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# A comparative study of the microstructure and water permeability between flattened bamboo and bamboo culm

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## Abstract

The objective of this study is to investigate the microstructure, water permeability and the adhesion of waterborne coating on the flattened bamboo. The flattened bamboo was obtained by softening bamboo culm at 180 °C followed by compression. The microstructure and chemical component of flattened bamboo were investigated by scanning electron microscopy, Fourier transforms infrared spectroscopy, and X-ray diffraction. The adhesion and interface structure of waterborne coating onto flattened bamboo surface were also examined. The result indicated that the parenchyma cells in flattened bamboo were compressed, and starch in the parenchyma cell was extracted during the softening and flattening process in which the main chemical component did not change significantly. The water permeability of both flattened bamboo and bamboo culm is dependent on the direction: longitudinal direction > tangential direction > radial direction. However, the water permeability in all three directions in flattened bamboo was higher than those in the untreated bamboo. In addition, alkali dye solution was found to more easily permeate through the flattened bamboo when compared to acid dye solution, and the permeability varied depending on alkali dye or acid dye concentration. The adhesion of water-based polyurethane coating on the flattened bamboo can reach the second level.

**Keywords:** Flattened bamboo, Microstructure, Water permeability, Adhesion

## Introduction

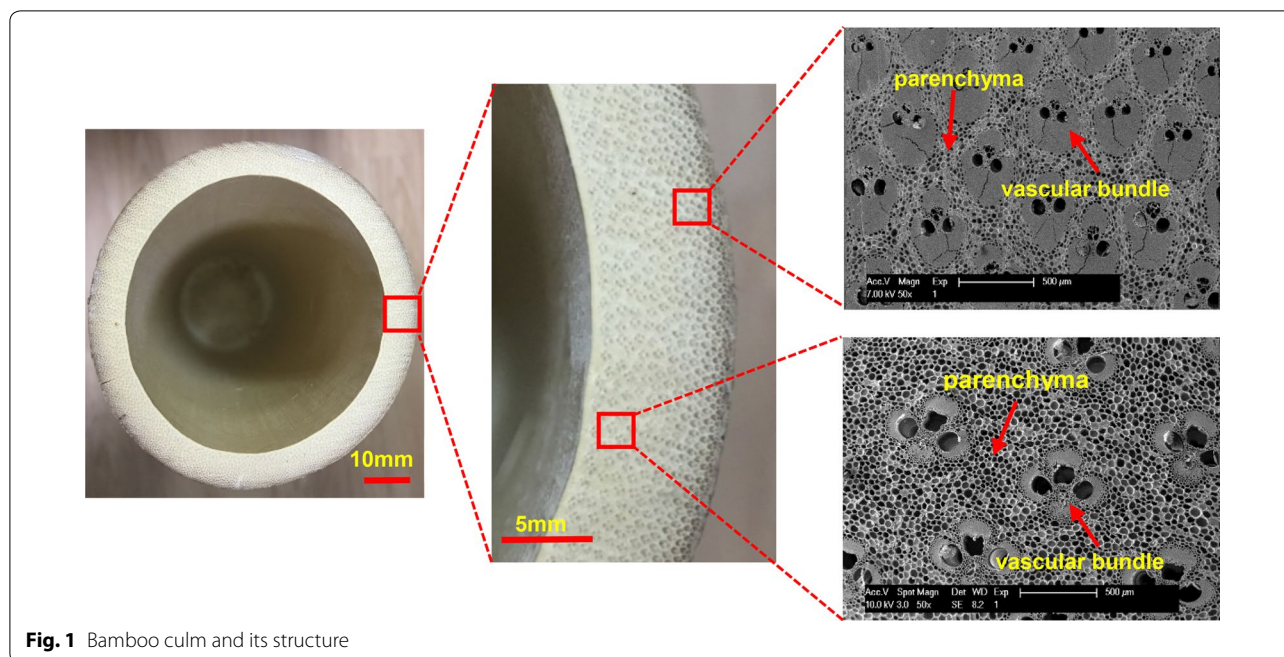
Bamboo, the fastest growing plant on earth, has attracted growing attention from both academia and industry because of excellent mechanical properties, beautiful color and special grain of bamboo. There are 88 families and more than 1642 species of bamboo around the world, including 39 families and 837 species in China [1]. As wood forest is decreasing quickly, the global bamboo forest is increasing by 3% every year [2]. The area of bamboo forest in China is 20% of that around the world (more than 32 million hm<sup>2</sup>), and the output value of bamboo industry in China increased from about 7.13 billion US dollar in 2007 to 33.7 billion US dollar in 2017 [3]. However, the tubular shape with hollow and anisotropic structure of the bamboo culm still limits its practical

application (Fig. 1). To date, laminated bamboo and bamboo scrimber, made from bamboo culm, are two mainly used bamboo-based panels intended for furniture and interior decoration application. However, for laminated bamboo, the low utilization ratio of bamboo (less than 40%) is a primary drawback because the inner and outer layers of bamboo need to be removed [4, 5]. Bamboo scrimber has very high content of adhesive (15–30%) and high density (1.05–1.25 g/cm<sup>3</sup>) [6], which is not environment friendly and too heavy when used in furniture and interior decoration. Therefore, to overcome the drawbacks in both laminated bamboo and bamboo scrimber, new manufacturing technologies for a new kind of bamboo-based panels have been explored.

In the 1980s, Maori [7] and Zhang et al. [8] invented the method of flattening bamboo culm to the bamboo board. However, the apparatus and technology were not good enough at that time, especially the apparatus, which limited its industrial production. Recently, as both the

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**Fig. 1** Bamboo culm and its structure

technology and the apparatus were improved, flattening of bamboo has been studied increasingly in academia and produced in the industry. Some researchers have reported how to flatten the bamboo culm into bamboo board effectively, such as softening in hot oil [9] or in saturated high-pressure steam [10], with different moisture contents [11], different press process [12], etc. Currently, one of the most efficient approaches is softening bamboo culm with saturated high-pressure steam at high temperature in a sealed container; the temperature and the pressure could be 180–190 °C and around 1.2 MPa [13].

