Dimensional Stability and Mold Resistance of Bamboo Slivers Treated by Alkali

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The aim of this study was to investigate the dimensional stability and mold resistance of slivers from the outer and inner layers of bamboo treated with alkali solutions at various concentrations. The microstructure of the bamboo slivers considerably changed as the parenchyma cells collapsed after alkali treatment followed by a drying process. The water absorption of the treated bamboo slivers increased, while the dimensional stability decreased, especially for the slivers from the inner layer of bamboo. The alkali treatment removed starch from the parenchyma cells in the bamboo slivers treated with a 2% to 15% alkali solution, resulting in a considerable improvement in the mold resistance. The mold resistance performance of inner bamboo slivers was greatly improved when treated at a low concentration (2%). No mold on the bamboo slivers was found even in a high humidity environment for a long period of time, *i.e.* 87 days. As the concentration increased up to 25%, alkali only removed starch from parenchyma cells that were near the surface of the bamboo slivers and caused partial damage to the parenchyma cells in the outer bamboo slivers. The wettability of the alkali-treated bamboo slivers was higher than that of the untreated samples due to the removal of lignin and a rougher surface. Based on the test results, alkali treatment is a simple yet highly effective method for improving mold resistance but would cause a reduction in the dimensional stability of the bamboo slivers.

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Keywords: Bamboo slivers; Alkali treatment; Microstructure; Dimensional stability; Mold resistance

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INTRODUCTION

Bamboo, one of the fastest-growing plants, is usually processed into multi-scale units for different end-uses, *e.g.*, bamboo strips, bamboo slivers, bamboo bundles, and individual bamboo fibers (Yu *et al.* 2014; Yu *et al.* 2015; Deng and Wang 2018; Yang *et al.* 2020). The structure and properties of bamboo units at different scales vary, as bamboo has a gradient structure (Chen *et al.* 2015). Bamboo is traditionally split into bamboo slivers for bamboo weaving products. Recently, the use of bamboo slivers has been expanded to the field of bio-composites (Chen *et al.* 2019; Shi *et al.* 2019; Chen *et al.* 2021c). There are many modification methods for improving the properties of bamboo strips and bamboo fibers, including hot oil, densification with or without delignification, filling resin, and alkali treatment (Das and Chakraborty 2006; Dixon *et al.* 2016; Chen *et al.* 2017; Salvati *et al.* 2018; Kalali *et al.* 2019; Tang et al., 2019; Chen *et al.* 2020a; Li *et* *al.* 2020; Wang *et al.* 2021). However, few studies have reported the effect of modification on bamboo slivers, especially in terms of a comparative study between the slivers from the outer and inner layers of bamboo. Alkali treatment is a popular method for modifying bamboo fibers and other plant fibers to obtain a high-performance reinforcement effect in composites (Cai *et al.* 2015; Huang and Young 2019; Kathirselvam *et al.* 2019; Akinyemi *et al.* 2020; Xia *et al.* 2020). The structure and properties of the treated bamboo fibers were determined according to the alkali treatment conditions, *i.e.*, concentration, time, temperatures, and the size of the bamboo unit itself (Das and Chakraborty 2006; Liu and Hu 2008; Chen *et al.* 2017; Chen *et al.* 2018). According to the previous research, the water absorption of bamboo fiber composites decreased from 61% to 26% when treated with 5% NaOH for 0.5 h, which was due to the reduction of the hydroxyl group in the cell wall of the fiber molecule by chemical treatment (Kushwaha and Kuma 2010). The wettability of bamboo fibers was enhanced when treated by NaOH solution with lower concentrations, while it was reduced with alkali treatment at high concentration (25%) (Chen *et al.* 2018). It was shown that the water absorption and wettability of bamboo fiber were improved after alkali treatment.

The effect of the alkali treatment on bamboo strips is different from its effect on bamboo fibers, in terms of the microstructure, mechanical properties, and cellulose crystallinity (Ray *et al.* 2005; Salvati *et al.* 2018). This could be due to the fact that a bamboo sliver is a specific unit consisting of fibers surrounded by parenchyma matrix, which is not as thick as a bamboo strip. As a result, a gradient structure can be avoided, as suggested in Fig. 1. In previous studies, it was found that parenchyma cells reacted differently with alkali in comparison to fibers (Chen *et al.* 2021b; Yuan *et al.* 2021). The bamboo slivers obtained from the outer layer and inner layer of bamboo have different parenchyma cell volume fractions (Fig. 1b and Fig. 1c). Although processing bamboo into thin bamboo slivers could avoid a gradient structure in a bamboo product, the difference in the parenchyma cell volume fractions of the slivers from the outer and inner layers of bamboo might still cause a discrepancy in the structure and properties.

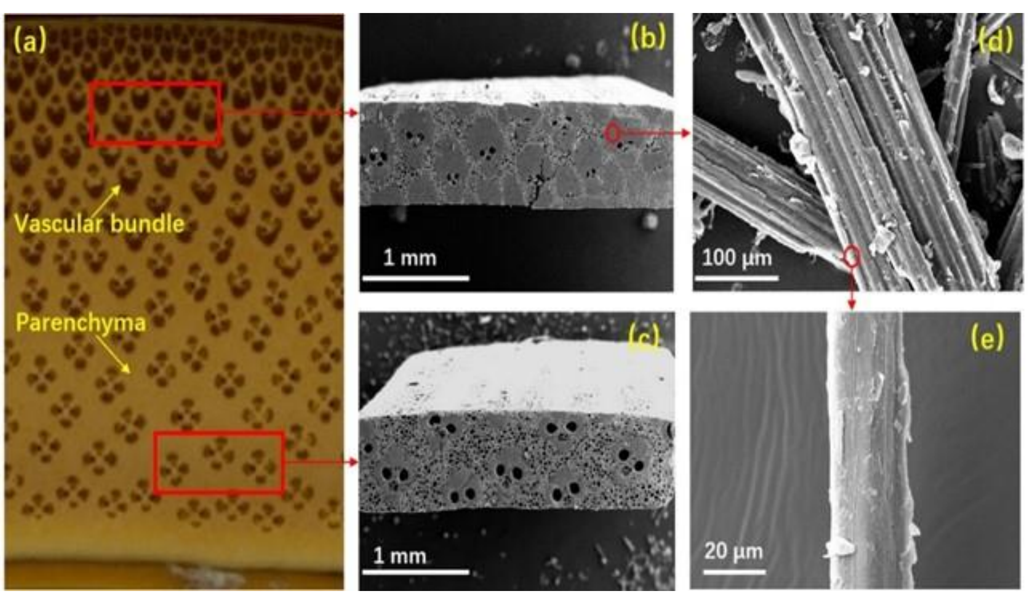


Fig. 1. The structure of the bamboo units at multi-scale: (a) bamboo culm; (b) a sliver from the outer bamboo; (c) a sliver from the inner bamboo; (d) a bamboo fiber bundle; and (e) an individual bamboo fiber

Besides, there are nutritional substances, *i.e.*, starch, sugar, and protein in bamboo, and these are ideal for mold growth when bamboo is stored in a warm and humid environment. The mold can cause discoloration, which has a serious impact on the use, storage, and transportation of bamboo products. Hence, the treatment of bamboo against mold is very important. Many scholars have improved the mold resistance of bamboo by oil heat treatment, acid treatment and ZnO/PMHS coatings, and achieved good results (Chen *et al.* 2019; Hao *et al.* 2021; Yu *et al.* 2022). However, there have been few reports on the influence of alkali treatment on the mold resistance performance of bamboo. A two-step NaOH treatment has been reported to improve mold resistance of bamboo strips, in which the bamboo strips were soaked in 1% NaOH solution at 140 °C after hydrothermal treatment at atmospheric pressure (0.2 to 0.3 MPa), and then the treated bamboo strips were baked at 180 °C for 2 hours (Cheng *et al.* 2013).

In a previous study, the tensile strength and the flexibility of bamboo slivers treated with alkali were drastically improved, especially for the slivers from the inner layer of bamboo, which widely broadens the application of bamboo slivers (Chen *et al.* 2021a). This study further investigated the effect of alkali treatment on the dimensional stability and mold resistance of bamboo slivers. In this research, the microstructure, dimensional stability, water wettability, and mold resistance were examined for bamboo slivers from the outer and inner layers of bamboo and were treated with different alkali solution concentrations.

EXPERIMENTAL

Materials

Sample preparation

Moso bamboo (*Phyllostachys pubescens*) was obtained from Zhejiang, China, and dried to a moisture content of 8% to 12%. The bamboo was cut into bamboo slivers with a length of approximately 120 mm, a width of approximately 4 mm, and a thickness of approximately 1 mm from the outer and inner layers of the bamboo culm, respectively. Then the bamboo slivers were immersed in sodium hydroxide (NaOH) solutions with various concentrations, *i.e.*, 2%, 5%, 10%, 15%, and 25%, for 2 h at room temperature. The treated bamboo slivers were then washed until neutral. All the treated bamboo slivers were dried in an oven at a temperature of 50 °C for 8 h.

