Directional Laminated Thermally Modified Bamboo: Physical, Mechanical, and Fire Properties

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Laminated bamboo with radial (LBR) and tangential (LBT) layered structures was manufactured using heat-treated moso bamboo and phenol-formaldehyde adhesive. The physical, mechanical, and fire-related properties were determined. The results showed that layer structure and heat treatment had an impact on the properties of laminated bamboo. LBR showed good mechanical properties, though heat treatment compromised its integrity somewhat. Heat treatment decreased the lightness and increased the green-red index, blue-yellow index, saturation, and total color difference. The samples exhibited changes in two HRR peaks during the combustion process, corresponding to two main release stages for smoke production. Heat-treatment improved the heat rate release (HRR), total heat release (THR), and the effective heat of combustion (EHC) properties, but also they decreased the smoke performances, resulting in higher total suspended particulate (TSP), specific extinction area (SEA), CO, and CO_2 yield. LBR is suggested to be manufactured for possible use as a structural engineering material.

Keywords: Laminated bamboo; Heat treatment; Layer structure; Mechanical and fire performance

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INTRODUCTION

Bamboo is one of the most important non-forest products in China. The favorable stiffness and strength properties of bamboo make it a promising material for the manufacturing of various engineered composite products (Nugroho and Ando 2001). Laminated bamboo is a popular type of commercial engineered composite that is widely applied in the fields of construction, furniture, and decoration. It can be manufactured in well-defined dimensions and is created by gluing together bamboo material in various forms (*e.g.*, strands or mats) to form rectangular boards, similar to lumber (Mahdavi *et al.* 2010). Correal *et al.* (2010) reported that laminated bamboo is an excellent lumber alternative, as it possesses mechanical properties equivalent to the best structural woods in Colombia. Sulastiningsih and Nurwati (2009) reported that the density of laminated bamboo varied from 0.71 to 0.75 g/cm^3. Its MOR and MOE ranged from 393.7 to 969.4 kg/cm^2 and 74,100 to 102,000 kg/cm^2, respectively. Sinha *et al.* (2013) reported that laminated bamboo exhibits higher allowable and average strength values in tension and bending, and comparable stiffness values, with much less variability than Douglas fir. However, laminated bamboo has some disadvantages, such as poor dimensional stability, natural decay resistance, and color change in response to light irradiation.

Heat treatment technology is the most effective and economical way to improve the aforementioned problems. Salim *et al.* (2008) found that degradation of cellulose and hemicellulose in heat-treated bamboo was attributable to plasticization of lignin during heating, which, at the same time, hydrolyzed the starch content. Sulaiman *et al.* (2006) investigated the shear strength of oil treated laminated bamboo and found that the glue line delamination increased as the temperature and duration of oil heat treatment increased. Hou *et al.* (2010) found that the temperature and duration of heat treatment had significant impacts on the surface wettability of bamboo. Manalo and Acda (2009) confirmed that the improvement in dimensional stability along the longitudinal direction of bamboo and reduction in strength properties for three species of heat-treated Philippine bamboo were correlated with temperature, but duration seemed to have little or no effect on the physical or mechanical properties. Cheng *et al.* (2013) investigated mold resistance of moso bamboo treated by two step heat treatment. They found that strong degradation of hemicelluloses, modification of lignin, and creation of phenolic compounds in the bamboo by the heat treatment could inhibit mold growth to some extent. Lee *et al.* (2012) confirmed that layered structure had an impact on the physical and mechanical properties of laminated bamboo. However, there is a lack of sufficient information concerning the characteristics of heat-treated laminated bamboo.

In this study, laminated bamboo was manufactured using moso bamboo with different layer structures. The physical properties, mechanical properties, and fire performances of heat-treated laminated bamboo were investigated. The results will be used to develop and guide laminated bamboo utilization.

