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ARTICLE

Effect of Steam Explosion Technology Main Parameters on Moso Bamboo and Poplar Fiber

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ABSTRACT

One of the large-scale industrial applications of Moso bamboo and poplar in China is the production of standardized fiberboard. When making fiberboard, a steam blasting pretreatment without the addition of traditional adhesives has become increasingly popular because of its environmental friendliness and wide applicability. In this study, the steam explosion pretreatment of Moso bamboo and poplar was conducted. The steam explosion pressure and holding time were varied to determine the influence of these factors on fiber quality by investigating the morphology of the fiber, the mass ratio of the unexploded specimen at the end face, the chemical composition, and the tensile strength. The following conclusions were drawn: As the steam burst pressure and holding time increased, more cellulose and hemicellulose degradation occurred (the degradation of hemicellulose was greater than that of cellulose), the lignin content rose, and the fiber bundle strength decreased. The degradation of bamboo cellulose was slightly higher than that of poplar, and the degradation of poplar hemicellulose was significantly faster than that of bamboo. Furthermore, increasing the steam explosion pressure and pressure holding time could not effectively increase the lignin content. It is recommended to use a steam blasting pressure of 2.5 MPa or 3.0 MPa and a holding time of 180 s to perform steam blasting on bamboo and poplar specimens.

KEYWORDS

Fiber; binderless fiberboard; steam explosion; moso bamboo; poplar

1 Introduction

Most wood has a long growth cycle and slow recovery after felling. Improper felling can easily cause irreparable damage to the environment. China's *per capita* forest area share and overall forest coverage are lower than the world average [1]. This, combined with the implementation of natural forest resource protection projects since 1998, has caused the country's wood supply to significantly lag behind the demand. Therefore, finding suitable fast-growing biomass resources has become a research hotspot.

Bamboo and poplar are often used in Chinese plantation forests as supplementary or alternative resources for natural forest timber. Bamboo has the advantage of being the fastest growing plant in the world [2]; it can be grown in 4–5 years, and its physical and mechanical performance is stable [3].

Although there are more than 1,200 species of bamboo [4], Moso bamboo is the most common choice for plantation forests. China's existing bamboo forest area is about 6.41 million hm^2, of which the Moso bamboo forest area accounts for 4.68 million hm^2 (i.e., 72.96%) [5]. Poplar is a tree species with the advantages of fast growth, high yield, long annual growth, and wide adaptability. It is the preferred tree species for short-cycle industrial timber forests in China and one of the three most important fast-growing tree species for the development of fast-growing plantations in the world [6]. However, there are drawbacks to both Moso bamboo and poplar. Moso bamboo is hollow, cracks easily, rots easily, has sharp points, and is difficult to use in large-scale industrialization. Poplar has a loose fiber structure, relatively poor material quality, and greatly limited scope of application.

The main large-scale industrial applications of Moso bamboo and poplar are the production of standardized fiberboard, recombinant bamboo [7–9], and recombinant wood [10,11]. Conventional fiberboard is made by applying a certain amount of urea-formaldehyde resin or other adhesives to fiber. Urea-formaldehyde resin adhesive gradually releases free formaldehyde during use, posing a health threat to end users. There are two main methods adopted to solve the problem of free formaldehyde release: (1) using formaldehyde-free adhesives, and (2) implementing adhesive-free gluing. However, formaldehyde-free adhesives are expensive, and their adhesive performance is poor. Adhesive-free gluing shows greater potential for application to fiberboard production.

Adhesive-free gluing utilizes a synthetic resin adhesive (e.g., urea-formaldehyde resin or phenolic resin) to achieve "self-cementing" and adhesion. The success of the adhesion process depends upon the chemical composition of the wood material (biomass) and the ambient conditions. There are many board forming technologies, including the chemical catalysis method, the enzyme activation method, and various natural substance conversion methods (such as the common hot pressing method, steaming hot pressing method, and steam explosion pretreatment method). The chemical catalysis method causes secondary pollution, the enzyme activation method is cumbersome, and the water resistance and strength of the plate pressed by the common hot-pressing method and the steaming hot-pressing method are low. In comparison, the steam explosion pretreatment method is much more desirable since it causes no pollution to the environment and can realize the conversion of raw natural materials; for this reason it has gradually become a research hotspot.