Characterization

The surface morphology of the untreated and treated bamboo slivers and the cross-sections of the untreated and treated bamboo slivers after being immersed in water for 12 h were observed with an environmental scanning electron microscopy (ESEM) (FEI Quanta 200, Hillsboro, OR). The pore structure of the bamboo slivers treated with 15% NaOH was obtained *via* micro-computed tomography (Micro-CT) (NanoVoxel 3000, Sanying Precision Instruments Co., Ltd, Tianjin, China). The voltage and current were set at 80 Kv and 60 μA, respectively. The scanning time varied from 1.5 to 3 h, depending on the dimensions of the samples. The water absorption (WA), thickness swelling (TS), width swelling (WS), and volumetric swelling (VS) of the treated and untreated slivers from the outer layer and inner layer of bamboo were calculated according to GB/T standard 1931 (2009), GB/T standard 1934.1 (2009), and GB/T standard 1934.2 (2009), respectively, as shown in Eqs. 1 through 4,

$$\mathrm{WA}(\%) = \frac{m_1 - m_0}{m_0} \times 100 \quad (1)$$

$$\mathrm{TS}(\%) = \frac{t_1 - t_0}{t_0} \times 100 \quad (2)$$

$$\mathrm{WS}(\%) = \frac{w_1 - w_0}{w_0} \times 100 \quad (3)$$

$$\mathrm{VS}(\%) = \frac{v_1 - v_0}{v_0} \times 100 \quad (4)$$

where m_0, t_0, w_0, and v_0 are the weight (g), thickness (mm), width (mm), and volume (g/cm^3) of the untreated and alkali-treated bamboo slivers before being immersed in water for 12 h, respectively, while m_1, t_1, w_1, and v_1 are the weight (g), thickness (mm), width (mm), and volume (g/cm^3) of the corresponding samples after being immersed in water for 12 h. The untreated and alkali-treated bamboo slivers were stored in an ambient environment (a temperature of 20 to 28 °C and relative humidity (RH) of 54% to 72%) for 3 months to examine mold resistance. The contact angles of distilled water on the untreated and treated bamboo slivers were determined with a Krüss DAS100S (Hamburg, Germany). The CCD cameras recorded the process of a water droplet dropping on the bamboo sliver surface. The volume of the water droplet was 2 μL.

RESULTS AND DISCUSSION

Microstructure

Figure 2 shows that the color of the bamboo slivers was altered when treated at different alkali concentrations. The color became increasingly darker as the alkali concentration increased. In addition, the color of the slivers from the inner layer of bamboo was more pronouncedly altered compared to the outer layer of the bamboo when treated at the same alkali concentration.

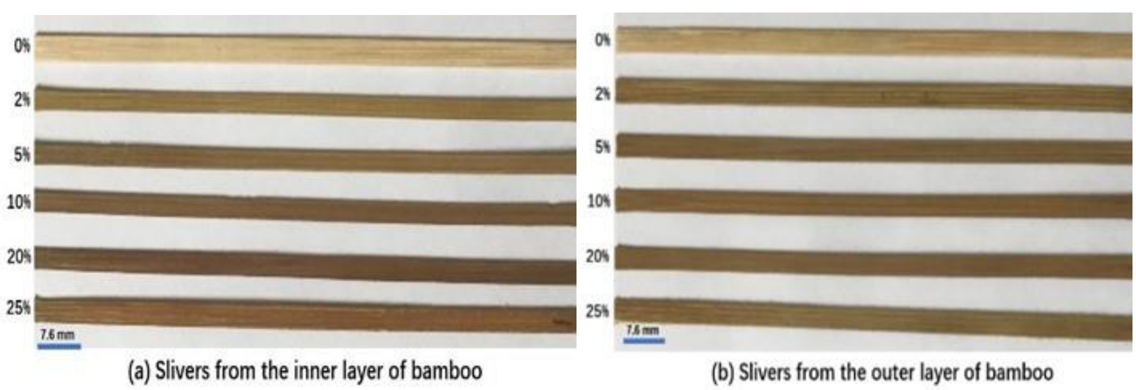


Fig. 2. Photographs of the untreated and treated bamboo slivers showing the change in the color: (a) the inner layer; and (b) the outer layer

Figures 3 and 4 show the parenchyma cells in the slivers from the outer layer and the inner layer of the bamboo, respectively. The collapse of the parenchyma cells was increasingly more severe as the alkali concentration continued to increase, but the damage of the cell walls within the parenchyma cells only occurred when treated at an alkali concentration of greater than 5% and 10% for the slivers from the inner and outer layers of the bamboo, respectively. This indicated that the parenchyma cells in the slivers from the bamboo inner layer were easier to collapse during the alkali treatment in comparison to the parenchyma cells from the outer layer. Meanwhile, the fibers in the slivers were not considerably altered, as shown in Figs. S1 and S2 (see Appendix). The interface between the fibers was degraded when treated with 25% NaOH and the fibers partly separated from the sliver surface, as shown in Fig. S3. The severity of the damage to the parenchyma cells and fibers was different due to the differences in their chemical components, microstructure, and properties, which lead to them reacting differently when treated under the same alkali conditions (Huang *et al.* 2015; Zhang *et al.* 2018; Jin *et al.* 2019; Lian *et al.* 2020; Chen *et al.* 2021b).

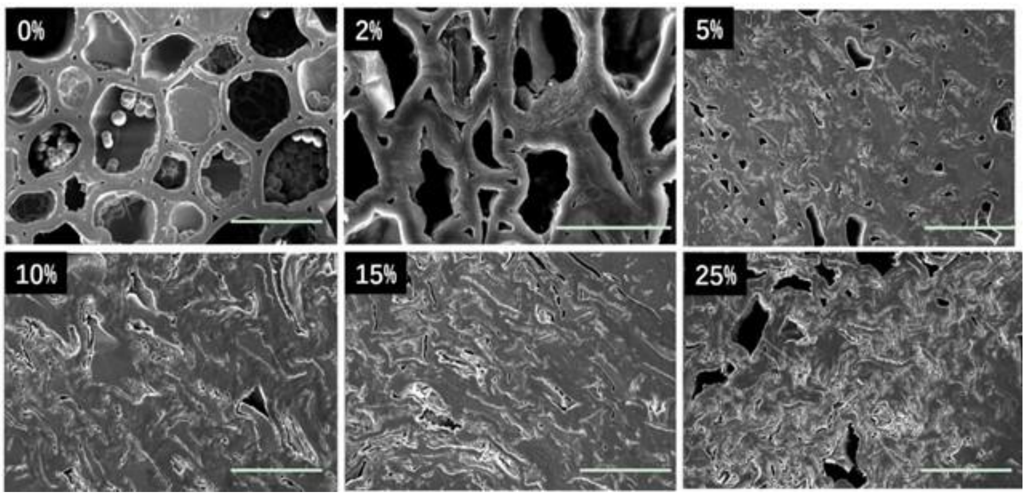


Fig. 3. Cross-section of the parenchyma cells in the slivers from the inner layer of the bamboo treated with different concentrations (scale bar = 50 μm)

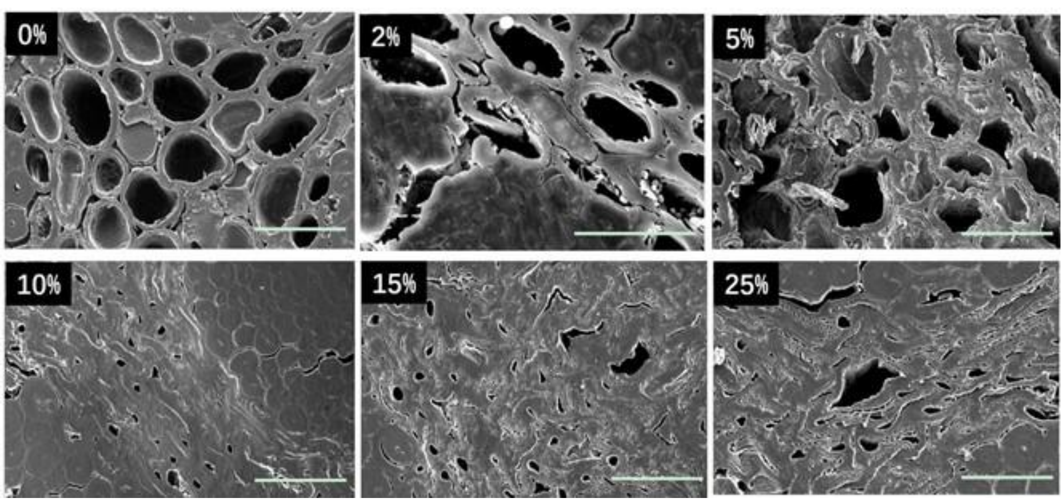


Fig. 4. Cross-section of parenchyma cells in the slivers from the outer layer of the bamboo treated with different concentrations (scale bar = 50 μm)

The density of the bamboo slivers treated with a 15% NaOH solution increased up to the maximum values of 1.7 and 1.45 g/cm^3 for the slivers from the inner and outer layer of the bamboo, respectively (the untreated samples were 0.87 and 1.22 g/cm^3, respectively). Figure 5 shows the corresponding microstructure observed *via* Micro-CT. The parenchyma cells collapsed in a greater amount in the slivers from the inner layer of the bamboo compared to the outer layer. In addition, the parenchyma cells near the surface of the slivers collapsed more pronouncedly than the parenchyma cells in the middle part, especially in the slivers from the outer layer of the bamboo. This was probably due to the fact that the alkali solution could more easily interact with the parenchyma cells near the surface than those in the middle part. The porosity of the untreated slivers from the outer and inner layer of bamboo was 35.52% and 43.64%, respectively. The 15% NaOH treatment resulted in a considerable decrease in the porosity, leading to reductions of 64% and 80%, respectively. This indicated that the parenchyma cells in the inner bamboo samples changed more with respect to the alkali treatment than the outer bamboo samples did.

