The Influence of Saturated Steam on Moso Bamboo Quasi-static Micromechanical Properties: Nano-Scale Evaluation

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Article

The influence of Saturated Steam on Moso Bamboo Quasi-static Micromechanical Properties: Nano-Scale Evaluation

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Abstract:

In this paper, in order to analyze the quasi-static properties of Moso bamboo, a new, environmentally friendly and eco-friendly method was used for bamboo thermal modification under the effect of saturated steam. Under saturated steam heat treatment, the chemical composition in bamboo decreased, and the bamboo cell wall shrunk slightly. The increased crystallinity index of cellulose and decreased intensity of peaks belong to hemicellulose were confirmed by XRD and Fourier transform infrared (FTIR) spectroscopy. In addition, the highest modulus of elastic and hardness of treated bamboo were 22.5GPa and 1.1GPa at 180°C/10 min. These conclusions confirmed the micro-mechanical properties of the bamboo cell wall were enhanced by saturated steam heat treatment. The $\mathbf{E_r'}$ of differently treated bamboo increased with increasing temperature and time, while the $\mathbf{E_r''}$ and tan δ negatively as a function of increasing frequency. Furthermore, this thermal modification can be regarded as a useful, environmental-friendly and eco-friendly treatment to outdoor use of bamboo-based materials.

Keywords: Moso bamboo; saturated steam; modulus of elastic; hardness.

1. Introduction

Bamboo belongs to the Gramineae family and has been widely used in many fields in our daily life, such as furniture, construction, and so forth (**Wang et al. 2019b; Yuan et al. 2020; Wang et al.**). Scientific and reasonable application of bamboo can effectively reduce the demand for the woody resource(**Zhang et al. 2013**). On this respect, more attention has been paid to bamboo due to its excellent mechanical properties, fast growth, and stable performance(**Li et al. 2015; Tang et al. 2019**). However, bamboo is easily affected by fungi, moisture, and injurious insect due to its abundance in polysaccharides and starch, which limits the outdoor utilization of bamboo-based products. Meanwhile, when bamboo-based engineered bamboo materials are applied for long-term usage, it is easy to produce problems like short product life, low dimensional stability, and low resistance to biodegradation. So, it is of great importance to improving the physical and mechanical properties of bamboo to solve the above problems.

Thermal modification has been widely applied in making bamboo-based products, which can effectively improve the physical and mechanical properties of bamboo products. The aim of thermal modification is to change the polysaccharide and starch content and microstructure of bamboo tissue, to improve the macro-mechanical properties such as color (aesthetic purposes), modulus of elasticity, equilibrium moisture content, and so on. The inert gas, water, and oil were the three main traditional heat treatment mediums that the treatment temperature and treatment time in the range of 150℃ – 250℃, and 2 – 6 h, respectively. However, traditional thermal modification leads to the evaporation completely of moisture content in bamboo, which leads to a negative effect on the macro-mechanical properties of bamboo with increasing severity of treatment. Therefore, scientists are urgent to find a rapid and gentle heat treatment medium for the modification of bamboo. Saturated steam is steam that is controlled by pressure and at a temperature lower than the boiling point. Thus, saturated steam heat treatment can provide a high temperature and high humidity environment for modification simultaneously. It is of great interest to study the mechanical properties of bamboo in nanoscale and microscale ranges.

Previous literatures focus on the macroscale properties and surface changes of moso bamboo after thermal modification. For example, **Wang et al** studied the influence of saturated steam pretreatment on the drying quality of bamboo culms,

results showed that saturated steam can effectively improve the drying quality of bamboo culms and reduce cracks. However, he did not reveal the reason from nano-scale perspective. Micro-level study are rare in this field. **Wang Q et al** studied the effects of different treatment temperature and time on the mechanical and chemical composition of moso bamboo with different initial moisture contents. **Yuan T et al** reveled the infulence of different treatment parameters on equilibrium moisture content, oven-dried density, and color on moso bamboo. So, the study of effect of saturated steam on moso bamboo in nano-scale are rare. In addition, Quasi-static indentation was used to characterizes the micro-mechanical properties of biomass materials such as wood, bamboo, and straw by means of nanoindentation(**He et al. 2019a, b; Guan et al. 2020**). It is also a successful approach for determining the modulus of elasticity and hardness of a single cell wall. In addition, for the application of bamboo in oscillation stress and long-term bearing, viscoelastic is an interesting topic. For this purpose, Nanoindentation technology is applied for analyzing these problems and is suited to this purpose. Moreover, combining quasi-static indentation and other modern test instruments can deeply understand the nanomechanical properties of bamboo cell wall.

In this paper, the bamboo is heat-treated by saturated steam at different temperatures and times and then analyzed by means of Fourier transform infrared (FTIR) spectroscopy, environmental scanning electron microscope (SEM), X-ray diffraction (XRD), wet chemistry method, and quasi-static Nanoindentation.

2. Materials and methods

2.1. Materials preparation

Natural three-year-old Moso Bamboo (*Phyllostachys pubescens*) with average dimensions of 50*20*t mm (length * width * wall thickness) were collected from JiangXi Province, China. The initial moisture content of samples was 90%. bamboo culms were subjected to heat treatment at different temperatures (160, 180℃) for different periods (15, 30min).The bamboo culms were placed in pressurized steam equipment. After treatment, all samples were placed in a constant temperature and humidity equipment (HWS-250, Jinhong Co., Ltd., China) for 2 weeks under 20℃ and 65% (relative humidity).