Many studies have reported on the use of steam explosion treatments in particleboard and fiberboard fabrication. For example, Lu et al. [12] used a high-temperature and high-pressure blasting treatment on I-72 poplar to prepare binderless particleboard. It was found that the performance of the binderless particleboard prepared by poplar fiber treated with a blasting pressure of 3.0 MPa and a holding time of 1 min was good, but the modulus of rupture (MOR) was only 17.7 MPa, and the internal bonding strength (IB) was 0.183 MPa in boiling water for 2 h. Ziegler-Devin et al. [13] used steam explosion to treat Short Rotation Coppice willow. Sauvageon et al. [14] used steam explosion to prepare cottonized hemp fibers and pointed out that the best parameters were time = 4.1 min and temperature = 191°C. Chadni et al. [15] used steam explosion to treat spruce sawdust to extract high molecular weight hemicelluloses. Laemsak et al. [16] used steam explosion technology to treat oil palm leaves to prepare binderless boards. The fiber pressed under the conditions of steam pressure 2.45 MPa and holding time 5 min had the highest strength. When the density was 1.2 g/cm^3, the binderless fiberboard met the requirements of S-20 grade in JISA5905-1994 (fiberboard). Quintana et al. [17] studied the steam explosion technology of banana bundles to prepare binderless fiberboard and reported that the quality of the fiberboard was good at a steam pressure of 2.0 MPa and a holding time of 40–80 min. Mancera et al. [18] added treated lignin to grape branches treated by steam explosion to prepare binderless fiberboard. The treatment temperature was 218°C, and the holding time was 6 min. Takagi et al. [19] prepared bamboo fiber and bamboo powder by treating bamboo once at 170°C and 40 min, and seven times at 175°C and 6 min. Karakoti et al. [20] used steam explosion to separate ultrafine fibers from hibiscus fibers, with a steam pressure of 2.0 MPa and a holding time of 60 min. A team of researchers headed by Luo et al. [21–24] prepared a binderless fiberboard via steam explosion, using bamboo as raw material under a steam pressure of 3.0 MPa and a holding time of 180 s. The fiberboard's MOR and IB were 15.9 MPa and 0.48 MPa, respectively. On this basis, poplar fiber and walnut shell powder were added to improve the performance of the fiberboard. Luo et al. [25] used steam blasting to treat palms. The experiments showed that the performance of the binderless board pressed with palm fiber after steam explosion treatment was greatly improved compared with the untreated palm binderless board. By processing reeds via steam explosion, the effects of steam explosion pressure and holding time on fiber morphology, wettability, chemical composition, and ash and silicon content were analyzed [26].

The above studies conducted research on the preparation of fiberboard by steam explosion, with the findings demonstrating that the performance of fiberboard is directly related to the quality of the fiber prepared, and the quality of the fiber depends on the main factors of steam explosion pressure and holding time [27]. However, there are few reports on the effects of steam explosion pressure and holding time on the quality of Moso bamboo and poplar fiber.

In this study, steam explosion pretreatment was conducted on a large number of Moso bamboo and poplar samples sourced from China. The morphology of the fiber, the mass ratio of the specimen at the end face, the chemical composition, and the tensile strength were compared before and after steam explosion and under various steam explosion parameters to determine the effects of different steam explosion pressures and holding times on fiber quality. Finally, the best steam explosion pressure and holding time were identified to provide a reference for further research on the steam explosion pretreatment of plant fibers.

2 Material and Methods

2.1 Material Preparation and Pretreatment

Poplar (Populus × euramericana 'San Martino' I-72) veneer and Moso bamboo (*Phyllostachys edulis*) branches were respectively obtained from Huai'an City of Jiangsu Province and the Forest area of Nanjing Forestry University in China. The average basic density of poplar specimens was 390 kg/m^3, and the average basic density of bamboo specimens was 720 kg/m^3.

First, the poplar veneer was cut into wood chips of 4–6 cm in length, 1.5–2.5 cm in width, and 0.2 cm in thickness, and bamboo branches were cut into bamboo chips of 2.5–5.5 cm in length, 0.5–1 cm in width, and 0.5–1 cm in thickness. Next, the poplar and bamboo chips were soaked in water for 1 h at 25°C. Finally, steam explosion of bamboo and poplar chips was carried out by changing the steam explosion pressure and holding time.