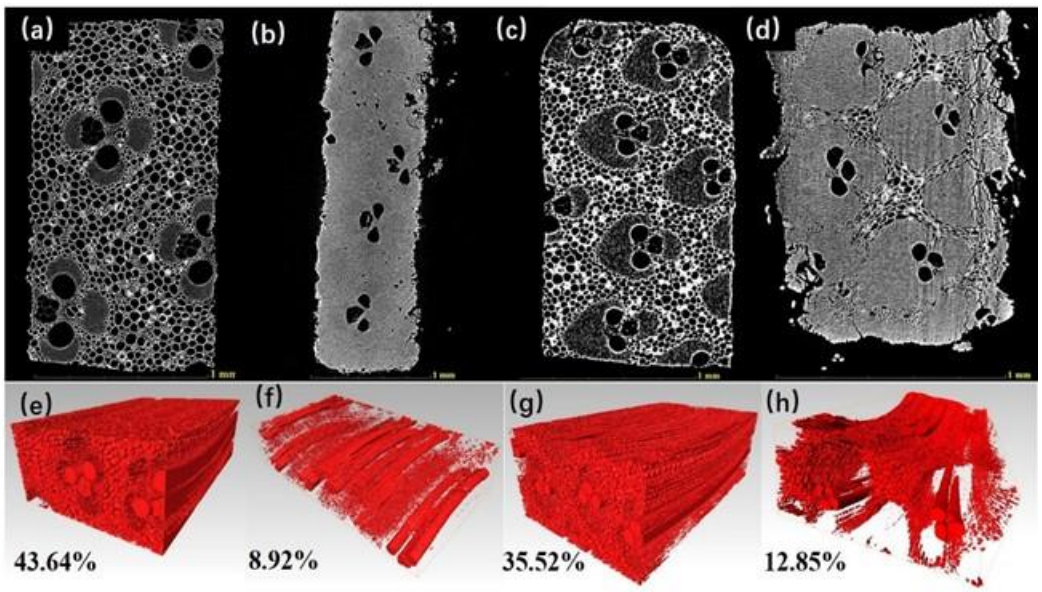


Fig. 5. The cross-sectional morphology and pore structure of the bamboo slivers: (a) and (e) the untreated inner bamboo; (b) and (f) the 15% NaOH treated inner bamboo; (c) and (g) the untreated outer bamboo; and (d) and (h) the 15% NaOH treated outer bamboo

Water Absorption and Dimensional Stability

The water absorption and dimensional stability are shown in Fig. 6. Relevant data are shown in Table S1-S4. The water absorption of the untreated slivers from the inner layer of bamboo was much higher than the water absorption of the untreated slivers from the outer layer of bamboo. The former had a greater amount of parenchyma cells that possessed a larger lumen and thinner cell wall as well as a higher hemicellulose content; as such, they more easily swelled in water (Jin *et al.* 2019; Chen *et al.* 2020b; Lian *et al.* 2020). When treated at various alkali concentrations, the water absorption by the bamboo slivers was higher than the water absorption by the untreated slivers, except for the 15% NaOH treated slivers from the inner layers of the bamboo. This was primarily due to the partial removal of lignin and hemicellulose during the alkali treatment, which led to greater accessibility of the hydroxyl groups (Chen *et al.* 2021b). The increase in the water absorption by the treated slivers from the inner layer of the bamboo was more pronounced than the increase in the water absorption by the treated slivers from the outer layer of bamboo due to the higher volume fraction of parenchyma cells within the inner layer of bamboo.

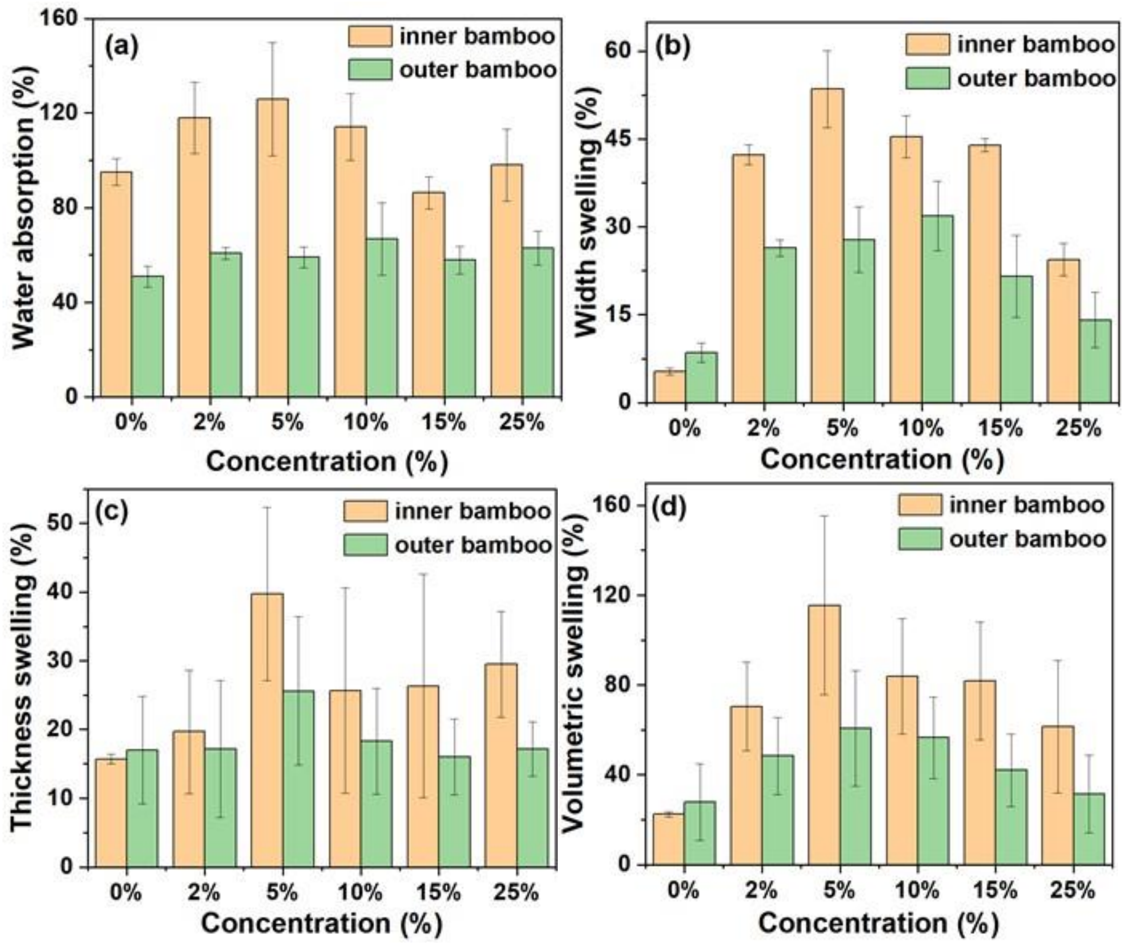


Fig. 6. The water absorption and dimensional stability of the bamboo slivers: (a) water absorption; (b) width swelling; (c) thickness swelling; and (d) volumetric swelling t

The width and thickness swelling amounts of the treated bamboo slivers were higher than the width and thickness swelling of the untreated slivers. The treated bamboo slivers from the inner layer of the bamboo swelled considerably more compared to the treated slivers from the outer layer of the bamboo, as the former had more parenchyma cells, which collapsed more easily during alkali treatment and the subsequent drying process. As shown in Figs. 7 and 8, the parenchyma cells in the treated slivers still collapsed even after the 12-h immersion in water when compared with the untreated slivers. The parenchyma cells had greater swelling in the treated slivers from the inner layer compared to the parenchyma cells from the outer layer of the bamboo after the immersion in water. As shown in Figs. S4 and S5, there was no considerable change in the fibers, which was probably due to the fact that there were more fibers in the slivers from the outer layer of the bamboo compared to the slivers from the inner layer of bamboo. This prevented the parenchyma cells from swelling in the water, as the fibers governed the deformation and movement of the other cell lumens (Chen *et al.* 2020b). Therefore, the parenchyma cells in the slivers from the inner layer of the bamboo collapsed during the alkali treatment and had more pronounced swelling when immersed in water compared to the slivers from the outer layer of the bamboo. The thickness, width, and volume swelling of the slivers from the outer layer and the inner layer of the bamboo reached their maximum when treated with 5% NaOH, which was likely due to the fact that the parenchyma cells collapsed the most severely and there was less damage to the parenchyma cell walls compared to the samples treated at other alkali concentrations.