2.2. X-ray diffraction (XRD) analysis

The different treated bamboo specimens were ground into powder and sieved through an 80 mesh screen. The samples were then placed in an oven for 12 hours until the moisture content was 0%. Then, the XRD method (Ultima-IV combination X-ray diffractometer, Japan) was utilized to analyze the crystallinity of bamboo cellulose at different treatment temperatures and times. Data were collected in the 2-theta scanning range from 10° to 80°. Based on Segal's formula, the XRD analysis results constituted the average of three replicate experiments, and relative crystallinity can be calculated as below:

$$C_rI=(I_{002}-I_{am})/I_{002} \times 100\%, \quad (1)$$

where CrI represents the relative content of crystallinity, and I_{002} and Iam denote the the maximum in the intensity of the (200) peak and the minimum in the intensity between the overlapped $(1\bar{1}0)$/(110) and the (200) peak.

2.3. Fourier transform infrared spectroscopy (FTIR)

The powders used in XRD analysis were also used to FTIR analysis on a FTIR spectrometer (500-4000 cm^{-1} range, 32 accumulations, 2 cm^{-1} resolution; Bruker Corporation, Karlsruhe, Germany). KBr Pellet Method were used to further analyze the chemical functional groups. The FTIR analysis for each sample was based on averages of three replicate experiments.

2.4. Oven-dried density and mass loss

The treated and untreated bamboo were possessed into the average size of 10*10*T mm (length*width*thickness) and the density was tested by oven-drying method. Ten samples were repeatedly collected from each group for analysis The percentage of mass loss following saturated steam heat treatment was calculated by formula as below:

$$\%ML = 100\ (M_0-M_1)/M_0 \quad (2)$$

Where m_0 represents the initial oven-dried specimen mass, m1 represents the oven-dried specimen mass after saturated steam heat treatment

2.5. Chemical compositions analysis

In this step, the treated bamboo samples were ground and screened into powder using 40 and 80 screens. The main chemical composition (cellulose, hemicellulose, and lignin content) of samples was determined and calculated according to NREL'S LAPs. All data were represented as averages of three replicate experiments, closest to 0.1%.

2.6. Nanoindentation (NI)

Samples treated by saturated steam, together with untreated samples, were processed into small blocks of 0.5 * 0.5 * 1mm^3, the cross-section of bamboo samples were polished by a diamond knife, as shown in Figure 1, five samples were placed under constant temperature (21±1℃) and humidity (65±4%) for 24 hours before the tests. NI was performed on a load-controlled mode to obtain at least 30 valid indentations (see Figure 1). Loading was performed within 5s, the holding time was 5s, and unloading terminated within 5s. A peak load (400μN) were applied to all indents. All data were averages of 30 valid data.

2.7. Elastic modulus and hardness

Based on the formula according to Oliver (1992), the reduced elastic modulus and hardness can be calculated as formula follows:

$$H = \frac{P_{max}}{A} \tag{3}$$

where P_{max} is the peak load, and A denotes the projected contact area of the indents at peak load.

$$Er = \frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A}} \tag{4}$$

where Er, S(*dP/dh*), and β represent the combined elastic modulus of both the specimen and indenter, the initial unloading stiffness, and the correction factor to indent geometry (β = 1.034), respectively.

2.8. Creep behavior

In order to investigate the creep behavior of bamboo, specimens were held for 200s after uploading by a maximum load of 400μN. Creep behavior can be calculated from the load-indentation depth graph based on Konnerth and Gindl's method.

$$C_{IT}(\%) = \frac{h_2 - h_1}{h_1} \times 100 \quad (8)$$

where h_2 and h_1 represent the final and first penetration depth of the segment, respectively.

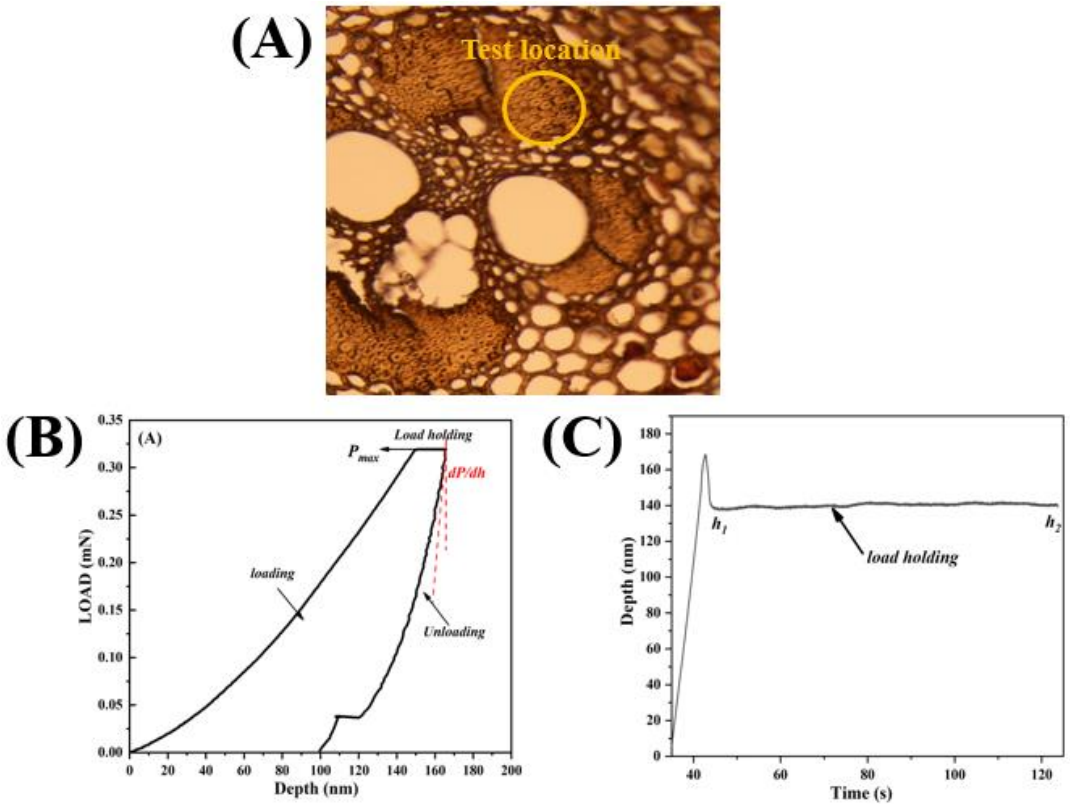

Figure 1. (A) Test area; Typical NI representative load-depth(B) and depth-time(C) curves of the bamboo fiber cell.