2.2 Experimental Device

For our observations, we used a ZW-U500 optical microscope produced by Shenzhen Zhongwei Kechuang Technology Co., Ltd., an Austria Bauer-MCNett fiber sieving instrument, a YJ-IID constant load testing machine (loading speed: 0.5 mm/min) developed by Yantai Xintiandi Test Technology Co., Ltd., and a digital micrometer (accuracy: ± 0.003 mm) produced by Shanghai Siwei Instrument Manufacturing Co., Ltd.

The environmental parameters of the tests were temperature 20–25°C and humidity 50%–60%.

2.3 Steam Explosion

Steam ejection was carried out by a QBS-80, which is capable of the sudden release of high-density energy within 0.0875 s [28]. The steam exploding chamber of the QBS-80 is made of 2Cr13 stainless steel, and its volume is 400 mL.

The steam explosion pressures used in the tests were 2.0 MPa, 2.5 MPa, and 3.0 MPa, and the pressure holding times were 120 s, 140 s, 160 s, 180 s, and 200 s.

2.4 Chemical Analysis

Phenyl alcohol extraction in the chemical composition analysis was conducted in accordance with the provision GB10741-1989; the National Renewable Energy Laboratory (NREL) in the provision was adopted for cellulose, hemicellulose, and lignin content tests.

2.5 Morphology and Evaluation Criteria

After steam explosion, the fibers were naturally dried and finely ground, and the sieving value of the fibers was determined by the Bauer-MCNett fiber sieving instrument according to the relevant method in TAPPI T233.

The unexploded test piece on the end face refers to a test piece where at least one end face cannot form fiber separation under steam explosion.

In the tensile strength test, the fiber bundle diameters of poplar and bamboo were about 0.23 mm and 0.15 mm, respectively. Fifty fiber bundles were selected for each working condition. The fiber bundles were subjected to a quasi-static tensile test with the YJ-IID constant load tester at a tensile distance of 20 mm, and the tensile force F was measured. The fiber cross-sectional area A was measured using a ZW-U500 optical microscope. The fiber tensile strength was calculated by $\sigma = F/A$, and the average value was calculated as the basis for analysis and comparison.

3 Results and Discussion

3.1 Fiber Morphology

The ZW-U500 optical microscope was used to observe the morphology of fiber after steam explosion with various parameters, as shown in Figs. 1–6.

(a) (b) (c) (d) (e)

Figure 1: Poplar fiber under steam explosion pressure of 2.0 MPa. (a) 120 s, (b) 140 s, (c) 160 s, (d) 180 s, (e) 200 s

(a) (b) (c) (d) (e)

Figure 2: Poplar fiber under steam explosion pressure of 2.5 MPa. (a) 120 s, (b) 140 s, (c) 160 s, (d) 180 s, (e) 200 s

(a) (b) (c) (d) (e)

Figure 3: Poplar fiber under steam explosion pressure of 3.0 MPa. (a) 120 s, (b) 140 s, (c) 160 s, (d) 180 s, (e) 200 s

(a) (b) (c) (d) (e)

Figure 4: Bamboo fiber under steam explosion pressure 2.0 MPa. (a) 120 s, (b) 140 s, (c) 160 s, (d) 180 s, (e) 200 s

(a) (b) (c) (d) (e)

Figure 5: Bamboo fiber under steam explosion pressure 2.5 MPa. (a) 120 s, (b) 140 s, (c) 160 s, (d) 180 s, (e) 200 s

(a) (b) (c) (d) (e)

Figure 6: Bamboo fiber under steam explosion pressure 3.0 MPa. (a) 120 s, (b) 140 s, (c) 160 s, (d) 180 s, (e) 200 s

It can be seen from Fig. 1 that when the steam explosion pressure was 2.0 MPa, the holding times of 120–200 s had a poor effect on the overall blasting of poplar fibers, and the fibers were not well separated.

It can be seen from Fig. 2 that when the steam explosion pressure was 2.5 MPa and the holding time was 120–140 s, the poplar fibers were not well separated, but the effects were better than at the steam explosion pressure of 2.0 MPa. When the holding time was 160 s, the separation between the fibers was sufficient, and there was a small amount of visible debris. At a holding time of 180 s, the fiber separation was more uniform and sufficient, with a small amount of debris. At a holding time of 200 s, the amount of fiber debris increased significantly, and there was a small amount of fiber coking.