As the flattening of bamboo developed, there have been enormous potentials for furniture and interior decoration application in which the water permeability is of great importance and has been taken into account prior to its practical application. The water permeability affects the modification, adhesive bonding properties, adhesion of coatings on the flattened bamboo surface, etc. For example, as used in furniture and interior decoration, the flattened bamboo needs to be treated differently to obtain the high durability, different colors, and high-quality coatings, which are closely related to water permeability. At present, only a few researches on the water permeability of bamboo culm [14–16] and the effect of different treatments on the water permeability of bamboo culm [17, 18] have been reported. The water permeability of bamboo culm was determined by the structure in different directions and can be improved by the hydrochloric acid treatment, microwave treatment, and freeze-drying treatment.

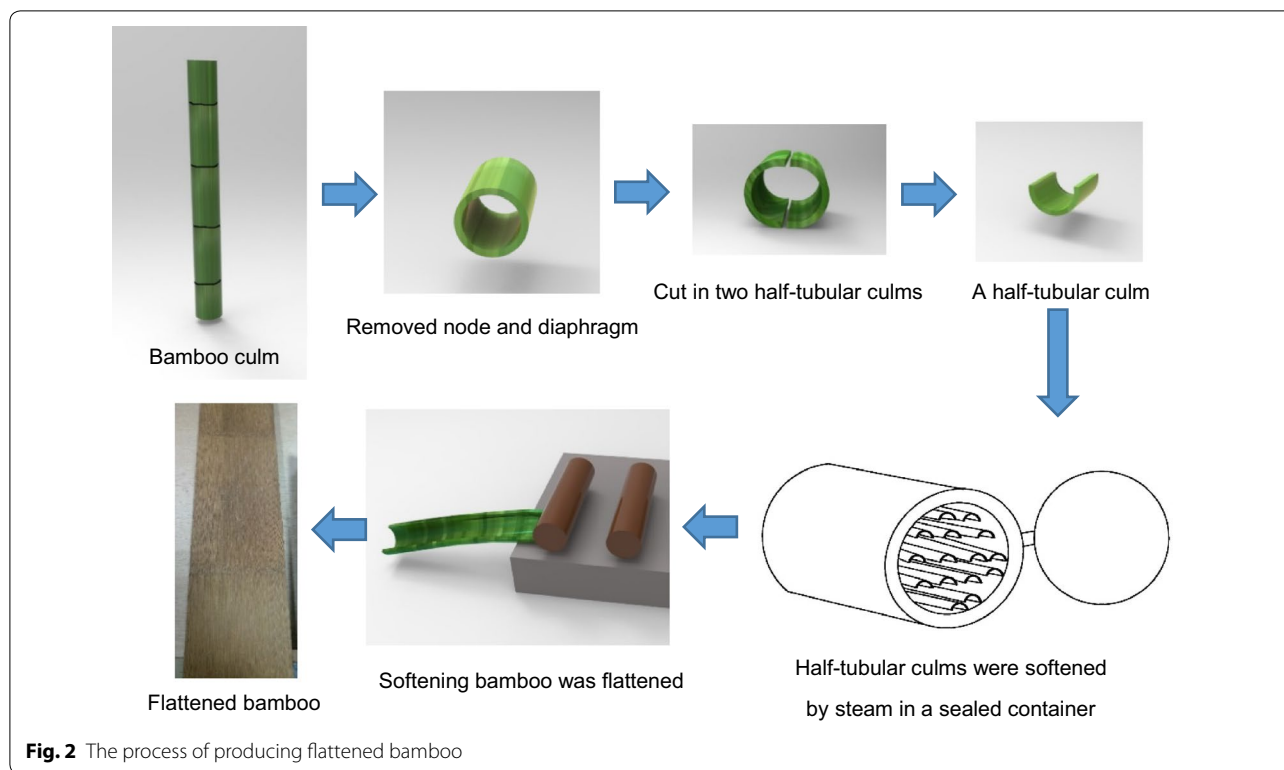
Flattened bamboo is a new material which is ready to be produced in large scale. However, there has been no reported research to evaluate the possibility of using flattened bamboo in furniture and interior decoration, especially about the water permeability of flattened bamboo, as well as the adhesion of the waterborne coating on its surface. Therefore, the objective of this study is to investigate the microstructure, chemical component, water permeability, and adhesion of the waterborne coating on the flattened bamboo, which will provide technical data for the application of flattened bamboo in furniture and interior decoration.

## Materials and methods

### Sample preparation

4-year-old Moso bamboo (*Phyllostachys heterocycla*) was obtained from Zhejiang, China. Flattened bamboo, provided by Zhejiang Dechang Bamboo & Wood Co. Ltd, China, was produced as shown in Fig. 2. The bamboo culm (moisture content >18%) was cut into 1 m. The node and diaphragm were removed. Then the culm was cut into two half-tubular culms and then grooved at about 2–3 mm in the inner surface and flattened after being heated by steam at 180 °C in a sealed container for 1–3 min [13]. The hot softened bamboo was pressed at 0.5–0.8 MPa to maintain its flattened shape and then sanded for a smooth surface.

The outer layer and inner layer of bamboo culm were first removed. Then the bamboo and flattened bamboo were ground into a powder, passed through a 200 mesh



and dried in the oven at 103 °C for 2 h for Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) testing.

#### Microstructure and chemical component test

Flattened bamboo and bamboo were selected randomly to observe the morphology of the cross section and radial section with a field emission scanning electron microscope (FE-SEM, XL30 ESEM FEG, FEI Company, OR, USA), the acceleration of which was 7 kV.