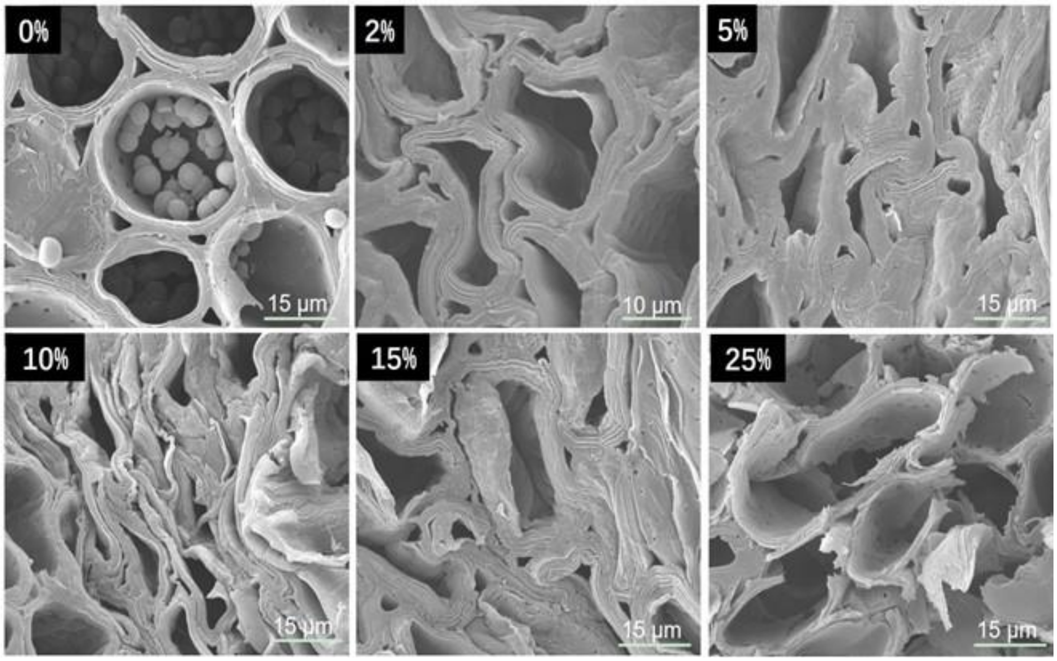


Fig. 7. Parenchyma cells in the slivers from the outer layer of the bamboo after a 12 h immersion in water

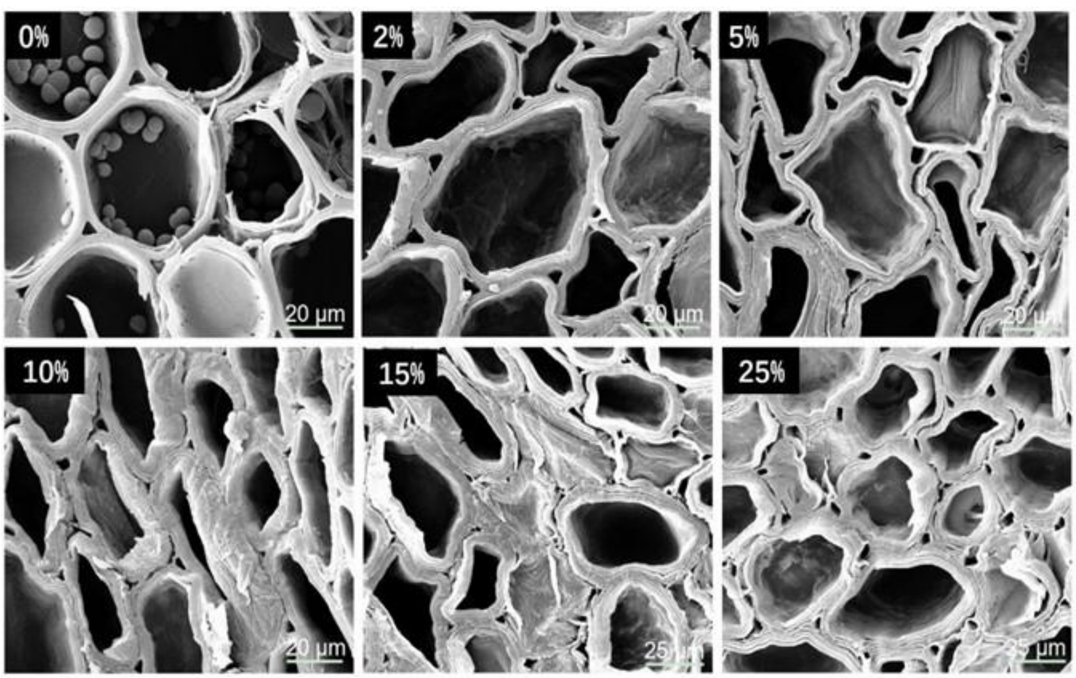


Fig. 8. Parenchyma cells in the slivers from the inner layer of the bamboo after a 12 h immersion in water

Starch

Figures 9 and 10 show the starch in the parenchyma cells in the slivers from the inner and outer layer of the bamboo after a 12 h immersion in water, respectively. There were multiple starch granules in the parenchyma cell in the untreated bamboo slivers (as shown in Fig. S6). When treated with NaOH at a concentration of 15% or lower, the starch was removed from the parenchyma cells from the slivers from both the outer and inner layer of the bamboo after being immersed in water for 12 h (as shown in Fig. 9b and Fig. 10b), as starch in bamboo has a similar amylose content to that of regular cereal starches that were extracted *via* NaOH solutions (Sodhi and Singh 2003; Felisberto *et al.* 2019). However, when treated with a 25% NaOH solution, starch in the parenchyma cells near the surface of the bamboo slivers was removed, while the starch in the middle part of the bamboo slivers still was present in the parenchyma cells (as shown in Fig. 9c and Fig. 10c). This indicated that the alkali treatment at low concentrations more easily penetrated the bamboo compared with a treatment at higher concentrations, possibly because the alkali solution at a high concentration prefers to react severely with bamboo first. This was consistent with the phenomenon that the fibers were peeled off from the sliver surface, as shown in Fig. S3. Therefore, an alkali solution with a lower concentration is more suitable for removing starch from the parenchyma cells in bamboo than an alkali solution with a higher concentration.

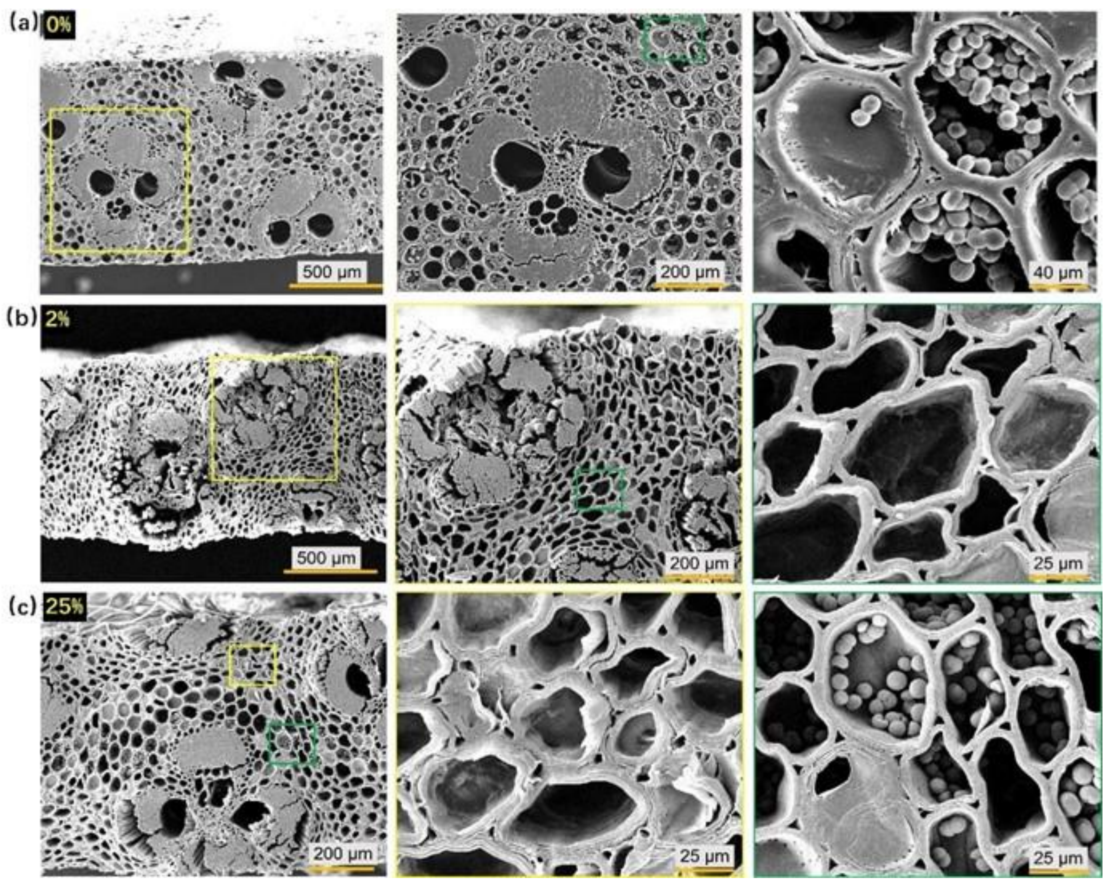


Fig. 9. Starch in the parenchyma cells in the bamboo slivers from the inner layer: (a) untreated; (b) treated with 2% NaOH after 12 h immersion in water; and (c) 25% after 12 h immersion in water

