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Original Article

High-Temperature Drying of Bamboo Tubes Pretreated with Polyethylen Glycol Solution[1]

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ABSTRACT

This study was conducted to develop a new drying technology in order to quickly and massively dry bamboo tubes without crack and check. The bamboo tubes with the diameter of 45 mm - 68 mm had been impregnated in the solution of PEG-1000, and then were dried under room temperature and high temperature, respectively. The cracks occurred on all control specimens while no cracks were found on PEG treated specimens during drying at room temperature due to effect of PEG restraining the circumferential shrinkage of bamboo tube. But the drying period of this method was too long (200 days) compared to 10 hours of kiln drying. During fast high temperature drying, cracks occurred on all control specimens, but no cracks were found on PEG treated specimens, which could be accounted for more solidified PEG due to higher drying temperature and faster drying rate, and the tension set formed on the surface of bamboo tube in the early stage of drying owning to high drying temperature and low relative humidity. Thus, it is advised that PEG treated bamboo tube should be fast dried at high temperature in order to not only prevent crack or check in short drying period but also increase the dimensional stability of the products made of bamboo tubes.

***Keywords*:** bamboo tubes, Polyethylene Glycol treatment, high temperature drying, percentage of Polyethylene Glycol retention, sorption isotherm

1. INTRODUCTION

Bamboo tubes generally have been slowly dried under well-ventilated shade. Such air drying method needed long drying period and inevitably incurred the cracks on large bamboo tube due to uncontrollable drying condition outside. Traditionally, the bamboo instruments such as danso (a short bamboo flute) and daegeum (a long bamboo flute) etc. were well-developed in Korea. Recently the mobile phone cradle with amplification functions using bamboo tube was developed (Fig. 1). In order to develop such high valued bamboo crafted products, a new drying technology to quickly, massively dry bamboo tubes without defects is

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needed to be developed.

One of drying methods to reduce the drying defects of wood was Polyethylene Glycol (PEG) drying method. PEG drying method has been used to reduce the drying defects, that often occurred during air drying and other artificial drying methods, of wood, especially, surface check, because the shrinkage of cell wall was restrained due to PEG penetrating into wood cell wall (Alma *et al*., 1996; Hardley, 2000; Mackay, 1972; Stamm, 1959). It was found out that after the water molecules were forced out because the hydroxyl group of cellulose in wood cell wall was easily combined with oxygen of ether due to PEG as a water-bone nonionic surface active agent, PEG in cell wall restrained shrinking of cell wall so that the crack or check on the surface of wood could be prevented (Ralph, 2006). It was important to improve the penetration rate of PEG in order to prevent surface checks. There should be free water in wood so that the mutual interchange between the free water and the solution of PEG was arisen to well happen penetration because of the water solubility of PEG (Loughborough, 1948). It was found that penetration rate was effected by the specific gravity of wood (Hong *et al*., 2013; Ralph and Edwards, 2004), and increased with increasing temperature (Yamaguchi *et al*., 1999). It was reported that wood cell wall selected low molecular weight of PEG to be penetrated from several molecular weight of PEG (Jeremic and Cooper, 2009). Wallstrom and Lindberg (1995) reported that the weights of specimens were increased by 20 percent after PEG-1500 was impregnated into *Pinus sylvestris* blocks by vacuum/pressure processes. However, only a little low molecular weight of PEG penetrated into cell walls resulting their expansion were barely recognizable. They concluded that low molecular weight of PEG was necessary to penetrate into cell wall. Mueller and Steiner (2010) insisted that PEG treatment was effective to reduce the color change of wood, especially, low molecular weight of PEG. Hoadley (2000) found out that the weight of 1000 was most suitable to prevent the surface checks of wood.

Fig. 1. Mobile phone cradle with amplification functions using bamboo tube.