The FTIR spectra of flattened bamboo and bamboo were measured in a spectrometer (VERTEX 80V, Bruker, German) within the range of 4000–400  $\text{cm}^{-1}$ , with a resolution of 4  $\text{cm}^{-1}$  and 64 scans. KBr pellet consisting of KBr and flattened bamboo and bamboo powder was prepared with a weight ratio of 100:1.

The crystal structure of cellulose in the flattened bamboo and bamboo was characterized using a X-ray diffractometer (Ultima IV, Rigaku, Japan). The XRD patterns of the flattened bamboo and bamboo were obtained in the diffractometer with a  $\text{CuK}\alpha$  radiation source (X-ray wavelength  $k=0.154178$  nm).  $2\theta$  was from 5° to 45°. The current and voltage for X-ray generation were 30 mA and 40 kV, respectively. The crystallinity index of cellulose was calculated from the height ratio between the intensity of the crystalline peak ( $I_{002}-I_{AM}$ ) and total intensity ( $I_{002}$ ).

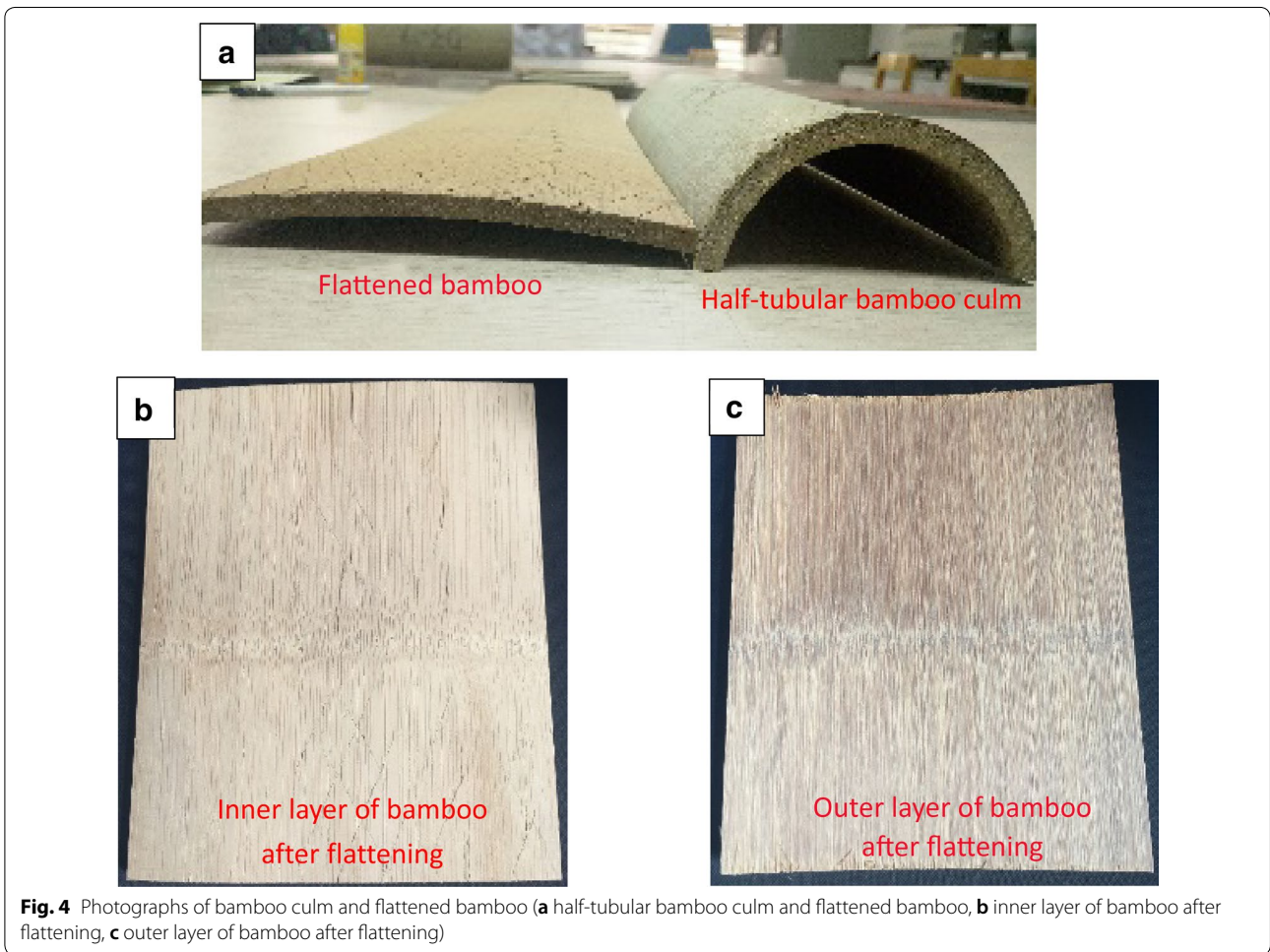
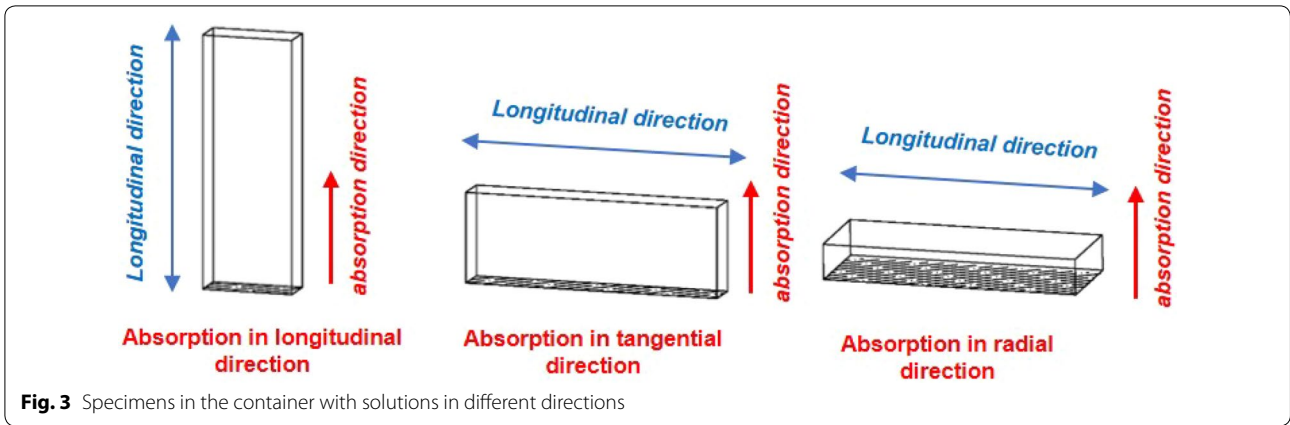
#### Water permeability test