2.9. Dynamic mechanical properties analysis

After the test of nanoindentation, the nanoDMA tests were tested by the same indenter and operated in a ramping dynamic frequency mode. The quasi-static load and the dynamic load was equal to 100 μN and 10 μN, respectively. The frequencies were ranged from 10 to 200 Hz and each frequency has 100 cycles. Data were collected from 30 valid indentations which were tested in five or six cells. The E_r' and E_r'' were calculated based on Chakravartula and Komvopoulus's method

$$E_r' = \frac{K_S\sqrt{\pi}}{2\sqrt{A}} \quad (9)$$

$$E_r'' = \frac{wC_S\sqrt{\pi}}{2\sqrt{A}} \quad (10)$$

$$\tan \delta = \frac{C_S W}{k_s} \quad (11)$$

Where A, ks, and Cs represents the projected area of the contact, contact stiffness and the damping coefficient of the sample, respectively.

The Ks can be calculated as below:

$$K_s = K - K_1 \quad (12)$$

Where K, and K_1 is the combined stiffness and the spring constant of the leaf springs holding the indenter shaft, respectively.

2.10 Data analysis

All data were ststistically analyzed using SPSS software. Ducan multiple range test were performed to analysis significant influence between groups. In this paper, different lowercase letters represents significant differences between groups.

3. Results and discussion

3.1 Oven-dried density and mass analysis

Results for oven-dried density, mass after saturated steam heat treatment of differently treated bamboo samples are shown in Figure2. Density and mass for untreated bamboo was found to be 0.82g/cm^3 and 0.76g, respectively. Expectedly, the density and mass decreased with an increase in treatment temperature and time. According to previous literature, which is attributed to the degradation of polysaccharides in the cell wall(Huang et al. 2018). In addition. The loss of volatile composition from extractives may also contribute to these observations when the treatment temperature above 160℃(Zhu et al. 2020).

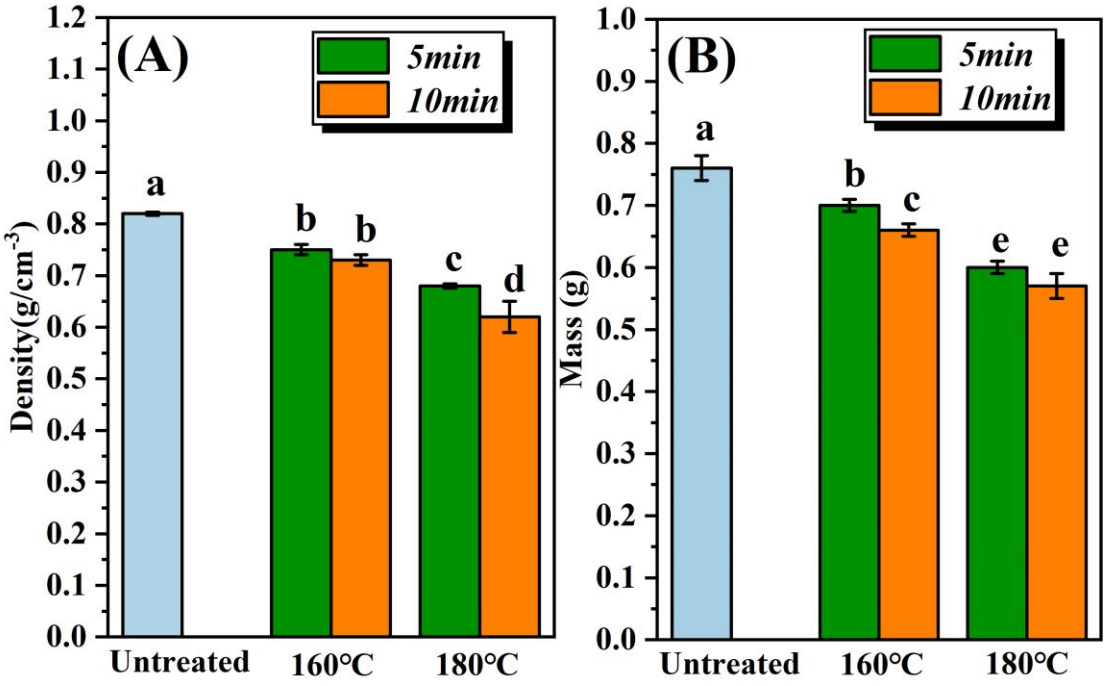

Figure 2. density and mass analysis of untreated and saturated-steam heat treatment sample The different letters represent significant differences between treatments ($p < 0.05$).

3.2 Microstructure

As shown in Figure 3 (A-C), SEM was applied for analyzing different treated bamboo samples. The microstructure of bamboo is totally different from wood. Bamboo is a natural material composited by two main components (vascular bundles and parenchyma cells). Parenchyma cell is the principal matrix of bamboo. Figure 3A shows the thin-wall cells exhibited spongiform and porous characteristics and vascular bundles is solid areas with hollow tubes. Figure 3B (1-3) illustrates that the volume of parenchyma cell became smaller after saturated steam heat treatment (160℃/15min). In addition, slightly shrank appeared in the thin-walled cells. Increased treatment temperature contributed to this phenomenon. Figure 3 (C) shows a visual comparison of the cross-section section of pre-and post-treatment bamboo samples. It can be observed from figure 3C that the parenchyma cells and vascular bundles have been collapsed by the saturated steam heat-treatment process. The separation between vascular bundles and parenchyma cells are obvious from the SEM images. This increase change in the bamboo cell wall is associated with increasing treatment temperature.