EXPERIMENTAL

Materials

The laminated bamboo was sampled from a bamboo factory in Zhejiang Province, China. The raw materials, 5-year-old moso bamboo (*Phyllostachys heterocycla*), were collected from a bamboo plantation. The moso bamboo was first made into bamboo strips. The samples were heat-treated at 140 °C for 3 h, conditions that are widely utilized in the Chinese bamboo industry for pretreatment. Heat-treated bamboo strips were impregnated using phenolic formaldehyde adhesive, then pressed firmly together in a hot press to manufacture laminated bamboo with radial and tangential layered structures, shown in Fig. 1. The density and moisture content of laminated bamboo are displayed in Table 1.

Table 1. Sample Information

Samples	Density (g/cm^3)	Moisture Content (%)
ULBT	0.63	6.39
HLBT	0.64	6.05
ULBR	0.62	5.42
HLBR	0.64	5.50

Determination of Physical and Mechanical Properties

The physical and mechanical properties of laminated bamboo were determined according to standard methods. Thickness swelling (TS), modulus of elasticity in bending (MOE), and bending strength (MOR) were performed according to GB/T 17657 (2013) (test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels). The impact bending strength was performed according to ISO 6603-1 (2000) and ISO 6603-2 (2000). Fire resistance tests were conducted with a cone calorimeter. Six replicates of each cone experiment were performed.