Rectangular samples of flattened bamboo and bamboo culm were cut to 70 mm (longitudinal)  $\times$  25 mm (tangential)  $\times$  5 mm (radial). The water permeability was investigated in acid dye (brilliant crocein) solution and alkali dye (basic red) solution as the two dye types are usually used to obtain different colors. Brilliant crocein was bought according to GB/T 25816-2010, and basic red reached the requirement in HG/T 2551-2007.

The specimens were weighed and then put on the wire mesh in a container with 1% brilliant crocein solution in different directions, as shown in Fig. 3. The specimens were coated with silicon rubber in other directions to prevent penetration. After 1, 2, 4, 7, 12, and 24 h, all the bamboo and flattened bamboo were weighed, respectively. The results of BLD (bamboo in the longitudinal direction), BRD (bamboo in the radial direction), BTD (bamboo in the tangential direction), FBLD (flattened bamboo in the longitudinal direction), FBRD (flattened bamboo in the radial direction), and FBTD (flattened bamboo in the tangential direction) were obtained. Five replicates were tested for each type of sample.

The specimens were weighed and then put on the wire mesh in radial direction in a container with brilliant crocein and basic red solution with the concentration of 1, 3, and 5%, respectively. After 1, 2, 4, 7, 12, and 24 h, all



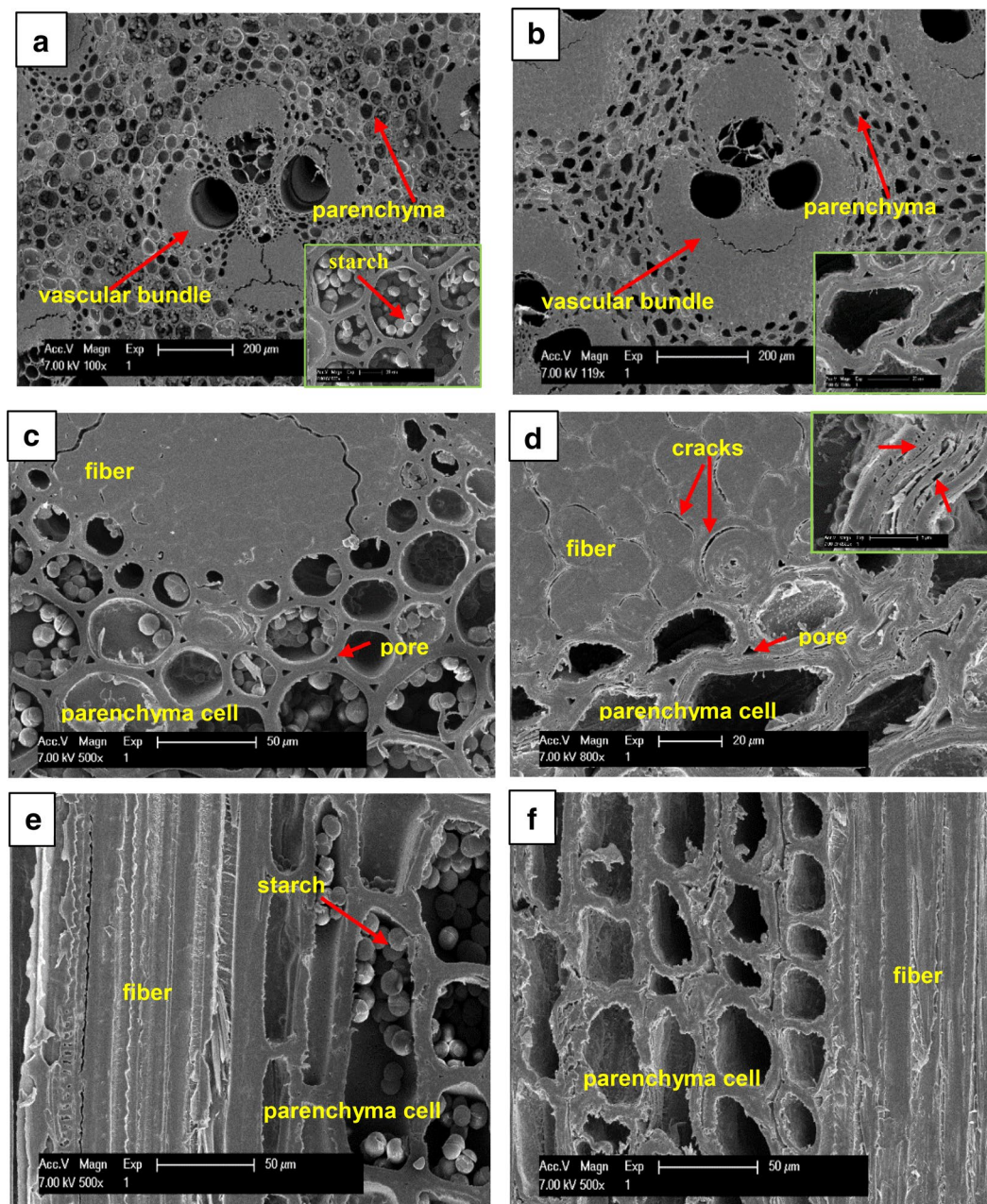


the bamboo and flattened bamboo were weighed, respectively. Five specimens were tested for each type.