Additionally, the decomposition of polysaccharides in bamboo cell wall is another reason for this conclusion.

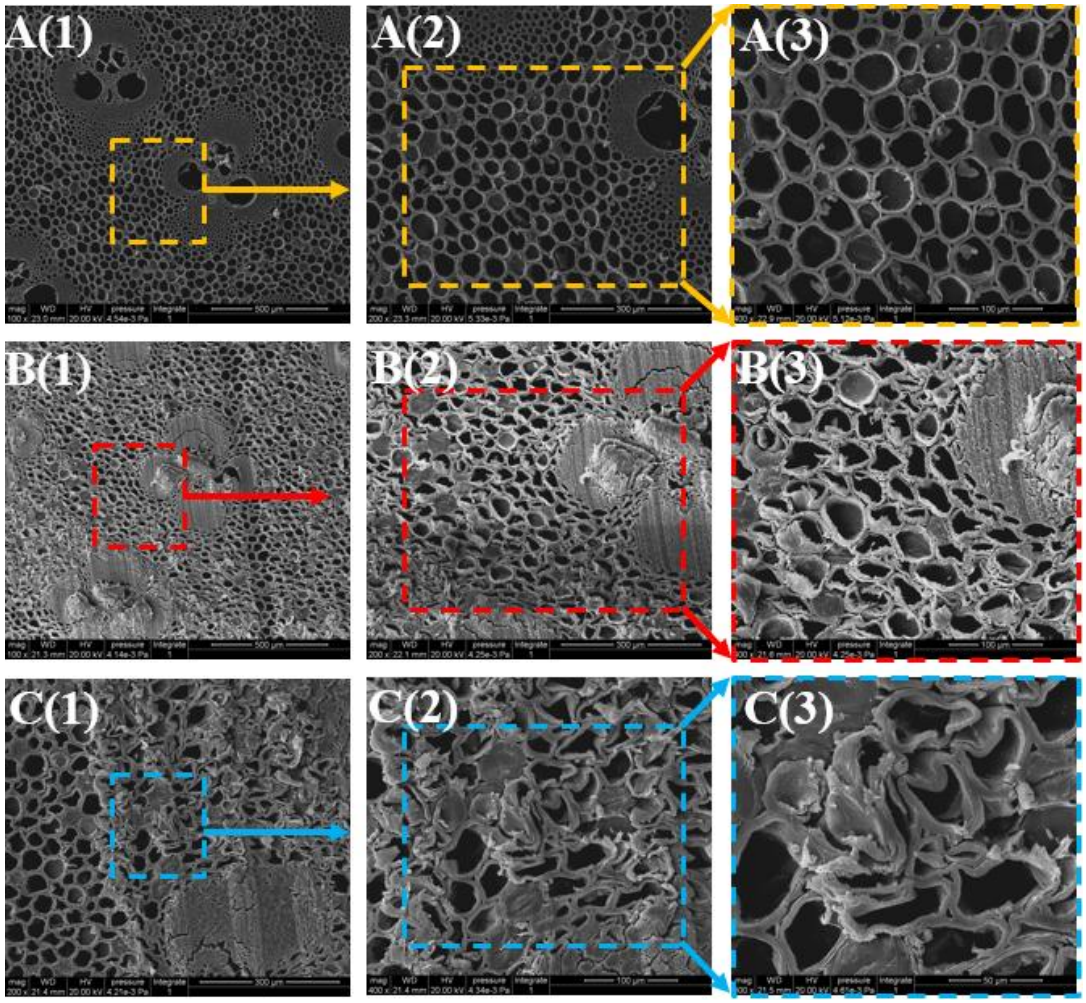

Figure 3: SEM images of cross-section different treated bamboo: (A) untreated; (B) 160℃/10min; (C) 180℃/10min

3.3 Main chemical composition

As shown in table 1, Due to thermal modification (TM) the hemicellulose content was negatively correlated with treatment severity. In addition, the content of cellulose was also negatively affected by heat treatment. Following treatment under 180℃ for 10 min, the relative hemicellulose content (19.7%) was reduced by around 7.8% compared with that of the untreated sample. This observation is in agreement with the previous literature. Xylan, the main component of hemicellulose, is sensitive to high-temperature conditions and is subjected to dehydration reactions(Ohmae et al. 2009). Moreover, the lignin content showed an increasing trend with the decrease of hemicellulose and cellulose levels. The lignin content observed upon 180℃ for 10min was significant at 32.5%, which was a 4.1% increment of that of control. This finding

supports previous conclusions in the literature. This is due to the condensation of hemicellulose by-products with lignin conducive to this phenomenon. In addition, considering the low thermal stability of polysaccharides in hemicellulose resulting from the branched and amorphous structure, it can be attributed to the hemicellulose in bamboo is easier to decompose than cellulose or lignin(Zhang et al. 2013). Furthermore, the conclusion of the reduction in hemicellulose' content in fiber cells was also confirmed by SEM.

Table 1. Relative contents of hemicellulose, cellulose, and lignin in the samples obtained after saturated-steam heat treatment.