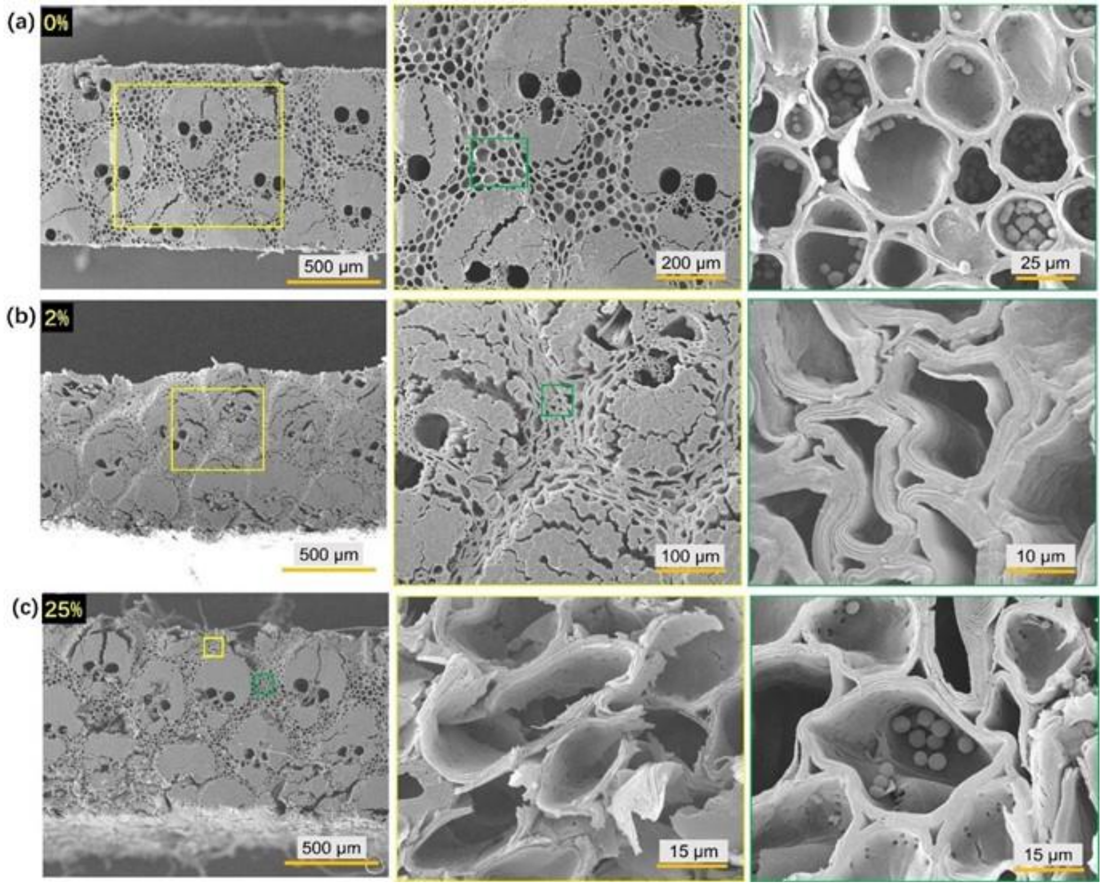


Fig. 10. Starch in the parenchyma cells in the bamboo slivers from the outer layer: (a) untreated; (b) treated with 2% NaOH after 12 h immersion in water; and (c) 25% after 12 h immersion in water

Mold Resistance

To observe the mold resistance of the bamboo slivers, the untreated and treated samples were placed in a room where the temperature and related humidity changed according to the environment for 87 d. The results of the mold resistance test of the treated bamboo slivers are displayed in Fig. 11. Mold occurred on the untreated bamboo slivers from the 10^{th} d and onwards, and there was more mold on the sliver from the inner bamboo compared to the slivers from the outer layer of the bamboo (as shown in Fig. 11b). All the treated bamboo slivers did not have mold, except for the bamboo slivers from the outer bamboo treated with 2% and 25% NaOH solutions, in which mold occurred from the 11^{th} d and onwards (as shown in Fig. 11c). As shown in Fig. 10c, the parenchyma cells near the surface of the bamboo slivers treated with 25% NaOH were broken and there was still starch in the parenchyma cells, which might account for mold appearing on the 11^{th} d. Although the amount of mold on the 25% NaOH treated bamboo slivers was lower at an early stage when compared to the untreated slivers, the mold grew more rapidly and eventually formed the largest amount, as the parenchyma cells with starch were broken. Even though there was also starch in the middle part of the 25% NaOH treated bamboo slivers from the inner layer of the bamboo (as shown in Fig. 9c), the mold resistance was still as good as the slivers treated with alkali at other concentrations, as the parenchyma cells with starch were intact (as shown in Fig. 11). Another reason for the good mold resistance was the collapse of cells. Previous research by the authors showed that the parenchyma cells in the inner and outer bamboo collapsed and formed an interlocking structure at a NaOH concentration greater than 5% (Chen *et al.* 2021a). This made it difficult for mold to enter the internal structures of the bamboo. When the bamboo slivers were treated with 2% NaOH, the starch almost disappeared in the inner bamboo; however, there was still some starch in the outer bamboo slivers (as shown in Fig. 4). That was due to the alkali being prone to reacting with the parenchyma cells, which made the starch in the inner bamboo easier to remove (Chen *et al.* 2021a; Chen *et al.* 2021b). This was why the outer bamboo slivers treated with 2% NaOH were still molded. The chemical analysis in previous research by the authors showed that the hemicellulose in the bamboo slivers was considerably reduced after the 2% NaOH treatment (Chen *et al.* 2021a). Hemicellulose is a polymer composed of different monosaccharides, which could be directly used as a nutrient source after being decomposed by mold (Alvarez-Vasco and Zhang 2013). This was another reason why the mold resistance of the treated bamboo slivers was improved. It suggested that the starch content, cell integrity, and chemical components drastically determined the mold resistance of the bamboo. The results suggested that the alkali treatment is an effective method for improving the mold resistance of the bamboo slivers, especially for the bamboo slivers from the inner layer of the bamboo. Improvement of mold resistance of bamboo slivers greatly prolongs their service life and widens application scopes.