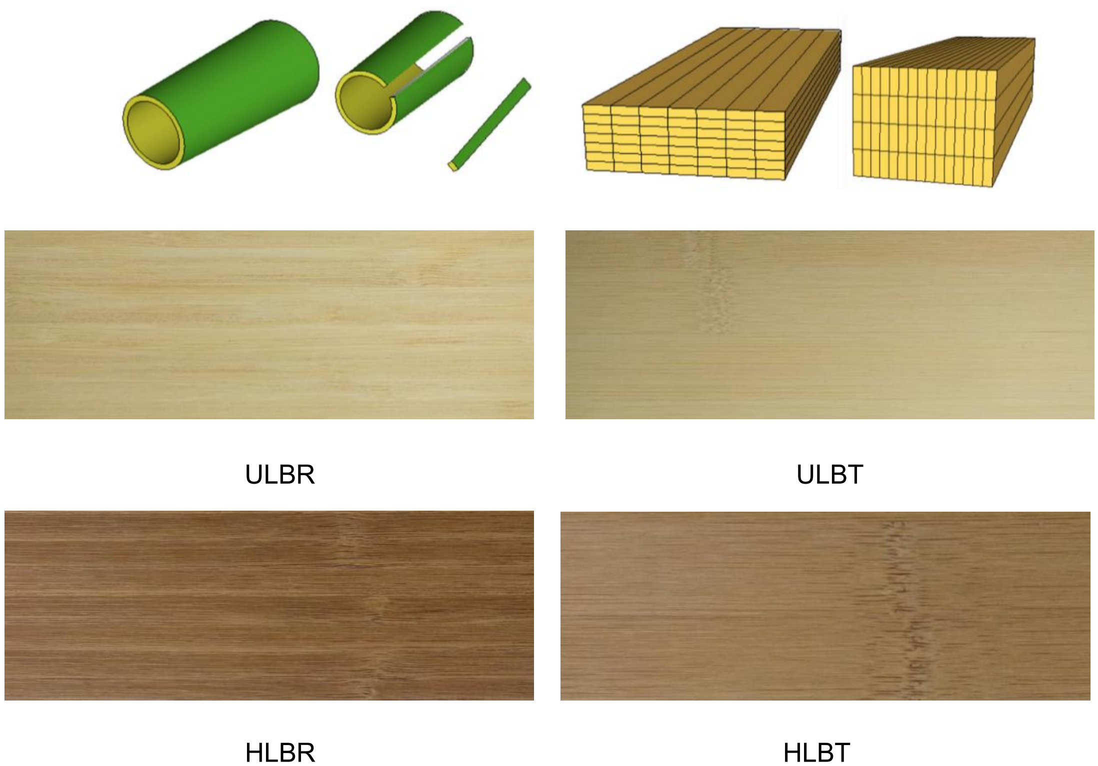

Fig. 1. Laminated bamboo

Determination of Color Change

The surface color of laminated bamboo was determined with a Minolta Croma-Meter CR-300 colorimeter (Osaka, Japan). Five replicates of each cone experiment were performed. The percentage of reflectance, collected at 10 nm intervals over the visible spectrum (from 400 to 700 nm), was converted into the CIELAB color system, where L^* is the lightness, and a^* and b^* are the chromatic coordinates on the green-red and blue-yellow axis, respectively. Based on the L^*, a^*, and b^* values, the difference in the lightness (ΔL^*), chroma coordinates (Δa^* and Δb^*), saturation (C^*), and total color difference (ΔE) were calculated as follows (Bekhta and Niemz 2003),

$$\Delta L^* = L^*_H - L^*_c \quad (1)$$

$$\Delta a^* = a^*_H - a^*_c \quad (2)$$

$$\Delta b^* = b^*_H - b^*_c \quad (3)$$

$$C^* = (a^*2 + b^*2)1/2 \quad (4)$$

$$\Delta E = (\Delta L^*2 + \Delta a^*2 + \Delta b^*2)1/2 \quad (5)$$

where L^*_H, a^*_H, and b^*_H are L^*, a^*, and b* for heat-treated samples; L^*_c, a^*_c, and b^*_c are L^*, a^*, and b^* for control samples, respectively.

Determination of Fire Performances

The laminated bamboo was cut into pieces with dimensions of 100 mm (length) × 100 mm (width) × about 10 mm (thickness) according to the requirement of ISO 5660-1 (2002). All samples were dried at temperature 105 °C until the mass stabilized. Fire performance of laminated bamboo was determined using a cone calorimeter (FTT0242, Fire Testing Technology Co. Ltd., West Sussex, UK). The tests were carried out along the horizontal orientation with a 50 kW/m^2 flux, using an edge frame. Three replicates of each cone experiment were performed.

Determination of Chemical Groups

The laminated bamboo was broken down to particles using a Wiley Mill. The pieces were then screened to get uniform particles ranging from 250 to 425 μm. The samples were mixed with potassium bromide (KBr) in an agate mortar with a mixing ratio of 1:200 (KBr: Bamboo). Triplicate spectra of samples were collected by attenuated total reflectance (ATR), using an 80V FTIR spectrometer (nexus 670, Nicolet, Madison, WI, USA). Three replicates of each sample were performed.

Determination of Crystallinity Index

The crystallinity index of laminated bamboo was determined using an X-ray diffractometer (Philips, Holland), with an X-ray generator and a Cu target (λ = 0.1540598 nm) with Kα (40 kv, 40 mA) radiation at room temperature. The scan rate was 2.50/min. Data were recorded each 0.020 (2θ) for the angle range of 2θ = 5 to 50°. The crystallinity index (CrI) was calculated as follows,

$$\mathrm{CrI} = \frac{I_{002} - I_{am}}{I_{002}} \tag{6}$$

where I_{002} is the overall intensity of the peak at 2θ (about 22º), and I_{am} is the intensity of the baseline at 2θ (about 18º).

RESULTS AND DISCUSSION

Physical and Mechanical Properties

Table 2 shows the physical and mechanical properties of laminated bamboo. LBT had a lower TS than LBR. Heat treatment decreased the thickness swelling of laminated bamboo, mainly due to the chemical changes during heat treatment. Figure 2 shows the FTIR spectra of control and heat-treated bamboo. The intensity of O-H stretching absorbance at 3429 cm^{-1} decreased when the bamboo was heat-treated. Based on this finding, it follows that the destruction of some hydroxyl groups decreased the bamboo's water absorption and thickness swelling. Ohmae *et al.* (2009) found that hydroxyl groups provided absorption sites for water and controlled absorption when the temperature of heat treatment was below 250 °C. Furthermore, the crystalline structure of bamboo cellulose may also affect water absorption and thickness swelling.