There were differences in the strength between PEG treated wood and control wood. Bjurhager *et al*. (2010) reported that the tensile Modulus of Elasticity of the *Quercus robur* L.treated with PEG-600 in the longitudinal direction was slightly effected while the compressive Modulus of Elasticity was reduced by 50 percent in the radial direction, and that there was no difference in the tensile Modulus of Elasticity in the longitudinal direction while there was a great difference in the compressive Modulus of Elasticity in the radial direction under the different PEG concentration. This was due to the strength being lowered because the ray tissue was accumulated with more PEG

Table 1. Drying schedule used for drying bamboo tubes

Step	Drying time (hr)	T_{db} (℃)	T_{wb} (℃)	EMC (%)
1	0	20.0	Off	-
2	5	120.0	Off	-
3	20	120.0	Off	-
4	25	65.5	46.0	5.0
5	35	65.5	46.0	5.0
6	45	20.0	Off	-

when PEG concentration was higher.

Although researches on PEG treated wood have been extensively conducted, researches on PEG treated bamboos have been few. Therefore, this study was conducted to develop a new drying technology in order to quickly and massively dry bamboo tubes without crack and check applying PEG drying method.

2. MATERIALS and METHODS

2.1. Specimen preparation

The green bamboo tubes with the diameter of 45 mm - 68 mm were cut into the specimens with the length of 400 mm and the total quantity of 30 pieces. The average green moisture content (MC) of bamboo tubes was 61.6 percent, its standard deviation was 6.3 percent. The specimen with the length of 50 mm to be used for measuring moisture content was obtained from the left part of a bamboo tube after the specimen for test was cut, and was weighted, oven dried under the temperature of 103 ± 2℃. The moisture content was calculated by equation [1].

$$M = \frac{W_M - W_{od}}{W_{od}} \times 100 \quad \cdots\cdots [1]$$

where M = moisture content (%), W_M = weight of specimen (g) at M% MC, W_{od} = oven-dry weight (g)

2.2. PEG treatment and drying

Twenty pieces of specimens had been impregnated in the solution of PEG-1000 (weight ratio of water and PEG was 2 : 1) for two weeks, and ten pieces of the specimens were put in plastic bags and had been stored in a room for two weeks. After two weeks, all specimens kept in a room for several days. And two pieces of PEG treated specimens were dried under the temperature of 103 ± 2℃ for 48 hours in oven, but no crack or check was found on the treated specimens. Two pieces of PEG treated and two pieces of control specimens were dried under the temperature of 20℃ for 200 days in a room.

16 pieces of treated and 8 pieces of control specimens were dried in a kiln dryer according to the drying schedule (Table 1). The temperature of 120℃ was maintained for 20 hours in

the drier after 5 hours of temperature rising time from 20℃ to 120℃. During the initial drying time of 20 hours, humidifying switch had been closed in order to fast dry because higher percentages of PEG retention could be formed at faster drying rate under higher drying temperature (Lee *et al*., 2015).

2.3. Percentage of PEG retention

Among PEG treated specimens two pieces of both kiln and room dried ones were chosen and soaked in acetone for two weeks. The aceton-extracted specimens were dried at room temperature for 24 hours, followed by oven drying. Percentage of PEG Retention (PPR) was calculated according to equation [2].

$$PPR = \frac{W_{od} - W_{atn}}{W_{atn}} \times 100 \quad [2]$$

where PPR = percentage of PEG retention (%), W_{od} = oven dry weight of specimen (g), W_{atn} = oven dry weight after acetone extraction (g)

2.4. Saturated salt solution test

Saturated salt solution test was conducted to obtain the sorption isotherm curves for treated and control specimens. The relative humidity inside desicator at the temperature of 20℃ is presented in Table 2 (Hoadley, 2000). The Equilibrium Moisture Content (EMC) of spruce under each condition is also showed in the Table 2. Six pieces of the specimens with length of 50 mm were cut from two pieces of kiln dried treated and two pieces of kiln dried control specimens, respectively. After these specimens were oven dried, six pieces of the specimens were put into six desiccators, respectively, and kept them in well-sealed desiccator for one month, then weighted after taking out of the desiccator, and at last oven dried. The room temperature where the desiccators were located was around 20℃.