Time	Cellulose		Hemicellulose		Lignin	
	160°C	180°C	160°C	180°C	160°C	180°C
Untreated	36.9		25.6		27.3	
5min	33.5	32.4	23.3	22.5	29.9	30.4
10min	30.3	28.3	21.5	19.7	30.3	32.5

3.4 XRD analysis

Cellulose, the main composition of bamboo, is the main reason for the strength of lignocellulose materials. As it is known to all, the amorphous and crystalline region are two main components of cellulose and their relationship further influence the micromechanical properties of the bamboo cell wall. Figure 4 shows the XRD patterns and degree of crystallinity of different treated bamboo specimens. The crystallinity indexes were obtained by Eq.1. Expectedly, the degree of crystallinity increased after saturated steam heat treatment. Both treatment temperature and duration clearly made a positive impact on the relative crystallinity of cellulose, while the mean CrI value of the untreated sample was 50%. As shown in Figure 4, the relative degree of crystallinity was positively correlated with thermal modification severity. In other words, both temperature and duration positively contributed to crystallinity. The obvious increment in the CrI was specimens treated at 180℃for 10 min. Saturated steam treatment at 180℃ for 10 min results in higher CrI compared with that of the control. the change from 50.0% to 62%, which is a 24% increment, It was attributed to the decomposition of hemicellulose. Additionly, the proportion of paracrystalline cellulose also decreases due to the acidic environment. Thus, the relative crystallinity of bamboo is further increased.

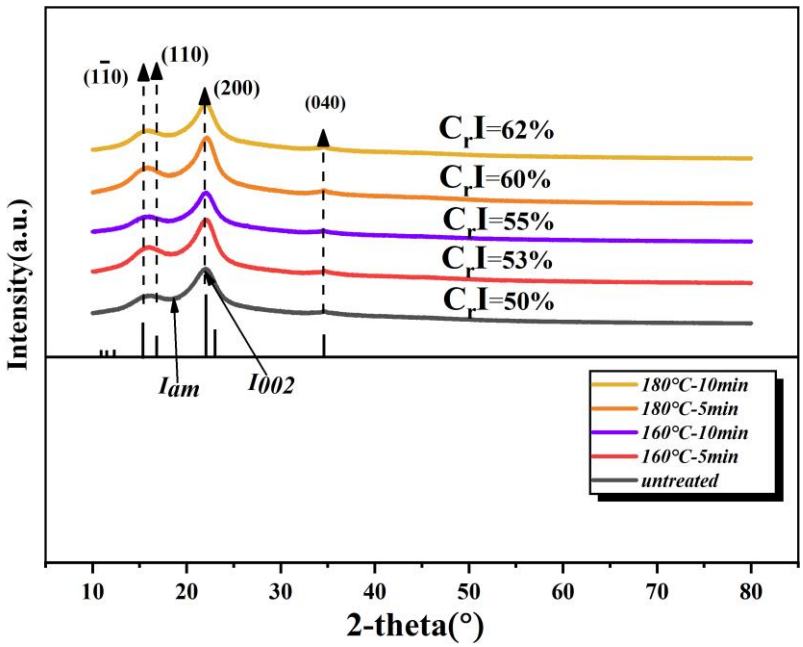

Figure 4. XRD curves and crystallinity index of untreated and different treated sample (relatively degree of crystallinity are shown in picture).

3.5 FTIR analysis

FTIR spectroscopy of the untreated bamboo and differently treated bamboo is a method to analyze the bamboo chemical components. The relevant data of this study are shown in Figure 5. The peak at 890cm^{-1} can be assigned to C-H, which represents C H deformation in cellulose. The 890 cm^{-1} of samples treated at different temperatures did change too much show the main structure of cellulose is still intact. The peak at 3341cm^{-1} and 2850 cm^{-1} represented stretching vibration of -OH and stretching vibration of C-H vibration. These two peaks decreased in comparison to that of the control. These results illustrated that saturated steam heat treatment decreased the hydroxyl groups in bamboo. The 1730 cm^{-1} peak, which represented C=O stretching vibration in hemicellulose, and the intensity of 1730cm^{-1} decreased, which is maybe the decomposition of hemicellulose. The peaks at 1163 cm^{-1} and 1328 cm^{-1} correspond to C-O-C stretching vibration and O-H stretching vibration, respectively. The visible weakening of the above peak (1163 cm^{-1} and 1328 cm^{-1}) is due to the hydrolysis of hemicellulose. Additionally, the characteristic peaks of lignin (1590cm^{-1}) increased,

which further confirmed the increase in lignin content. Lignin condensation with by-products (arise from hydrolysis of hemicellulose) conductive to this phenomenon.

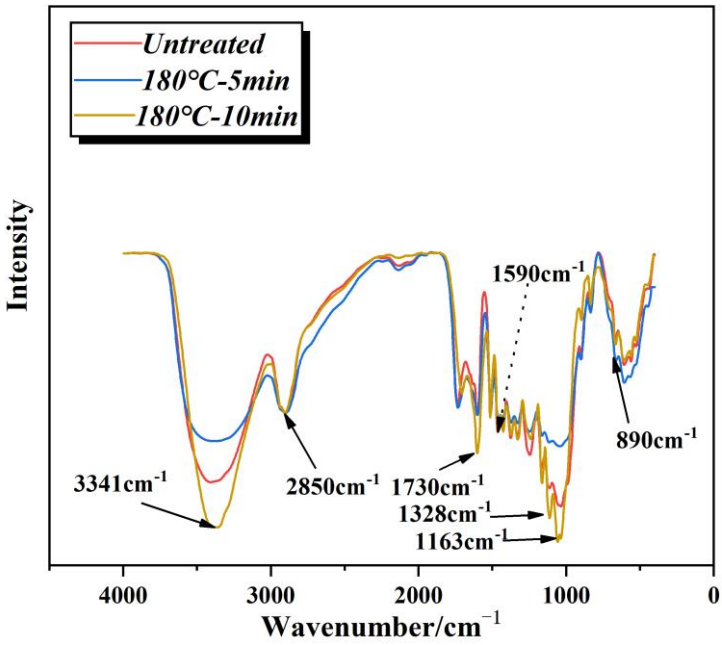

Figure 5. Normalized FTIR curves of bamboo samples at different time and same temperature.