Water absorption weight and water absorption rate were calculated by Eqs. (1) and (2) [15]:

$$P = \frac{M_1 - M_0}{A}, \tag{1}$$

$$V = \frac{M_1 - M_0}{AT}. \tag{2}$$



**Fig. 5** Microstructure of bamboo culm and flattened bamboo (a cross section of bamboo culm, b cross section of flattened bamboo, c cross section of fiber and parenchyma cell in bamboo, d cross section of fiber and parenchyma cell in flattened bamboo, e radial section of bamboo, f radial section of flattened bamboo)

$P$ —water absorption weight,  $g/cm^2$ ;  $M_0$ —weight of samples before absorption, g;  $M_1$ —weight of samples after absorption, g;  $A$ —area of absorption,  $cm^2$ ;  $V$ —water absorption rate,  $g/cm^2 h$ ;  $T$ —time of absorption, h.

**Adhesion of waterborne coating on the flattened bamboo test**

The flattened bamboo was cut into 15 cm (longitudinal)  $\times$  12 cm (tangential)  $\times$  1 cm (radial). The waterborne polyurethane coatings were applied by brush on the flattened bamboo as one layer. It was heated at 50 °C and kept for 2 h. The coated samples were dried in a cool, dry environment for 7 days.



The degree of adhesion of the coating film was classified according to GB/4893.4-85 standard methods by a cross-cut test. Classification 1: the edges of the cuts are completely smooth; none of the squares of the lattice is detached. Classification 2: there is detachment of small flakes of the coating at the intersections of the cuts; slight detachment along the edges of the cuts. Classification 3: the coating has flaked partly or wholly discontinuously or continuously along the edges of the cuts. Classification 4: the coating has flaked partly or wholly on different parts of the squares. A cross-cut area not greater than 50% is affected. Classification 5: some squares have flaked partly or wholly. A cross-cut area greater than 50% is affected.

## Results and discussion

### Microstructure and chemical components of flattened bamboo

The photographs of bamboo culm and flattened bamboo are presented in Fig. 4. There is slight difference in the color and the grain between the inner layer and outer layer of flattened bamboo. It mainly resulted from the chemical component and structure of bamboo.

The microstructures of bamboo and flattened bamboo in cross section and radial section are shown in Fig. 5. The basic units in bamboo are vascular bundles where bamboo fibers exist, and parenchyma consists of parenchyma cells. After softening and flattening, the parenchyma was compressed to a certain extent, and the starch in the parenchyma cells was extracted during the steam treatment (Fig. 5a, b). There was not significant change in the fibers in vascular bundles, although a few small cracks between fibers were expected (Fig. 5c, d), as the interface between fibers was weak [19]. However, a large number of cracks were developed in the parenchyma cell wall, including both in the layers and the interface between layers as shown in Fig. 5d. Moreover, the damage in the interface between the layers of the parenchyma cell wall was more pronounced when compared with the layers themselves. From the radial section (Fig. 5e, f), it also can be observed that the starch was removed, and the parenchyma cells were compressed where lots of cracks appeared the same as observed in the cross section.

The chemical structure of bamboo and flattened bamboo are evaluated with FTIR spectra from 4000 to 400  $\text{cm}^{-1}$  as shown in Fig. 6. The peaks in the FTIR spectra at 1605, 1510 and 1261  $\text{cm}^{-1}$  were due to lignin [20, 21], and the peak at 1737  $\text{cm}^{-1}$  in was due to C=O in hemicellulose [22], which were similar in both types of bamboo. As reported by Zhang et al. [10], the hemicellulose in flattened bamboo steadily decreased with the increase of softening temperatures and disappeared when treated at 160 and 180  $^{\circ}\text{C}$  for 8 min. In our study, the bamboo was steam heated at 180  $^{\circ}\text{C}$  for 1–3 min; it

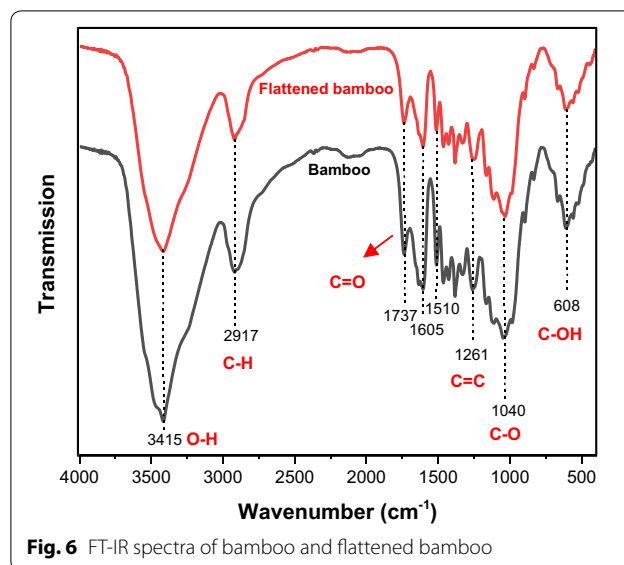


Fig. 6 FT-IR spectra of bamboo and flattened bamboo

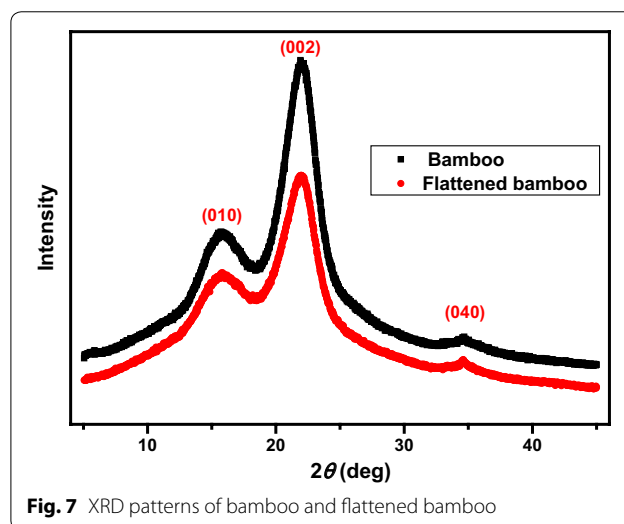


Fig. 7 XRD patterns of bamboo and flattened bamboo

indicated if the treatment time was short, the hemicellulose would not degrade much even when the temperature was up to 180  $^{\circ}\text{C}$ .