It can be seen from Fig. 3 that when the steam explosion pressure was 3.0 MPa and the holding time was 140 s, the poplar fiber separation effect was equivalent to the fiber separation effect of the steam explosion pressure of 2.5 MPa and the holding time of 160 s. When the holding time was 160 s, individual fibers were coked. When the holding time was 180 s, the fiber separation was uniform and sufficient, and the amount of coked fiber increased slightly. When the holding time was 200 s, the amount of fiber debris increased significantly, and the fiber coking was serious.

It can be seen from Fig. 4 that when the steam explosion pressure was 2.0 MPa, the holding times of 120–200 s had a poor effect on the overall explosion of bamboo fibers, and the fibers were not well separated. The separation effect of bamboo fiber was worse than that of poplar fiber under the same conditions. It can be seen from Fig. 4(a) that the separation of bamboo fibers mainly occurred in the parenchyma tissues between the vascular bundles.

It can be seen from Fig. 5 that when the steam explosion pressure was 2.5 MPa and the holding time was 120–140 s, the bamboo fibers were not well separated, but the separation was better than with the steam explosion pressure of 2.0 MPa and holding time of 120–180 s. At a holding time of 160 s, the separation between the fibers was sufficient, and there was a small amount of visible debris. At a pressure holding time of 180 s, the fiber separation was more uniform and sufficient, with a small amount of debris, but there were still some bamboo segments that were not blasted and separated. When the pressure holding time was 200 s, the amount of fiber debris increased significantly, and the fiber was scorched a little.

It can be seen from Fig. 6 that at a steam explosion pressure of 3.0 MPa and a holding time of 140 s, the bamboo fiber separation effect was equivalent to that of a steam explosion pressure of 2.5 MPa and a holding time of 160 s. At a holding time of 160 s, the fiber separation was somewhat uniform, and individual fiber coking occurred. When the holding time was 180 s, the fiber separation was more uniform, and the amount of coking fiber increased, but not significantly. When the holding time was 200 s, the fibers were shorter, the amount of fiber debris increased significantly, and the fiber coking was serious.

The poplar fibers after steam explosion (Figs. 1–3) were compared with the bamboo fibers after steam explosion (Figs. 4–6). Under the same pressure and holding time, the bamboo fibers were long and thin, whereas the poplar fibers were short and thick. The main reason is that the average length of the untreated poplar fiber was 1.30 mm, the average diameter was 22.60 μm, and the aspect ratio was 57.43 [29]. So the average length longitudinal fibers was short and the diameter was large. And the presence of wood rays between the longitudinal fibers increased the strength between fibers. The average length of the untreated bamboo fibers was 1.5–2.5 mm, the average diameter was 11–19 μm, the aspect ratio was 80–160 [30]. So the fibers were long, and the diameter was small. And there was no wood ray connection between the fibers, but only parenchyma between the vascular bundles [31]. So the strength between the longitudinal fibers of poplar was higher than that of bamboo, which made the separation of poplar fibers a little more difficult.

As can be seen from Figs. 1–6, the greater the steam explosion pressure and the longer the holding time, the better the fiber separation effect. However, once the pressure and holding time pass a certain threshold, the fibers will scorch.

The Bauer-MCNett fiber sieving instrument was used to sieve the fiber after steam explosion, and the mass ratio of the fiber was calculated with a sieve value below 100 mesh (fiber length 0.15 mm), as shown in Fig. 7. It can be seen from Fig. 7 that the mass ratio of poplar fibers below 100 mesh was significantly higher than that of bamboo. Because the poplar fibers were thinner, shorter, and of lower strength. Also because more of the poplar fibers were oriented longitudinally compared to the bamboo fibers.

The higher the steam explosion pressure and the longer the pressure holding time, the higher the mass ratio of the fiber below sieve value 100 mesh. At the steam explosion pressures of 2.5 MPa and 3.0 MPa, the holding time of 200 s will result in a significant increase in the short fiber mass ratio. In the case of high steam explosion pressure, if the pressure holding time is too long, the material will be excessively degraded, which is unfavorable for the post-production of fiberboard.

The same batch of materials was selected for the test piece, and the data were relatively concentrated, so the standard deviation of the test data was relatively small, and the law obtained from the test was reasonably representative.