3.6 Cell-wall mechanics

The elastic modulus and hardness values of different treated samples are shown in Figure 6. Results present that thermal treatment contribute positively to the stiffness of bamboo cell wall. For instance, the elastic modulus and hardness values of untreated bamboo fiber wall was around 17.8 GPa and 0.71 GPa. When treated at 160℃/10min, elastic modulus and hardness increased by 4.3% and 13.3%, respectively. When the temperature was set at 180℃ for 10min, their values improved by ca.15% and 36%, respectively. During the process of lignification of bamboo fiber, lignin forms a amorphous network which can enclose the holocellulose, which can improve the stiffness of micromechanical properties. Thus, increased lignin content positively influence the mechanical properties of bamboo cell wall. Increased crystallinity index and decomposition of hemicellulose may also enhance the mechanical properties as reported by wang et al. Therefore, this finding is in agreement with the previous literature(Wang et al. 2017, 2019a, 2020b). Under the conditions of high-temperature and pressure, such as high-temperature and high pressure saturated steam. The increased average micromechanical properties of the bamboo cell-wall was partly due

to the lignin condensation and partly due to the cross-linking reactions of by-products which arised from decomposition of hemicelluloses. In this study, elastic modulus and hardness showed a upward trendency with an increase in treatment temperature and time.

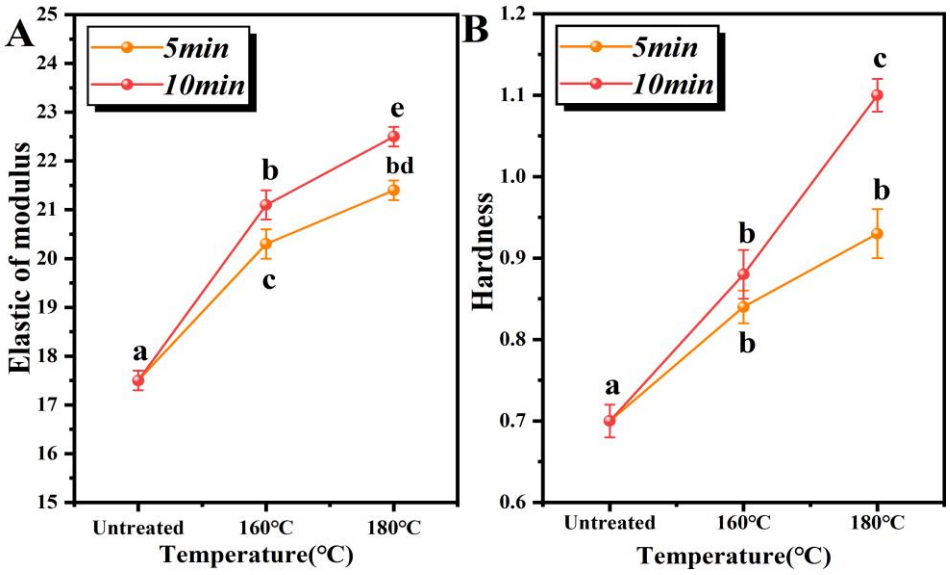

Figure 7. Elastic modulus and hardness of untreated control and bamboo under different temperatures and times periods. The different letters represent significant differences between treatments ($p<0.05$).

3.7 Creep behaviour analysis

As a biomass material, bamboo exhibits visco-elasticity. In addition, creep behavior is an important performance of woody material. The effects of saturated steam heat treatment on the creep ratio of bamboo cell wall were investigated by Nanoidentation. As is illustrated in Figure 8. the average creep ratio of the untreated sample was 27.2%, which was higher than that of the treated bamboo cell wall. In the same time, the treatment parameters of 180℃/10min obviously decreased the creep ratio. For example, The lowest creap ratio of bamboo sample was observed at 180℃/10min, which means the resistance of creep improved. Hemicellulosesare important components that may account for this creep behavior. As discussed above, when the treatment was performed at 180℃ or higher, the treatment severity contributed to a reduction in the content of hemicelluloses. Hemicellulose plays a matrix role in the cell wall, which is weakened by the decomposition of hemicellulose due to the high temperature and pressure condition. The condensation of lignin and the increased crystallinity may also contribute to this phenomenon(Qu et al. 2020).

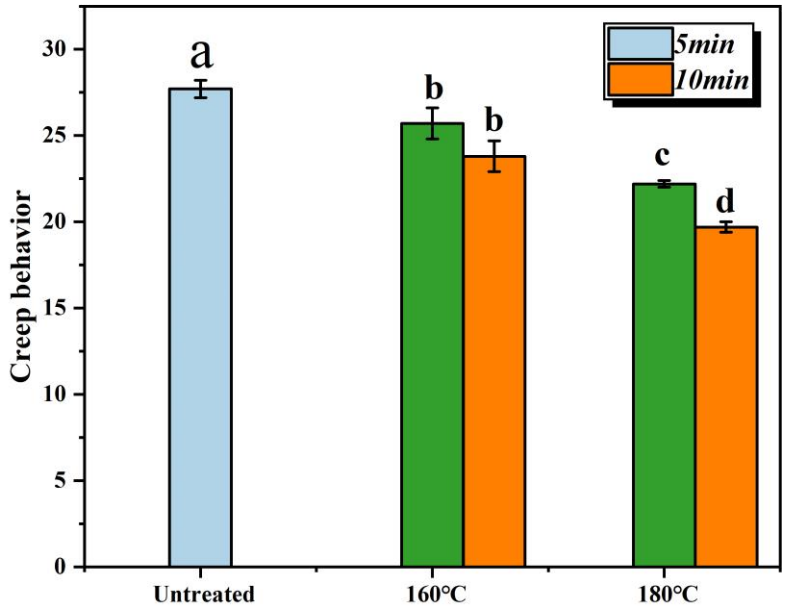

Figure 7. The creep ratios of bamboo fiber wall after saturated steam heat treatment. The different letters represent significant differences between treatments ($p < 0.05$).