Cellulose includes crystalline and amorphous regions. Water enters the amorphous region more easily than the crystalline region. Figure 3 shows that crystallinity index of bamboo materials increased after heat treatment. Thus, heat-treated laminated bamboo had more crystalline regions, making it more difficult for water to enter into the bamboo materials. Also, LBR had a higher MOE, MOR, and IS than LBT. Heat treatment decreased these mechanical properties. These results were similar to those reported by Bakar *et al.* (2013). Heat treatment reduced the overall values of compression strength, bending strength, modulus of elasticity in bending, Janka-hardness, impact bending strength, and tension strength of Scots pine (*Pinus sylvestris* L.) compared with controls (Kocaefe *et al.* 2010).

Table 2. Physical and Mechanical Properties of Samples

Samples	TS (%)	MOE (GPa)	MOR (MPa)	IS (KJ/m^2)
ULBT	7.06	7.66	106.86	295.3
HLBT	6.10	6.64	83.46	308.1
ULBR	10.13	9.31	119.03	344.4
HLBR	7.86	8.81	110.95	329.3

TS: thickness swelling; MOE: modulus of elasticity in bending; MOR: bending strength; and IS: impact bending strength.

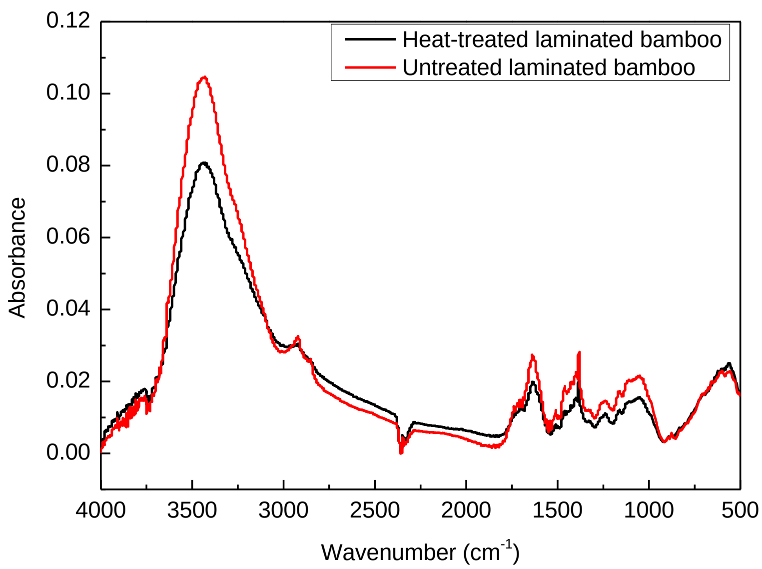

Fig. 2. The FTIR spectra of untreated and heat-treated bamboo

Color Change Analysis

Table 3 shows the color parameters of laminated bamboo. Heat treatment decreased the lightness (*L**) and increased the green-red index (*a**), blue-yellow index (*b**), saturation (*C**), and total color difference (Δ*E*). This was mainly attributed to the chemical changes in bamboo during heat treatment, confirmed by the FTIR spectra (Fig. 2).

Table 3. Color Parameters of Samples

Samples	Δ*L**	Δ*a**	Δ*b**	*C**	Δ*E*
LBT	-23.70	5.51	2.67	6.12	24.48
LBR	-18.50	4.41	2.20	4.93	19.15

LBT and LBR are laminated bamboo with tangential and radial layered structures, respectively.

Esteves *et al.* (2008) found that decreases in lightness had solid correlations with glucose (R^2 = 0.96), hemicelluloses (R^2 = 0.92), and lignin (R^2 = 0.86). The removal of total extractives and extractives soluble in cold water increased the color saturation (*C*) of *P. radiata* wood (Vinha *et al.* 2015). The lightness change (ΔL^*) was the most important parameter affecting the color change, which was in accordance with the results of Cui *et al.* (2007).