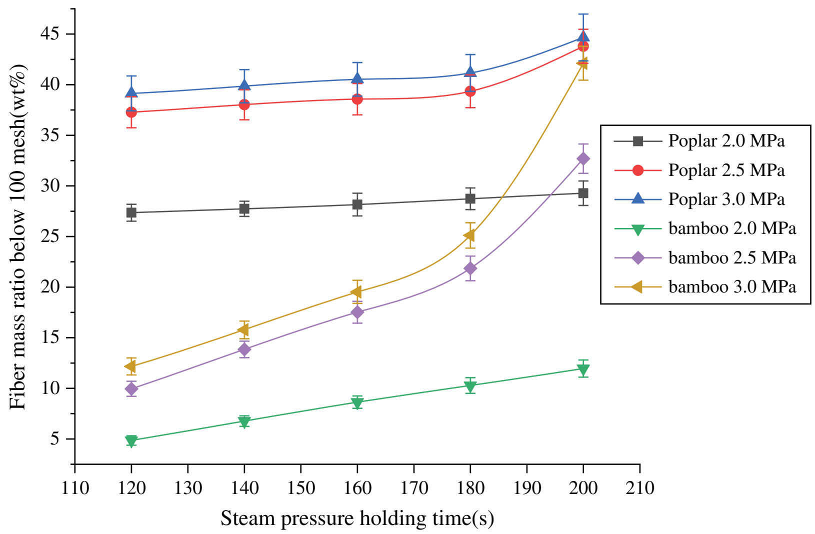

Figure 7: Fiber mass ratio below sieve value 100 mesh

3.2 Mass Ratio of Unexploded Specimens on End Face

To further study the sufficiency of the fiber separation of the test piece under steam explosion, at least one end surface of the test piece that could not form fiber separation was selected after steam explosion, and its mass was compared with the total mass of the test piece to calculate the cross-section. The mass ratio of blasting test pieces is shown in Fig. 8.

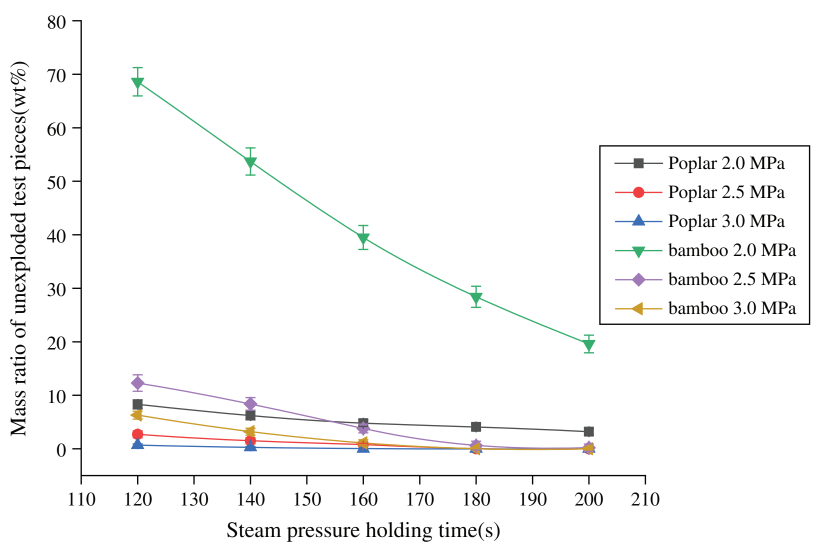

Figure 8: Mass ratio of unexploded test pieces

It can be seen from Fig. 8 that at a steam explosion pressure of 2.0 MPa, the mass ratio of the unexploded specimens of bamboo was significantly higher than that of other cases, mainly because the bamboo specimens were thicker, the longitudinal fiber sides were thin-walled, and there was no direct side channel [31]. When the steam explosion pressure was low, the amount of water vapor entering the parenchyma was low, so when the pressure was suddenly released, the pressure difference between the inside and outside of the bamboo specimen was small. When the steam explosion pressure was 2.0 MPa, the standard deviation of the bamboo specimen was higher than at other working conditions, but this did not affect the analysis of the test results.

When the steam explosion pressure was 2.5 MPa and the holding time was 180 s, fibers were not effectively blasted apart in some individual sections of bamboo specimens. Under the steam explosion pressure of 3.0 MPa and holding time of 180 s, the bamboo and poplar specimens were effectively separated.