3.8 Dynamic mechanical properties of bamboo fiber wall

Figure.8 represents the relationship between the dynamic indentation of bamboo fiber wall and frequency. Accordingly, the loss modulus, storage modulus, and loss tangent of differently treated bamboo samples were lower than that of the untreated sample, the storage modulus and loss tangent decreased with an increase of temperature, which was mainly owing to the fact that the decomposition of hemicellulose and melting. In addition, the storage modulus increased slightly with an increase of temperature while loss tangent decreased significantly. This is maybe the relationship between molecular chains and different frequencies. In detail, lower frequency leads to a slight influence on flexible molecular chains; The main chain negatively corresponds to frequency, in other the main chain movements decreased with increasing frequency. In conclusion, the loss modulus decreased significantly. Enhanced frequency contributed negatively to the loss tangent, this is due to the shorter molecular chain rearrangement time resulting in the stiffening of material(Yang et al. 2020; Hao et al. 2021). Figure 8. (D) (E) (F) presents the influence of different frequencies on the storage modulus, loss modulus, and loss tangent of different duration treated bamboo

samples. Treatment time has slight effect on the dynamic mechanical properties of moso bamboo.

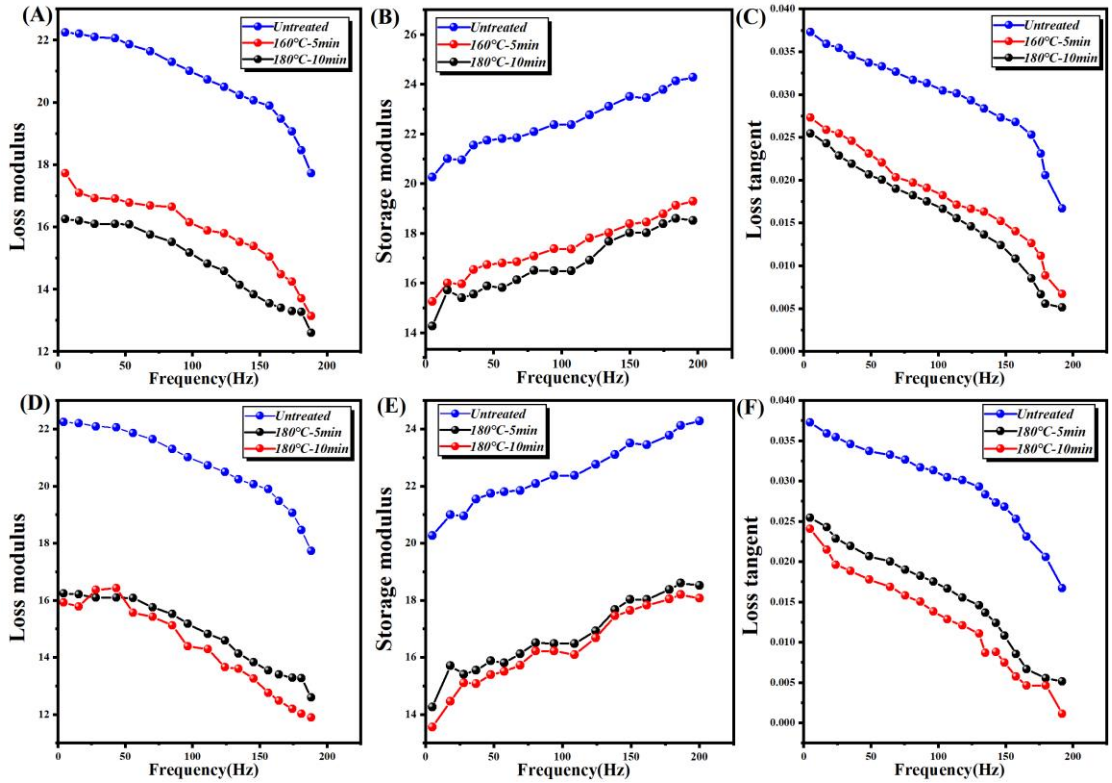

Figure.8 The dynamic mechanical properties of bamboo cell-wall at different temperature and time. A and D: E_r''(loss modulus); B and E: E_r' (storage modulus); C and F: tan δ (loss tangent).

4. Conclusions

The average density and mass of the saturated steam heat treatment treated bamboo decreased with an increase in temperature and time. Saturated steam can effectively reduce the content of hemicellulose and increased the crystallinity index. The bamboo cell wall shrunk due to the high temperature and high pressure. However, the modulus of elastic and hardness of bamboo cell wall increased from 19.8GPa to 25.5GPa and from 0.68GPa to 1.1GPa due to the increased lignin content and increased crystallinity degree. The observation was confirmed by wet chemical method, FTIR, XRD, and Nanoindentation. Furthermore, dynamic indentation revealed a decreased loss modulus and loss tangent and enhanced storage modulus during thermal modification. the $\mathbf{E_r'}$ of differently treated bamboo increased with increasing temperature and time, while the $\mathbf{E_r''}$ and tan δ negatively as a function of increasing frequency.