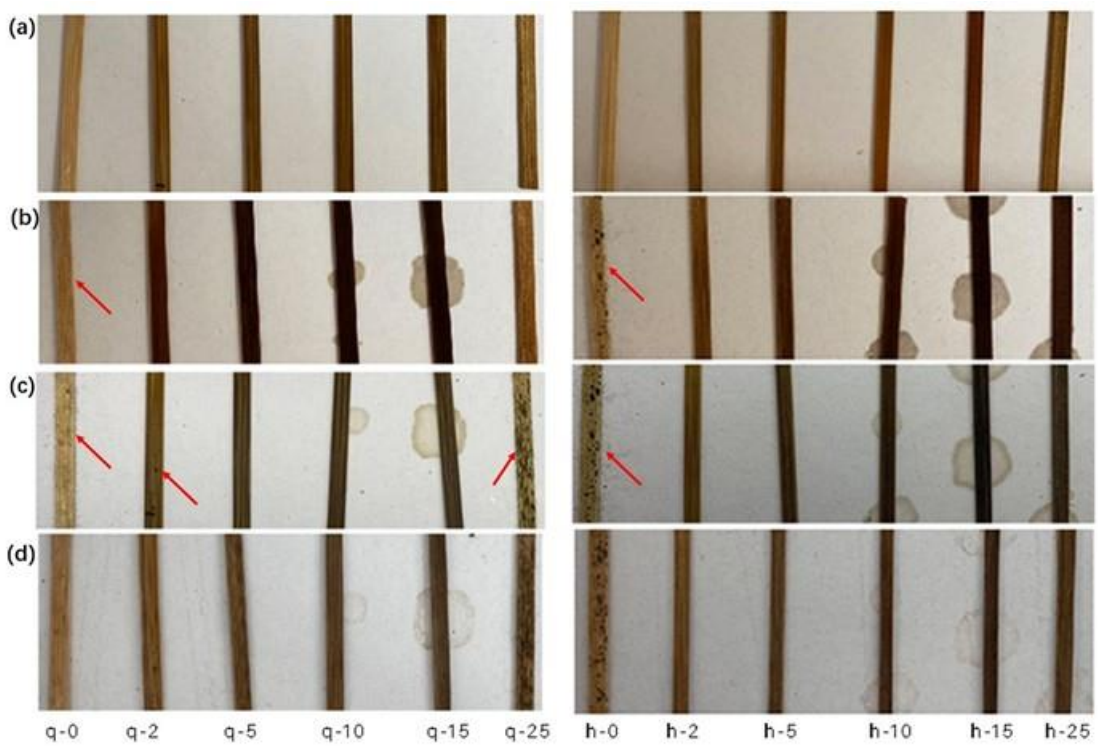
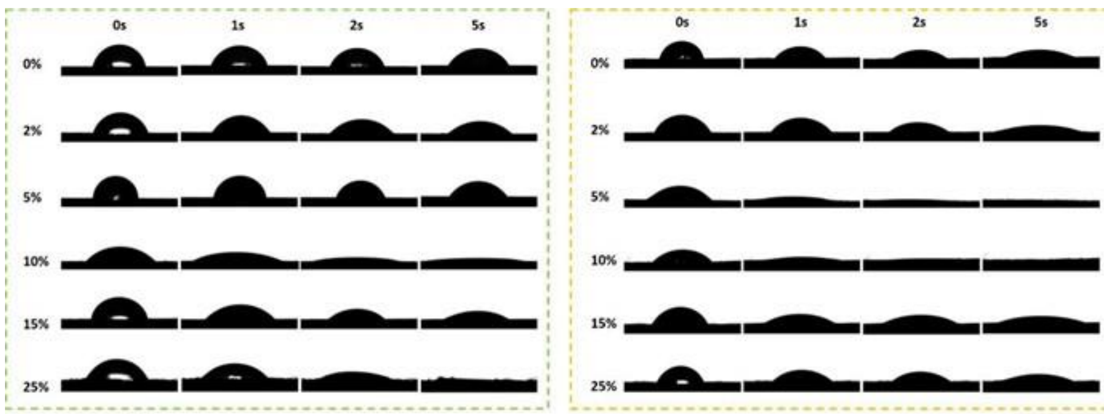


Fig. 11. The mold resistance of the untreated and treated bamboo slivers at room temperature and related humidity: (a) the 1st day (28 °C RH 67%); (b) the 10th day (26.5 °C RH 72%); (c) the 11th day (28°C RH 66%); and (d) the 87th day (20 °C RH 54%) (q-0, q-2, q-5, q-10, q-15, q-25 are slivers from the outer bamboo treated with NaOH at a concentration of 0%, 2%, 5%, 10%, 15%, and 25%, respectively; h-0, h-2, h-5, h-10, h-15, h-25 are slivers from the inner bamboo treated with NaOH at a concentration of 0%, 2%, 5%, 10%, 15%, and 25%)

Wettability

The water wettability of the untreated and treated bamboo slivers is shown in Fig. 12. The contact angles of the inner bamboo slivers were lower than the contact angles of the outer bamboo slivers, and water droplets dispersed faster on the surface of the inner bamboo slivers. This might be ascribed to the fact that there were more parenchyma cells and less fiber in the inner bamboo slivers than in the outer bamboo slivers. The parenchyma cells were softer and had a lower density than the fibers, and there were much more pits in the parenchyma cells, as shown in Fig. S6 (Huang *et al.* 2015). In addition, the parenchyma cells had a higher hemicellulose content than the fibers, and hemicellulose is hydrophilic (Jin *et al.* 2019; Chen *et al.* 2021b).



(a) Outer Bamboo Slivers **(b)** Inner Bamboo Slivers

Fig. 12. Water wettability of the: (a) outer bamboo slivers; and (b) inner bamboo slivers

The water contact angles of the treated bamboo slivers were lower, and the water droplet was easier to spread on the surface of the treated bamboo slivers compared with the untreated slivers. This was regardless of the position in which the slivers were from in the bamboo, because the alkali treatment removed hydrophobic lignin from both fibers and parenchyma cells (Chen *et al.* 2021b). As shown in a previous study by the authors, alkali treatment can remove both hydrophobic lignin and hydrophilic hemicellulose in the fibers, but it only can remove hydrophobic lignin in the parenchyma cells (Chen *et al.* 2021a,b). When treated at the same alkali concentration, more hydrophilic hemicellulose in the slivers from the outer layer of the bamboo was removed, as there were more fibers compared with the inner layer of the bamboo. Therefore, the water contact angles on the surface of the inner bamboo slivers were smaller compared to those on the outer bamboo slivers treated with the same alkali concentration and the water droplet spread faster in the inner bamboo slivers. The structure change of the cells in the bamboo was another factor that contributed to the quick dispersal of the water on the bamboo surface. The parenchyma cells collapsed after alkali treatment and the moisture content was lower after drying, which made it easier for water to enter the cells. The inner bamboo slivers contained more parenchyma cells, which could store more water, and the large number of pits on the parenchyma cells made water more easily transport between the cells and absorb water faster. Therefore, the contact angle of the inner bamboo slivers was smaller than that of the outer bamboo slivers. The wettability of the slivers from both the outer and inner layer of the bamboo increased when treated at a lower alkali concentration and then decreased at a higher concentration. For the outer bamboo slivers, the wettability reached the maximum when the concentration used was 10%, while the bamboo slivers from the bamboo inner layer increased to its maximum when treated with a 5% NaOH solution. This was in good agreement with the water absorption characteristics, as shown in Fig. 6a. The wettability of the bamboo slivers was primarily due to the combined influences of the chemical compositions and the surface topography.

CONCLUSIONS

In this study, a simple yet highly effective approach to improving mold resistance of bamboo slivers have been developed, in which alkali solution at various concentration was applied to treat bamboo slivers.

1. The microstructure of the parenchyma cells and fibers in the bamboo slivers were altered differently when treated with the alkali solutions. The extent of water absorption and wettability of the treated bamboo slivers considerably increased, as the chemical composition was partly removed, and the parenchyma cells collapsed.
2. The dimensional stability of the treated bamboo slivers decreased, especially the slivers from the inner layer of the bamboo. The width and thickness swelling of the treated bamboo slivers were much higher than the width and thickness swelling of the untreated bamboo slivers.
3. The starch in the parenchyma cells of the bamboo slivers could be removed *via* alkali treatment when the concentration was lower than 25%. The alkali treatment considerably improved the mold resistance of the bamboo slivers, especially for the slivers from the inner layer of the bamboo, which showed great mold resistance at low concentration (2%). As for the bamboo slivers from the outer layers, the mold grew fastest and most severely on the surface of the 25% NaOH treated slivers when compared to the untreated slivers. This might be largely due to the fact that starch in the middle part of the slivers was not removed, and the parenchyma cells were broken.

Although the improvement in mold resistance of bamboo sliver treated by facile NaOH solution was very encouraging, the dimensional stability has been a little compromised. In future research, how to improve mold resistance while maintaining dimensional stability is still a big issue that needs to be addressed to improve market acceptance and broaden applications of bamboo slivers.

DECLARATIONS

Availability of Data and Materials

All the data generated or analyzed during this study are included in this published article and its supplementary information files.

Competing Interests

The authors have declared no conflict of interest.

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Author's Contributions

Hong Chen designed the experiments and was a major contributor to data analysis and writing the manuscript. Jieyu Wu partly analyzed the data and was a major contributor in conducting the experiments. Jiangjing Shi helped Jieyu Wu conduct part of the experiments. Ge Wang and Wenfu Zhang conceptualized, planned, supervised, and financed the research. All authors read and approved the final manuscript.