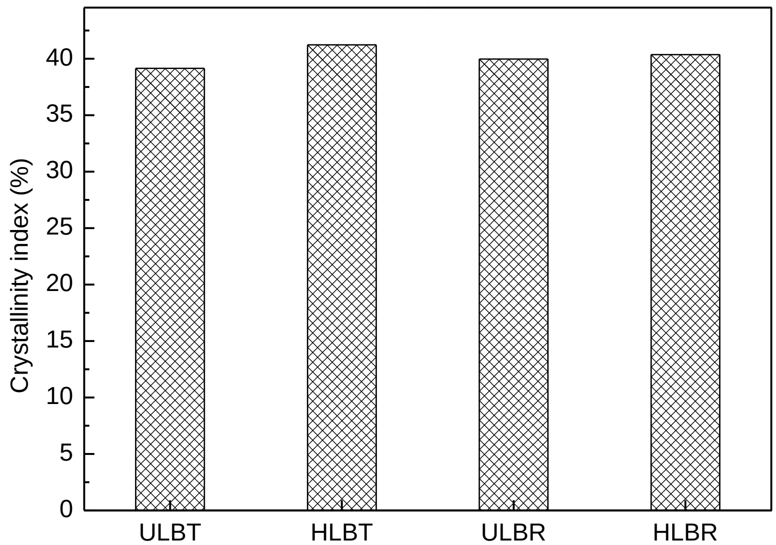

Fig. 3. The crystallinity index of samples

Fire Performances

The heat release rate (HRR) from cone calorimetry is a very important parameter to evaluate the fire intensity of materials. From a reaction-to-fire point of view, a HRR of 1 or 3 min from ignition, as well as the PHRR and time to ignition (TTI), gives important information on the first stage of fire development (Arao *et al.* 2014). Figure 4 shows the HRR of laminated bamboo. There were two HRR peaks. The first HRR peak rapidly increased when the samples were respectively burned with the TTI of 29s for ULBT, 21s for HLBT, 20s for ULBR, and 21s for HLBR. The first HRR peak was mainly due to the combustion of volatiles, which resulted from the sample surface's thermal decomposition during the testing process. Mi *et al.* (2016) found that the volatiles of bamboo had a lower combustion temperature. A char layer was subsequently formed on the sample surface, which inhibited the production of combustive gases (Jiang *et al.* 2014). The HRR gradually dropped to a somewhat steady-state rate. There were some random cracks on the surface due to the temperature difference of inner and outer samples. The volatile gases were concentrated in the cracks, causing faster ignition, which resulted in the second HRR peak. The second HRR peak of LBT was shifted farther to the right in the curve than LBR. Furthermore, heat-treatment decreased the HRR value compared with the control, especially for LBT. The flammability of samples was sensitive to the average HRR value. If the average HRR value was reduced to the point that it could not achieve the decomposition temperature of samples, the samples exhibited a self-extinguishing property. From this viewpoint, it could be anticipated that the average HRR value during the initial burning stage was the most important parameter in determining the flammability of materials (Arao *et al.* 2014).