Table 2. The relative humidities inside desiccators at the temperature of 20℃

Saturated salt solution	RH (%)	EMC
$CaCl_2 \cdot 2H_2O$	32.0	6.0
NaBr	58.0	10.0
$(NH_4)_2SO_4$	80.5	16.0
$ZnSO_4 \cdot 7H_2O$	90.0	20.0
Na_2SO_4	95.0	24.0
H_2O (distilled water)	100.0	30.0

3. RESULTS and DISCUSSION

3.1. Drying at room temperature

The drying curve of bamboo tubes at 20℃ temperature is displayed in Fig. 2. The initial MC of the treated specimens was higher than that of controls, and the drying rate of the treated specimens was faster than that of controls. It was found out that the drying of bamboo tubes at room temperature was very slow because the drying time from green to final MC of 7 percent needed 200 days.

The cracks occurred on some control specimens when average MC was 20.7 percent at

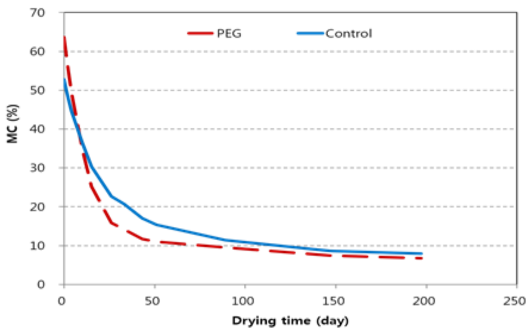

Fig. 2. Drying curves of the specimens dried in a room.

the drying time of 33 days, after that cracks were found on all other control specimens. However, no cracks were found on PEG treated specimens from the beginning to the end of drying. This proves that PEG treatment is effective to prevent cracks or checks on bamboo tubes during drying at room temperature.

3.2. Kiln drying

The dry bulb temperature and wet bulb temperature in the drying schedule of kiln drying are presented in Fig. 3. Humidification was not conducted from the beginning to the initial drying time of 20 hours, after that the EMC of 5 percent maintained until the end of drying in kiln after humidification of 5 hours. The drying curves of treated and control specimens during kiln drying are displayed in Fig. 4. The drying period of both treated and control specimens was 10 hours from the initial average MC of 61.0 percent for treated specimens and 51.2 percent for control specimens to nearly

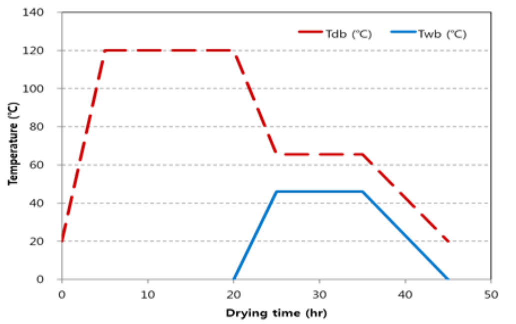

Fig. 3. The dry bulb and wet bulb temperatures during kiln drying.

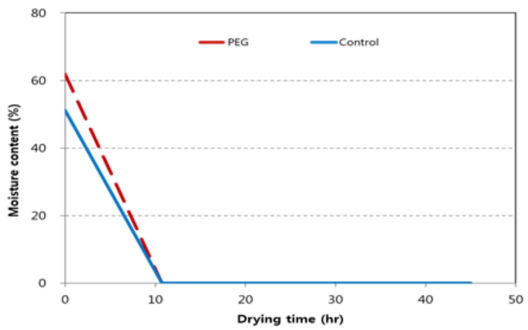

Fig. 4. The drying curves of treated and control specimens during kiln drying.

oven-dry condition.