3.3 Chemical Composition

Steam explosion technology mainly uses the sudden release of high-temperature and high-pressure water vapor to degrade wood material cellulose and hemicellulose into low molecular sugars and activate lignin. In the later hot-pressing process of preparing binderless fiberboard, the conversion of monosaccharides to furfural, the condensation of lignin and furfural, the combination of lignin and hemicellulose, and other processes can produce adhesion. The material fibers are glued together, so the binderless fiberboard has good performance [27].

To study the chemical composition of bamboo fiber and poplar fiber during steam explosion, the chemical composition of the fiber before and after steam blasting was measured, as shown in Figs. 9–12.

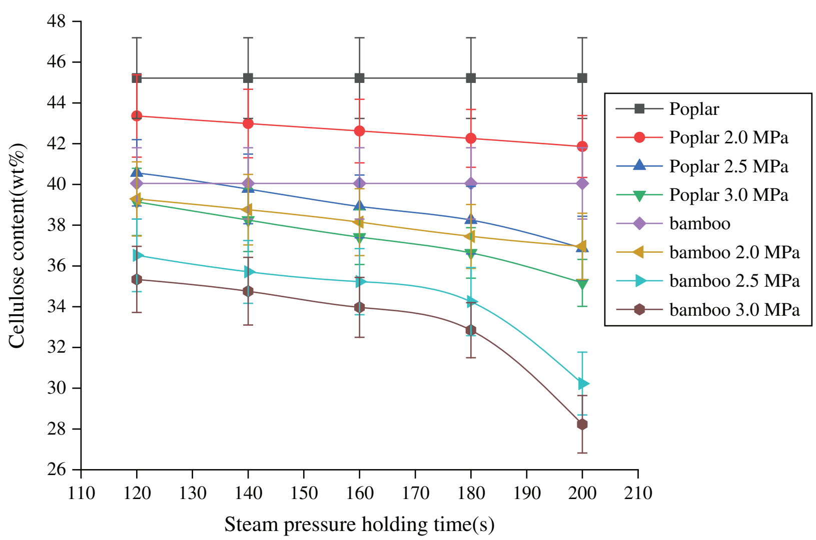

Figure 9: Cellulose content

It can be seen from Figs. 9 and 10 that as the steam explosion pressure and holding time increased, more cellulose and hemicellulose degradation occurred, and the degradation of hemicellulose was greater than that of cellulose. The degradation rate of bamboo cellulose was slightly higher than that of poplar cellulose, and the degradation of poplar hemicellulose was significantly faster than that of bamboo hemicellulose.