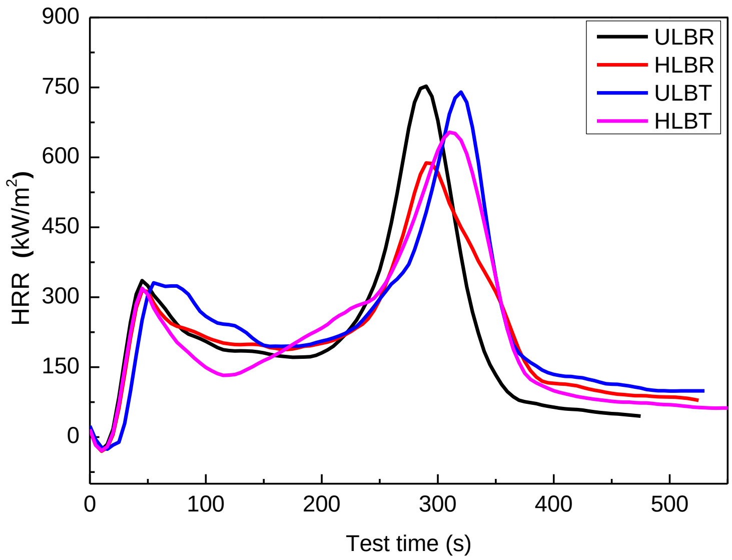

Fig. 4. HRR curves of samples

Table 4. Fire Characteristics of Bamboo Scrimber Flooring

Samples	TTI (s)	HRR_{mean} (kW/m^2)	THR (MJ/m^2)	EHC (MJ/kg)	TSP (m^2)	SEA (m^2/kg)	CO_{mean} (kg/kg)	$CO_{2\ mean}$ (kg/kg)
ULBT	29	253.61	126.80	20.93	3.5	65.11	0.0340	1.88
HLBT	21	218.80	118.20	20.14	4.1	77.49	0.0243	1.80
ULBR	20	232.94	106.00	18.84	3.2	64.47	0.0119	1.77
HLBR	21	230.46	115.30	19.64	3.5	66.92	0.0329	1.78

TTI: time to ignition; HHR: heat release rate; THR: total heat release; EHC: effective heat of combustion; TSP: total smoke production; and SEA: specific extinction area.

Total heat release (THR) is the total amount of calories released during the combustion, emitted from the surface of the object. It is important to understand the potential for fire spread when a fire occurs (Seo *et al.* 2016). Heat-treated LBT had a lower THR value, and heat-treated HLBR had a higher THR value compared with untreated samples, respectively. The effective heat of combustion (EHC) is the energy generated by combustion reactions per unit mass of samples, and it is calculated as the ratio of the heat release rate to the mass loss rate. It indicates the burning intensity of the volatile compounds in the flame and is helpful in the study of fire retardant (Xu *et al.* 2015). Heat-treatment had a similar effect on EHC of those samples with THR.

These parameters including smoke production rate (SPR) and specific extinction area (SEA) are very helpful in understanding smoke generation during the combustion process of laminated bamboo. Figure 5 shows the SPR curve for the samples. There were two main peaks, consistent with the results of the HRR curves. However, TSP of laminated bamboo exhibited two rapidly increasing stages, as depicted in Fig. 6. Heat treatment increased the samples' TSP values, respectively corresponding to 3.50 m^2 of ULBT, 4.10 m^2 of HLBT, 3.20 m^2 of ULBR, and 3.50 m^2 of HLBR. Similarly, the SEA value was respectively 65.11 m^2/kg, 77.49 m^2/kg, 64.47 m^2/kg, and 66.92 m^2/kg. Another important parameter that helps in understanding the fire hazard related to materials is the emission of toxic gases. The toxicity of gaseous products from the combustion of materials is determined by the emission of CO (Fang *et al.* 2013). The CO yield of samples was 0.0340 kg/kg of ULBT, 0.0243 kg/kg of HLBT, 0.0119 kg/kg of ULBR, and 0.0329 kg/kg of HLBR during the combustion process. The relatively higher CO yield was mainly due to incomplete material combustion. CO_2 yield of samples was significantly higher than CO yield, indicating it played an important role in smoke suppression during the combustion process of laminated bamboo. The CO_2 yield for the samples was 1.88 kg/kg of ULBT, 1.80 kg/kg of HLBT, 1.77 kg/kg of ULBR, and 1.78 kg/kg of HLBR. Heat treatment decreased the CO and CO_2 yield of LBT and increased that of LBR.