The XRD patterns of bamboo and flattened bamboo are shown in Fig. 7. There were three characteristic peaks in the XRD patterns of bamboo and flattened bamboo around 15.76°, 22°, and 34.74°, attributed to (110) and (200) and (004) reflections of the crystalline structure in cellulose I, and the reflection (004) is related to the longitudinal structure of cellulose [23]. Similar XRD patterns of cellulose in flattened bamboo were observed to that in bamboo, showing the similar cellulose I structure. It indicated that the softening and flattening process did not change the crystal form of cellulose. While the intensity

of (200) reflection in flattened bamboo was weaker than that in bamboo, it emphasized the decrease in the fraction of crystalline cellulose [24]. Also, the crystallinity index of cellulose in bamboo and flattened bamboo was 61.8% and 50.4%, respectively. The combination of steam treatment at 180 °C and compression in the flattening process might account for the reduction in the crystallinity index, which needs be further studied.

**Permeability of flattened bamboo in different directions**

The water absorption weight and rate of flattened bamboo and bamboo are presented in Fig. 8. The water absorption weight and rate were different in different directions in both bamboo and flattened bamboo. In the longitudinal direction, the water absorption weight and rate were much higher than that in the other two directions, for both flattened bamboo and bamboo. The water absorption weight and rate in tangential direction were higher compared with that in the radial direction for both types of bamboo. This was in accordance with the water vapor diffusion resistance of bamboo in the longitudinal direction being remarkably lower than that in the tangential and radial directions [16].

The water permeability was dependent on the structure of bamboo and flattened bamboo in different directions. Bamboo consists of parenchyma cells, with embedded vascular bundles composed of fibers, metaxylem vessels, and sieve tubes with companion cells [25]. As shown in Fig. 9, in the longitudinal direction, there were a number of vascular bundles, the structure of which was beneficial for water permeability, especially vessels and sieve tubes. However, in the tangential and radial direction, there was no tissue with straight conduits and interconnectivity, and water transport mainly relied on the pits in fibers, parenchyma cell wall and the pores between parenchyma cells. The vascular bundles

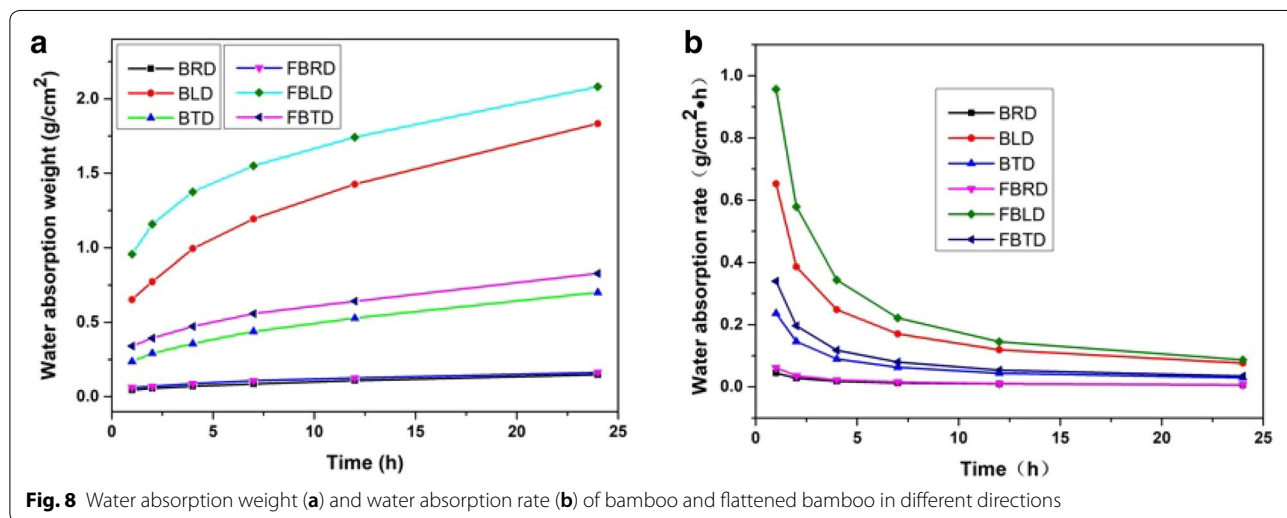
consisting of fibers prevented the water transport [16], as there were much fewer pits in the fiber and almost no pores between fibers in comparison to those in the parenchyma cell wall (shown in Fig. 9d). Therefore, the water permeability of flattened bamboo in different directions was similar to that of bamboo: longitudinal direction > tangential direction > radial direction, which was in accordance with the previous research on the water permeability of bamboo [14].