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Conflicts of Interest: The authors declare no conflict of interest.

Ethical Compliance

Research experiments conducted in this article with animals or humans were approved by the Ethical Committee and responsible authorites of our research organization (s) following all guidelines, regulations, legal, and ethical standards as required for humans or animals.

Reference

Guan M, Tang X, Du K, et al (2020) Fluorescence characterization of the precuring of impregnated fluffed veneers and bonding strength of scrimber in relation to drying conditions. Drying Technology 1–8. https://doi.org/10.1080/07373937.2020.1786109

Hao X, Wang Q, Wang Y, et al (2021) The effect of oil heat treatment on biological, mechanical and physical properties of bamboo. J Wood Sci 67:26. https://doi.org/10.1186/s10086-021-01959-7

He Q, Zhan T, Ju Z, et al (2019a) Influence of high voltage electrostatic field (HVEF) on bonding characteristics of Masson (Pinus massoniana Lamb.) veneer composites. Eur J Wood Prod 77:105–114. https://doi.org/10.1007/s00107-018-1360-6

He Q, Zhan T, Zhang H, et al (2019b) Robust and durable bonding performance of bamboo induced by high voltage electrostatic field treatment. Industrial Crops and Products 137:149–156. https://doi.org/10.1016/j.indcrop.2019.05.010

Huang X, Xie J, Qi J, et al (2018) Differences in physical–mechanical properties of bamboo scrimbers with response to bamboo maturing process. Eur J Wood Prod 76:1137–1143. https://doi.org/10.1007/s00107-018-1293-0

Li T, Cheng D, Wålinder MEP, Zhou D (2015) Wettability of oil heat-treated bamboo and bonding strength of laminated bamboo board. Industrial Crops and Products 69:15–20. https://doi.org/10.1016/j.indcrop.2015.02.008

Ohmae Y, Saito Y, Inoue M, Nakano T (2009) Mechanism of water adsorption capacity change of bamboo by heating. Eur J Wood Prod 67:13–18. https://doi.org/10.1007/s00107-008-0281-1

Qu L, Wang Z, Qian J, et al (2020) Effects of aluminum sulfate soaking pretreatment on dimensional stability and thermostability of heat-treated wood. Eur J Wood Prod. https://doi.org/10.1007/s00107-020-01616-8

Tang T, Chen X, Zhang B, et al (2019) Research on the Physico-Mechanical Properties of Moso Bamboo with Thermal Treatment in Tung Oil and Its Influencing Factors. Materials 12:599. https://doi.org/10.3390/ma12040599

Wang, Chen, Xie, et al (2019a) Multi-Scale Evaluation of the Effect of Phenol Formaldehyde Resin Impregnation on the Dimensional Stability and Mechanical Properties of Pinus Massoniana Lamb. Forests 10:646. https://doi.org/10.3390/f10080646

Wang Q, Wu X, Yuan C, et al (2020a) Effect of Saturated Steam Heat Treatment on Physical and Chemical Properties of Bamboo. Molecules 25:1999. https://doi.org/10.3390/molecules25081999

Wang X, Li Y, Deng Y, et al (2016) Contributions of Basic Chemical Components to the Mechanical Behavior of Wood Fiber Cell Walls as Evaluated by Nanoindentation. BioResources 11:6026–6039. https://doi.org/10.15376/biores.11.3.6026-6039

Wang X, Li Y, Wang S, et al (2017) Temperature-dependent mechanical properties of wood-adhesive bondline evaluated by nanoindentation. The Journal of Adhesion

93:640–656. https://doi.org/10.1080/00218464.2015.1130629

Wang X, Song L, Cheng D, et al (2019b) Effects of saturated steam pretreatment on the drying quality of moso bamboo culms. Eur J Wood Prod 77:949–951. https://doi.org/10.1007/s00107-019-01421-y

Wang X, Yuan Z, Zhan X, et al (2020b) Multi-scale characterization of the thermal – mechanically isolated bamboo fiber bundles and its potential application on engineered composites. Construction and Building Materials 262:120866. https://doi.org/10.1016/j.conbuildmat.2020.120866

Wang X, Zhao L, Deng Y, et al Effect of the penetration of isocyanates (pMDI) on the nanomechanics of wood cell wall evaluated by AFM-IR and nanoindentation (NI). 9

Wang X, Zhao L, Xu B, et al (2018) Effects of accelerated aging treatment on the microstructure and mechanics of wood-resin interphase. Holzforschung 72:235–241. https://doi.org/10.1515/hf-2017-0068

Yang L, Lou Z, Han X, et al (2020) Fabrication of a novel magnetic reconstituted bamboo with mildew resistance properties. Materials Today Communications 23:101086. https://doi.org/10.1016/j.mtcomm.2020.101086

Yuan T, Liu J, Hu S, et al (2021) Multi-scale characterization of the effect of saturated steam on the macroscale properties and surface changes of moso bamboo. 11:9

Yuan Z, Wu X, Wang X, et al (2020) Effects of One-Step Hot Oil Treatment on the Physical, Mechanical, and Surface Properties of Bamboo Scrimber. Molecules 25:4488. https://doi.org/10.3390/molecules25194488

Zhang YM, Yu YL, Yu WJ (2013) Effect of thermal treatment on the physical and mechanical properties of phyllostachys pubescen bamboo. Eur J Wood Prod 71:61–67. https://doi.org/10.1007/s00107-012-0643-6

Zhu W, Yao Y, Zhang Y, et al (2020) Preparation of an Amine-Modified Cellulose Nanocrystal Aerogel by Chemical Vapor Deposition and Its Application in CO_2 Capture. Ind Eng Chem Res 59:16660–16668. https://doi.org/10.1021/acs.iecr.0c02687