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APPENDIX

Supplementary Material

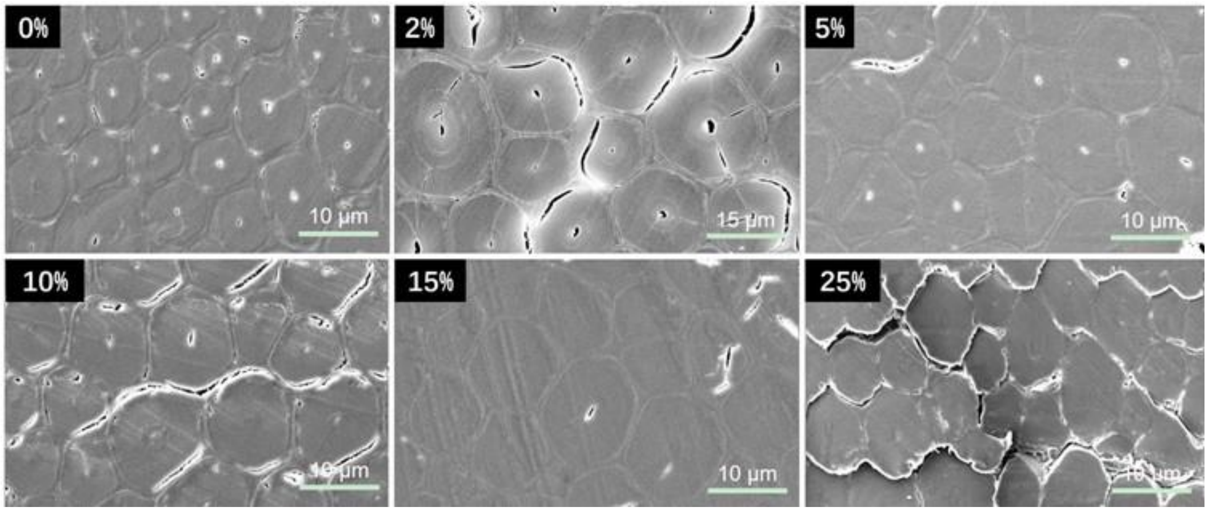

Fig. S1. Fibers in the slivers from the inner layer of bamboo after alkali treatment

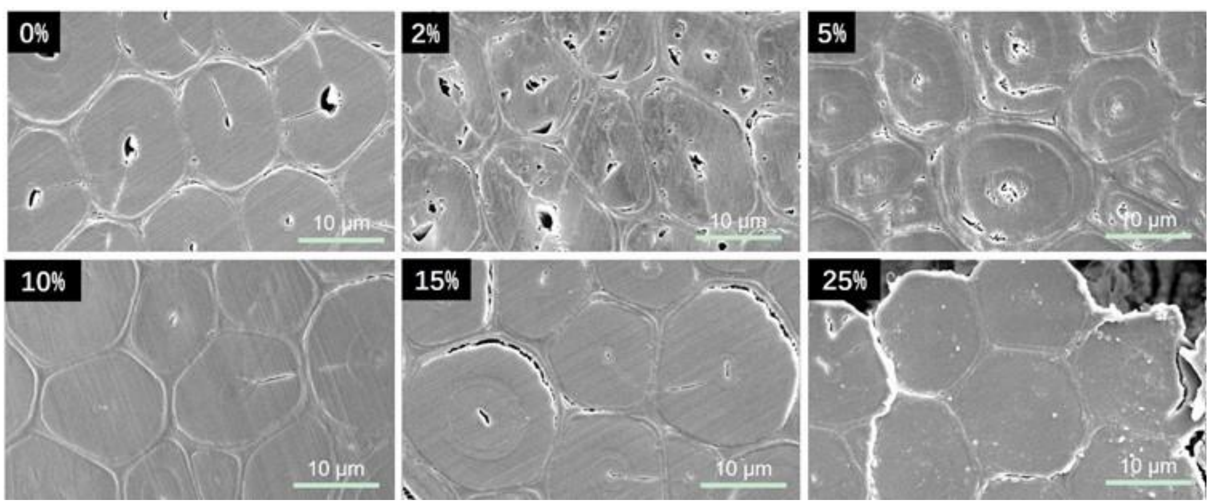

Fig. S2. Fibers in the slivers from the outer layer of bamboo after alkali treatment

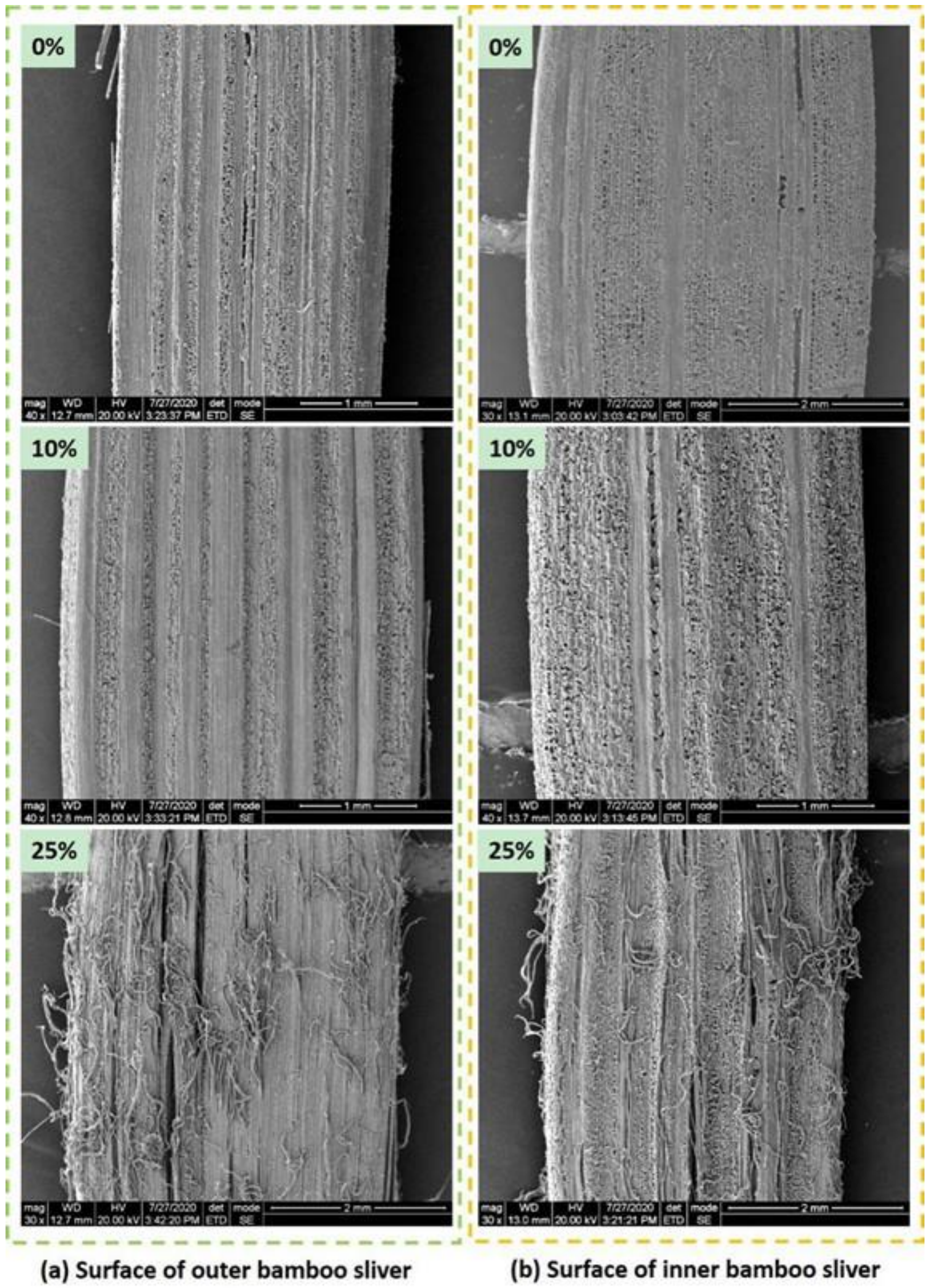

Fig. S3. The surface morphology of treated and untreated bamboo slivers

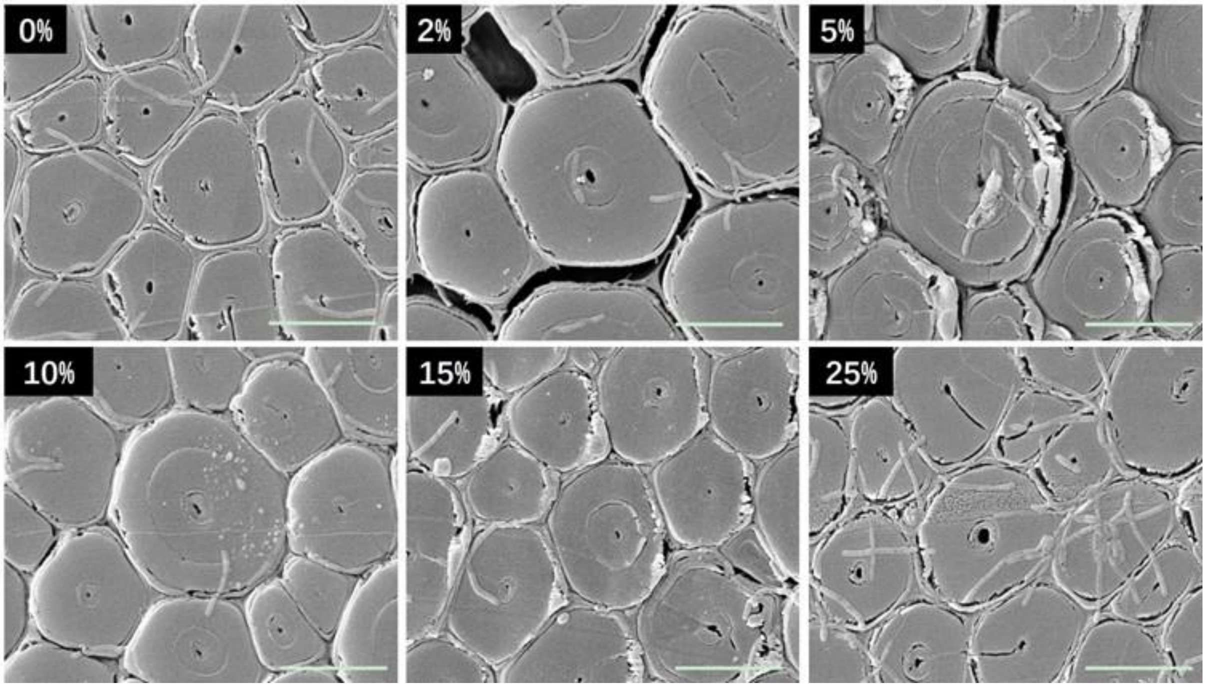

Fig. S4. Fiber in slivers from the inner layer of bamboo after being immersed in water for 12 h. (Scale bar =10 μm)