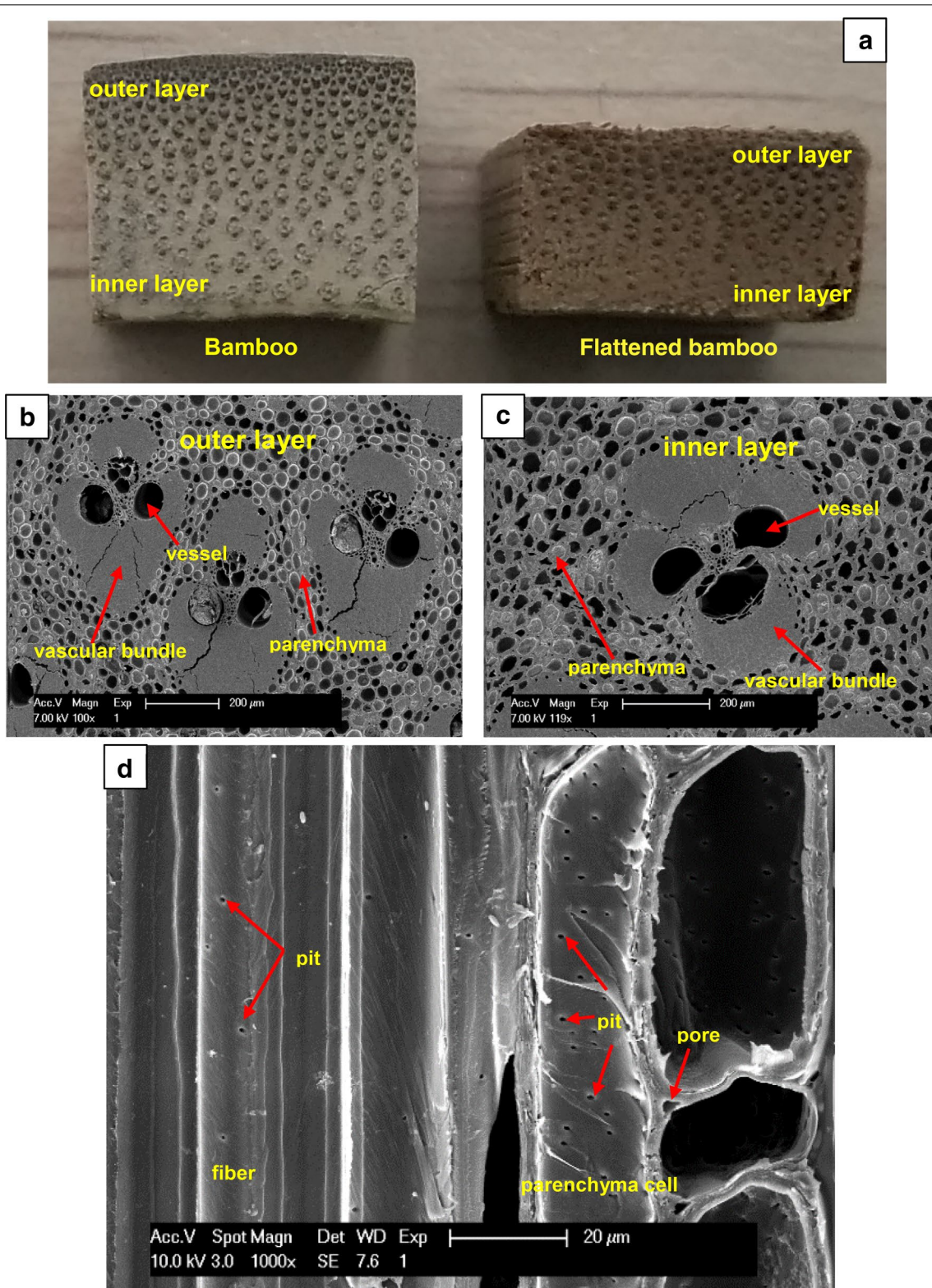
For flattened bamboo, the water permeability in three directions was higher than that in bamboo. As shown in Figs. 5 and 7, the extraction of starch and the cracks in parenchyma cell wall helped to improve the water permeability [17, 18], which happened in flattened bamboo. Also, the decreased crystallinity in cellulose may be in part attributed to improving the water permeability of flattened bamboo compared with unflattened bamboo.

**Permeability of flattened bamboo with different liquids**

The water absorption weight and rate of flattened bamboo and bamboo in different liquids with different concentrations are investigated in Fig. 10. In the brilliant crocein solutions, the water absorption weight and rate of bamboo decreased with increase in concentration, while those of flattened bamboo in the solution with concentration at 3% and 5% were similar when the absorption time was less than 12 h. Up to 24 h, the water absorption weight in 5% brilliant crocein solution was higher than in 3% solution. This might be because the damaged cell wall in flattened bamboo was more easily affected by the acid solution with higher concentration, as acid pretreatment enhanced the water permeability [17].