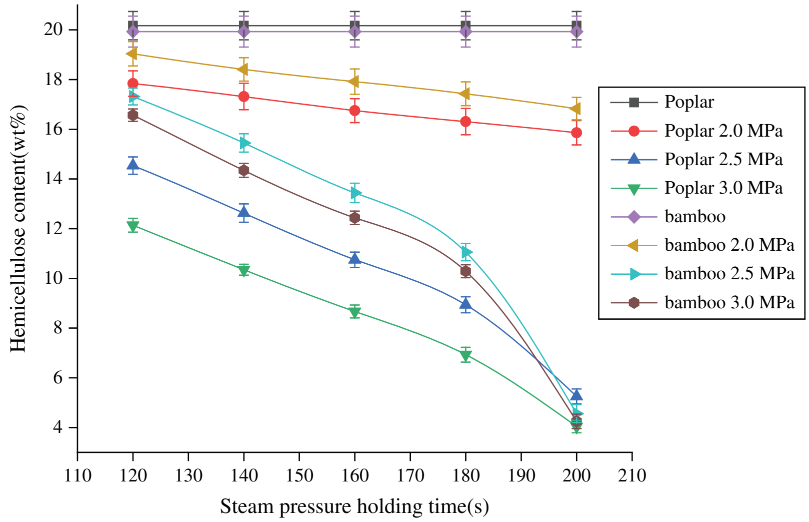

Figure 10: Hemicellulose content

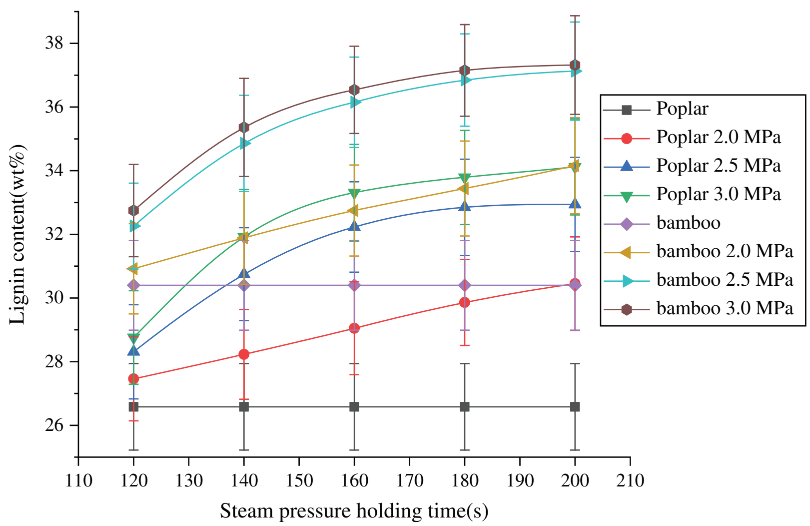

Figure 11: Lignin content

It can be seen from the standard deviation of Fig. 9 that the steam explosion pressure of 2.0 MPa caused no significant change in cellulose content compared with the untreated specimens. From the standard deviation of Fig. 10, it can be seen that the hemicellulose contents of untreated poplar and bamboo were not much different.

When the pressure holding time reached 200 s, under the steam explosion pressures of 2.5 MPa and 3.0 MPa, the degradation of cellulose and hemicellulose tended to accelerate.

It can be seen from Figs. 11 and 12 that steam explosion separated the fibrous cell wall from the intercellular layer. The lignin in the intercellular layer melted and then re-condensed [32]. The small molecules and hemicellulose in the intercellular layer formed a lignin–carbohydrate complex [33], leading to a decrease in the content of cellulose and hemicellulose and an increase in the content of lignin.

Under the steam explosion pressures of 2.5 MPa and 3.0 MPa, the increase of lignin content was not significant, whereas the increase of benzene alcohol extractive content was significant. Considering the standard deviation of the test data, the contents of lignin and benzene alcohol extractive at the steam explosion pressures of 2.5 MPa and 3.0 MPa were not much different. This shows that when the steam explosion pressure is high, once the pressure holding time passes a certain threshold, further increasing it does not effectively increase the lignin content.

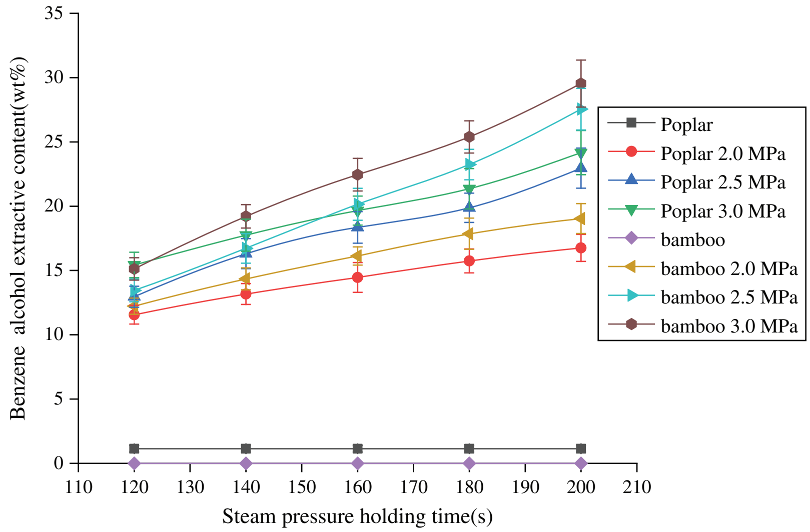

Figure 12: Benzene alcohol extractive content

3.4 Tensile Strength

When the integrity of the fiberboard is guaranteed, the tensile strength of the fiber has the most direct effect on the mechanical properties of the fiberboard. Therefore, the tensile strength of fiber bundles under different steam explosion conditions was studied, as shown in Figs. 13 and 14.

It can be seen from Figs. 13 and 14 that the strength of fiber bundles decreased with the increase of steam explosion pressure and holding time. When the steam explosion pressure was 3.0 MPa, the strength of the poplar fibre bundles decreased further and the mechanical properties of the fibreboards produced in the subsequent hot press were unfavourable. This was mainly due to the decomposition of cellulose and hemicellulose due to steam explosion [27]; when the steam explosion pressure was 3.0 MPa, the degradation rates of cellulose and hemicellulose increased.