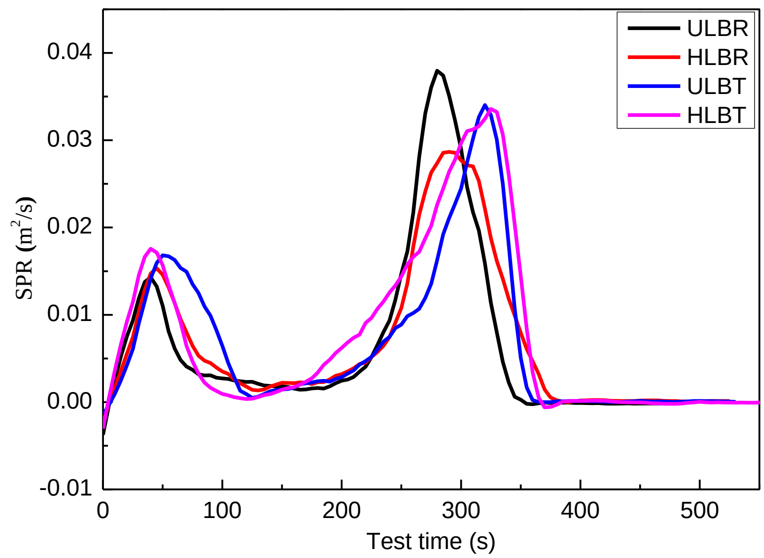

Fig. 5. SPR curves of samples

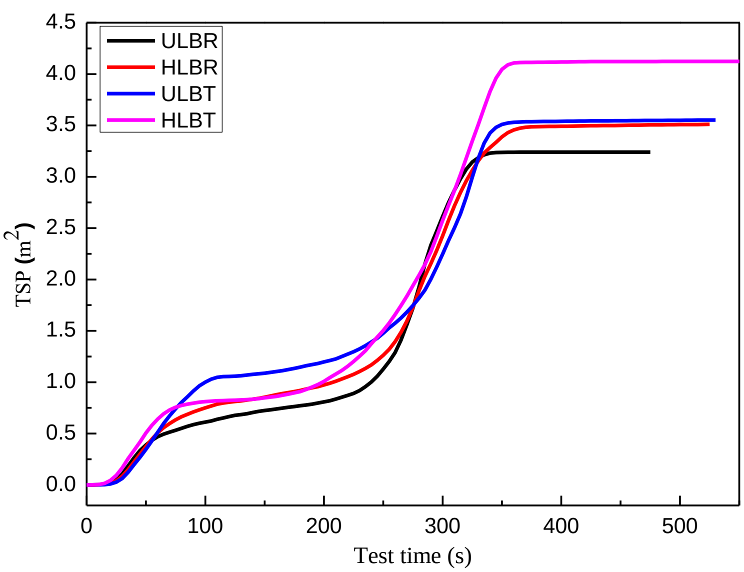

Fig. 6. TSP curves of samples

Through the comparison of the combustion performance before and after heat treatment, the TTI, HRR, THR, EHC, CO, and CO_2 yield of LBT decreased, whereas TSP and SEA increased slightly, indicating that the heat treatment had a certain flame retardancy.

However, the values of LBR increased, indicating that the fire risk of LBR increased. As for the manner of lamination, the thermal performance parameters of LBR were less than LBT without heat treatment. After heat treatment, the thermal performance parameters of LBR were smaller than LBT except HRR and CO yield. Above all, it is suggested for LBR to be manufactured for use as a structural engineering material.

CONCLUSIONS

1. Layer structure and heat treatment had an impact on the properties of laminated bamboo. LBT had a lower TS, MOE, MOR, and IS value than LBR. The mechanical properties of samples decreased when bamboo materials were heat-treated.
2. Similarly, heat treatment decreased the lightness and increased the green-red index, blue-yellow index, saturation, and total color difference in the samples. Lightness had a significant effect on color change. There were two HRR peaks during the combustion process of laminated bamboo, corresponding to two main release stages of smoke.
3. Heat-treatment improved the HRR, THR, and EHC properties of laminated bamboo. There were two HRR peaks during the combustion process of laminated bamboo, corresponding to two main release stages of smoke. It also decreased the smoke performances, resulting in a higher TSP, SEA, CO, and CO_2 yield.

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