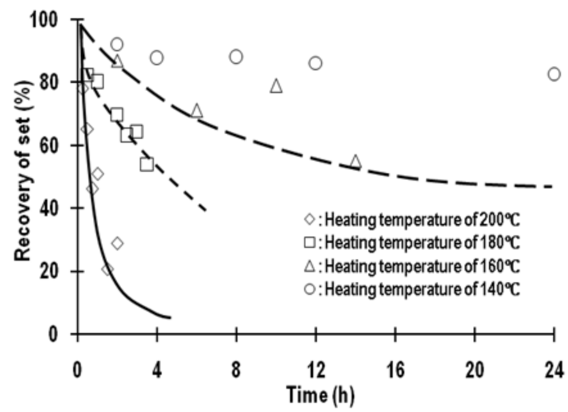

Figure 14 Relationships between recovery set and time for sugi wood in various heating temperature.

However, this trend different with oven-dry mousou bamboo and sugi wood, the residual stress relaxation was occurred and SRw less than 0.2 were observed when weight loss more than 8% for mousou bamboo. In the condition of oven-dry bamboo, decomposition of extractive component plays a more significant in the stress relaxation and SRw of bamboo as reported in the previous paper. This means that heating treatment for Gombong and Tali bamboos caused decomposition of chemical component of bamboo.

Conclusions

The apparent of stress-strain curve (SS-curve) of Indonesian bamboo was different with mousou bamboo and sugi wood. The apparent SS-curve of mousou bamboo was same in general SS-curve of wood under heating. The effect of heating temperature on yield stress of oven-dry bamboo had different results with the sugi wood. The yield stress of bamboo decreased slightly up to heating temperature of 140 °C, then it was significantly decreased with increasing temperature. The decreasing yield stress of bamboo at heating temperature above 140 °C could be due to degradation or decomposition of extractive component and hemicelluloses in bamboo by heating.

The heating conditions had significant effect on the stress relaxation of oven-dry bamboos. Time to achieve stress relaxation decreased with increasing heating temperature. The stress relaxation curves of bamboo were different with the sugi wood, stress relaxation of bamboo was attained faster than sugi wood. The tali bamboo had a fastest was attained stress relaxation than others type of bamboo.

The residual stress and strain recovery (SRw) decreased with decreasing weight loss. The most interesting finding is that Indonesian bamboo (gombong and tali bamboos) the residual stress was attained zero and stress recovery less than 0.2 when the weight loss at about 4%.

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