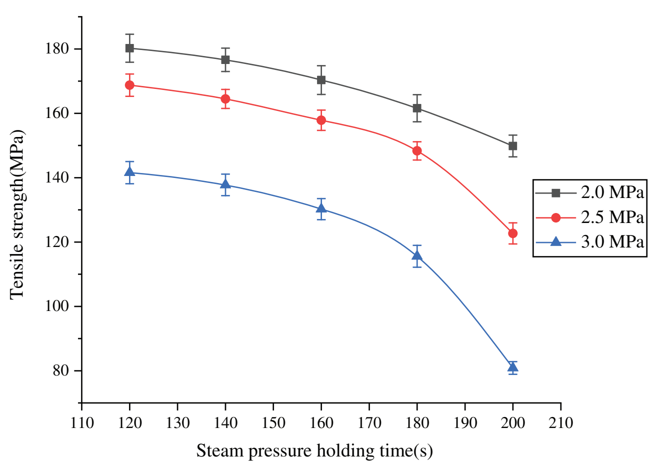

Figure 13: Bamboo fiber bundle strength

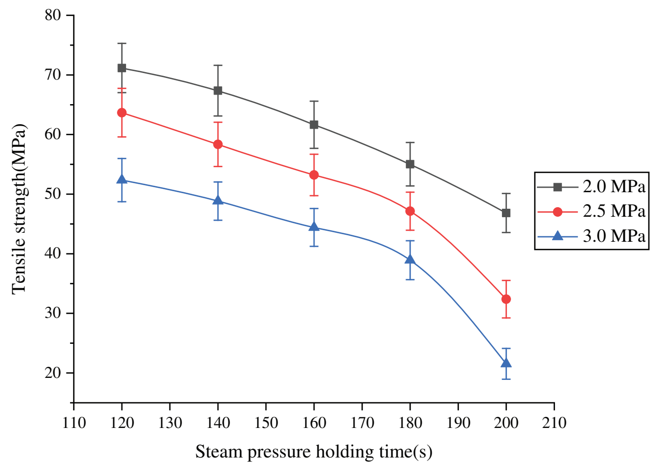

Figure 14: Poplar fiber bundle strength

The test data were relatively concentrated, the standard deviation was small, and the law obtained from the test was representative.

When the pressure holding time reached 200 s, under the steam burst pressure of 2.5 MPa or 3.0 MPa, the strength reduction rate of the fiber bundle increased.

4 Conclusions and Recommendations

4.1 Conclusions

The greater the steam explosion pressure and the longer the holding time, the better the fiber separation effect. It is difficult to separate the fibers with a steam explosion pressure of 2.0 MPa. At a steam explosion pressure of 3.0 MPa and a holding time of 200 s, the material degrades strongly and causes coking.

As the steam explosion pressure and pressure holding time increase, more cellulose and hemicellulose degradation occur (the hemicellulose degrades more than cellulose), and the lignin content rises. The degradation rate of bamboo cellulose is slightly higher than that of poplar cellulose, and the degradation of poplar hemicellulose is significantly faster than that of bamboo hemicellulose. Increasing the steam explosion pressure and pressure holding time cannot effectively increase the lignin content.

The fiber bundle strength decreases with the increase of steam explosion pressure and holding time. Under the steam explosion pressures of 2.5 MPa or 3.0 MPa, when the pressure holding time reaches 200 s, the strength of the fiber bundle decreases rapidly.

4.2 Recommendations

It is recommended to use a steam explosion pressure of 2.5 MPa or 3.0 MPa and a holding time of 180 s to perform steam explosion on bamboo and poplar specimens.

A steam explosion pressure of 2.5 MPa and a holding time of 180 s failed to effectively blast apart fibers of individual bamboo specimens. At a steam explosion pressure of 3.0 MPa and a holding time of 180 s, some fibers had been excessively decomposed, causing coking. If the long-term safe use of the steam explosion equipment is considered, a steam explosion pressure of 2.5 MPa and a holding time of 180 s are the preferred options.

This article is based on the conclusion of low-density fast-growing broad-leaved trees with a density of about 390 kg/m^3 (length 4–6 cm, thickness 0.2 cm) and perennial gramineous plants with a density of about 720 kg/m^3 (length 2.5–5.5 cm, thickness 0.5–1.0 cm). As the density or thickness of the test piece decreases, the steam explosion pressure or holding time can be appropriately reduced, although this relationship needs to be further studied.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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