The cracks occurred on all control specimens, but did not occur on treated specimens after the end of drying, which could be accounted for two causes; one is that there was more solidified PEG in the outer layer of bamboo tubes, that restrains the circumferential shrinkage of bamboo tube, due to higher drying temperature and faster drying rate; the other is that the tension set was formed on the surface of bamboo tube in the early stage of drying, which can effectively prevent surface check, due to high drying temperature and low relative humidity

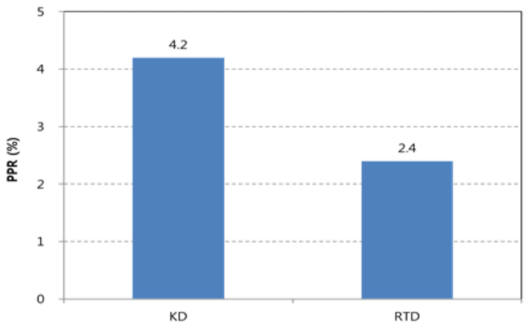

Fig. 5. The percentages of PEG retention of specimens after kiln drying and drying at room temperature.

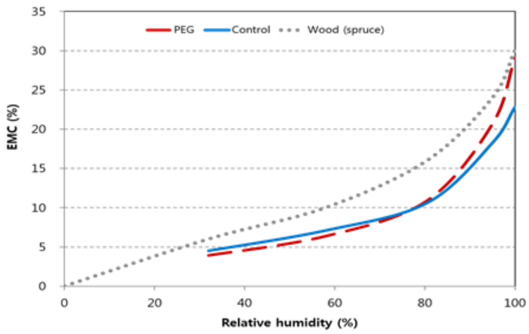

Fig. 6. Adorption isotherm curves of bamboo tubes at 20℃.

(Yamashita al etc. 2012). This proves that PEG treatment is effective to prevent cracks or checks on bamboo tubes during high temperature drying.

3.3. Percentage of PEG retention

The percentages of PEG retention of PEG treated specimens after kiln drying and drying at room temperature are showed in Fig. 5. The percentage of PEG retention of specimens after kiln drying was 1.8 percent higher than that of specimens after drying at room temperature. This could be due to more PEG being solidified in bamboo tubes because the specimens were dried by higher drying temperature in kiln drying compared to that in room drying. This is agreement with the conclusion from wood (Lee *et al*., 2015). From this conclusion, it is advised that PEG treated bamboo tube should be fast dried at high temperature in order to not only prevent crack or check in short drying period also increase the dimensional stability of the products made of bamboo tubes.

3.4. Adsorption isotherm curves

Adsorption isotherm curves of bamboo tubes, obtained by saturated salt solution test, are showed in Fig. 6. The EMC of control specimens under low relative humidity presented higher value than that of PEG treated specimens while that of the treated specimens under high relative humidity showed higher value than that of control specimens, which can be attributed to the increased oven-dry weight by residual PEG because according to equation [1], MC becomes lower when oven-dry weight is increasing. The EMC of spruce in the Table 2. is presented as a dotted line in Fig. 6. The EMC of bamboo tube showed lower value than that of spruce in all relative humidity range.

4. CONCLUSIONS

This study was conducted to develop a new drying technology in order to quickly and massively dry bamboo tubes without crack and check. The bamboo tubes with the diameter of

45 mm - 68 mm had been impregnated in the solution of PEG-1000, and then were dried under room temperature and high temperature, respectively. The results of this study were as follows:

1) The cracks occurred on all control specimens while no cracks were found on PEG treated specimens during drying at room temperature. But the drying period of this method was too long (200 days) compared to 45 hours of kiln drying.
2) During fast high temperature drying, cracks occurred on all control specimens, but no cracks did on PEG treated specimens, which could be accounted for more solidified PEG due to higher drying temperature and faster drying rate, and the tension set formed on the surface of bamboo tube in the early stage of drying owning to high drying temperature and low relative humidity. It is advised that PEG treated bamboo tube should be fast dried at high temperature in order to not only prevent crack or check in short drying period also increase the dimensional stability of the products made of bamboo tubes.
3) The EMC of the treated specimens under high relative humidity showed higher value than that of control specimens.

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