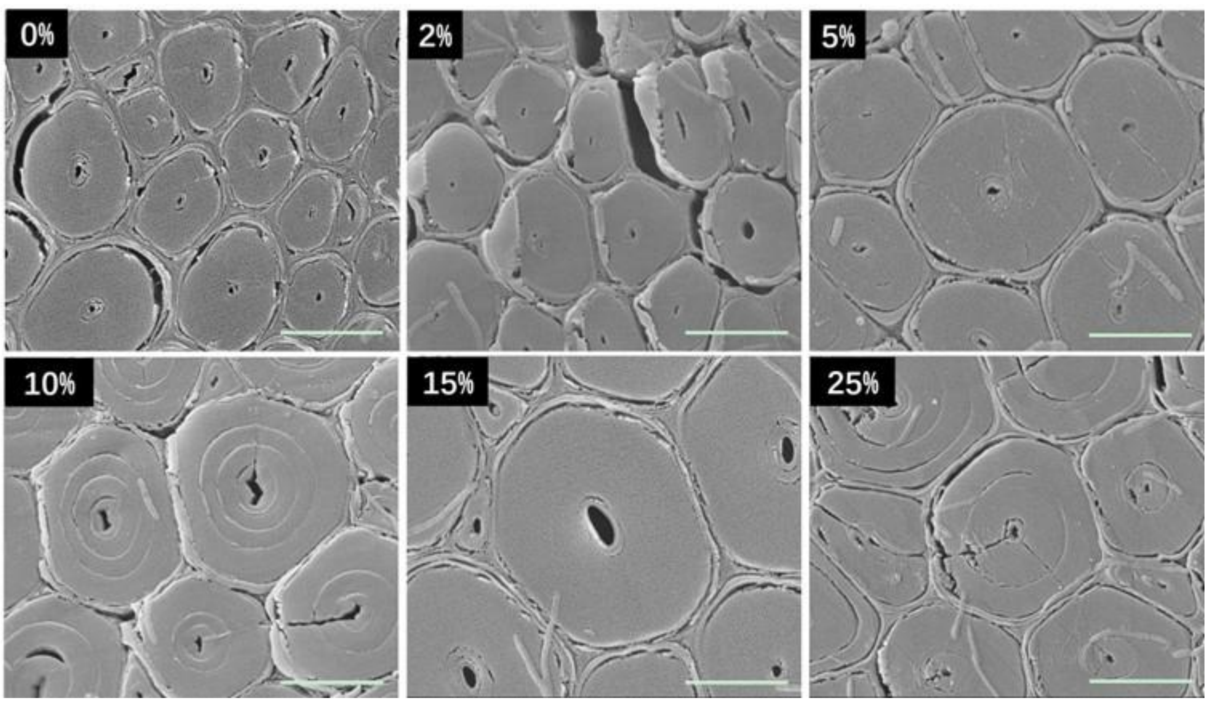

Fig. S5. Fibers in the slivers from the outer layer of bamboo after being immersed in water for 12 h. (Scale bar =10 μm)

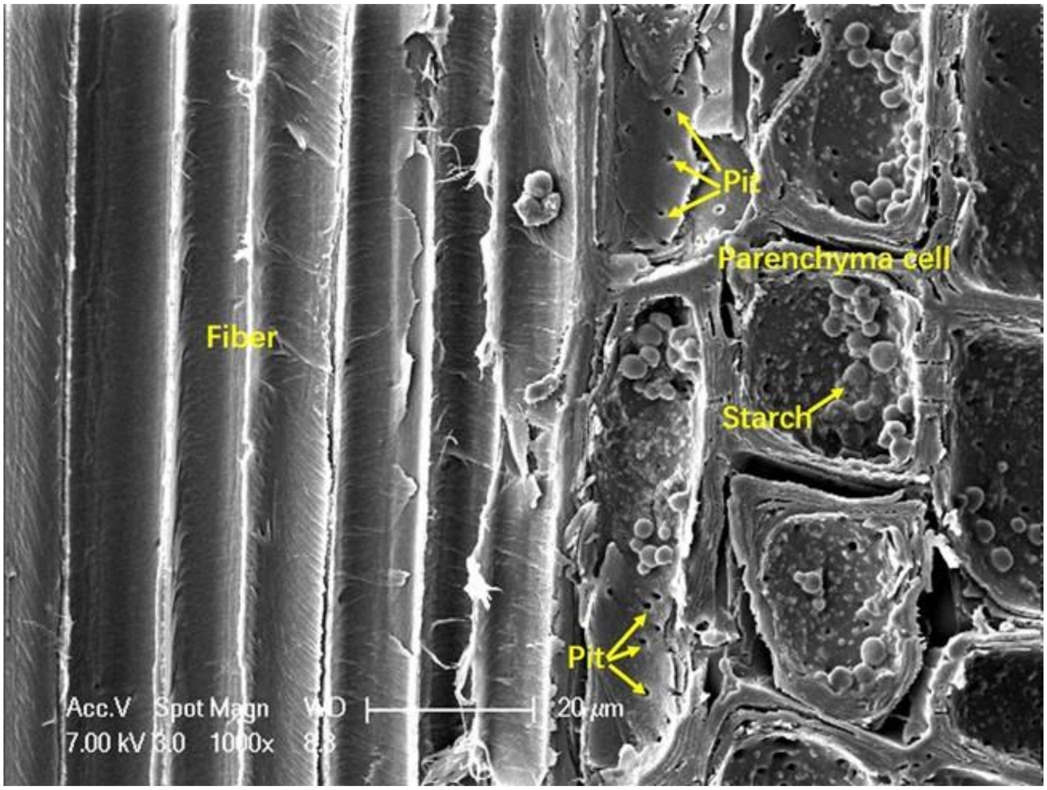

Fig. S6. The structure of fiber and parenchyma cell

Table S1. Water Absorption of Bamboo Slivers

Concentration	Water Absorption of Outer Bamboo (%)	Water Absorption of Inner Bamboo (%)
Untreated	50.96 (±5.67)	95.07 (±4.45)
2%	60.75 (±2.507)	117.94 (±15.03)
5%	59.01 (±4.34)	125.93 (±23.92)
10%	114.16 (±14.20)	66.47 (±15.35)
15%	86.33 (±6.85)	57.91 (±5.89)
25%	98.03 (±15.18)	62.93 (±7.14)

Table S2. Width Swelling of Bamboo Slivers

Concentration	Width Swelling of Outer Bamboo (%)	Width Swelling of Inner Bamboo (%)
Untreated	8.53 (±1.63)	5.31 (±0.55)
2%	26.44 (±1.40)	42.31 (±1.71)
5%	27.80 (±5.62)	53.53 (±6.53)
10%	31.90 (±5.95)	45.38 (±3.57)
15%	21.59 (±7.04)	43.97 (±1.12)
25%	14.10 (±4.73)	24.41 (±2.81)

Table S3. Thickness Swelling of Bamboo Slivers

Concentration	Thickness Swelling of Outer Bamboo (%)	Thickness Swelling of Inner Bamboo (%)
Untreated	17.02 (±7.81)	15.71 (±0.71)
2%	17.20 (±9.99)	19.67 (±9.00)
5%	25.61 (±10.79)	39.73 (±12.54)
10%	18.31 (±7.71)	25.70 (±14.92)
15%	16.05 (±5.55)	26.34 (±16.25)
25%	17.17 (±3.95)	29.50 (±7.72)

Table S4. Volume Swelling Coefficient of Bamboo Slivers

Concentration	Volume Swelling Coefficient of Outer Bamboo (%)	Volume Swelling Coefficient of Inner Bamboo (%)
Untreated	27.85 (±9.99)	22.46 (±1.09)
2%	48.43 (±13.87)	70.49 (±11.78)
5%	60.74 (±20.39)	115.48 (±26.01)
10%	56.55 (±15.58)	83.85 (±18.65)
15%	42.00 (±15.06)	81.84 (±23.45)
25%	31.43 (±8.93)	61.43 (±9.80)