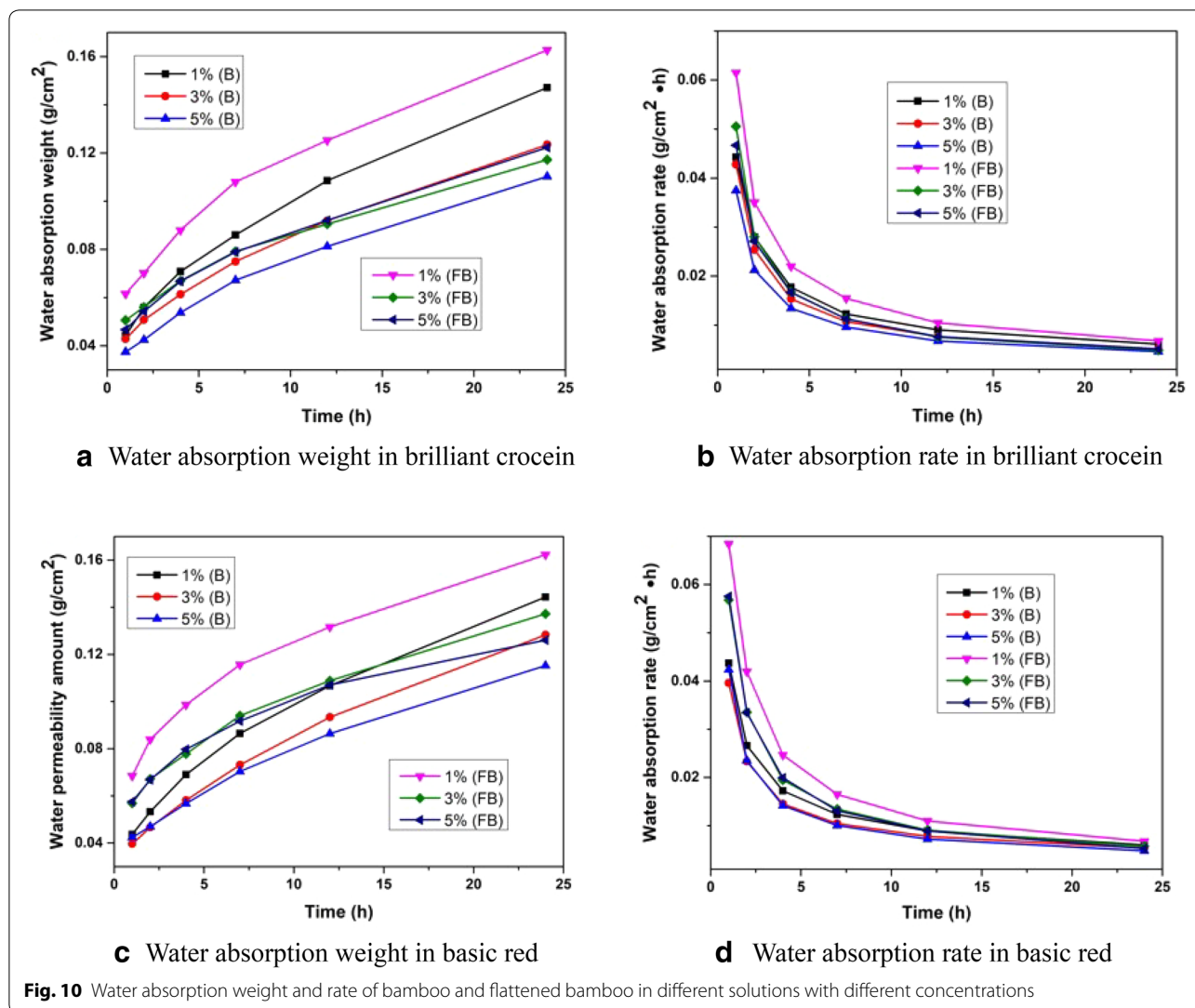
In basic red solutions, the water absorption weight and rate of flattened bamboo and bamboo decreased when the concentration increased. With increase in the





**Fig. 9** The vascular bundle and parenchyma distribution and the pit distribution (**a** cross section, **b** cross section of bamboo, **c** cross section of flattened bamboo, **d** radial section of bamboo)





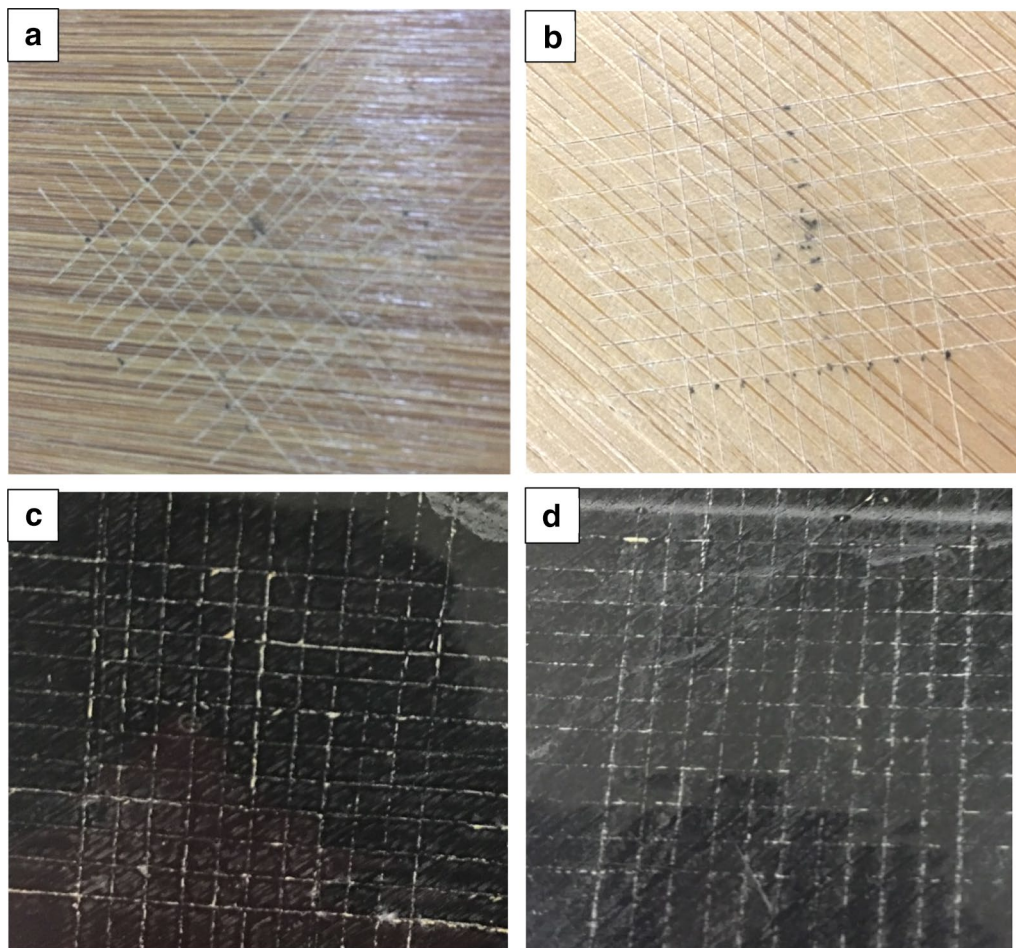
concentration, the increased dye molecules block up the pits in the cell wall and the pores between parenchyma cells. When the concentration increased from 3 to 5%, the water absorption weight and rate of flattened bamboo were similar when the absorption time was less than 12 h. A similar phenomenon happened in the bamboo when the absorption time was less than 7 h.

With the same concentration, the water permeability of flattened bamboo was higher in basic red solution compared with that in brilliant crocein solution. By contrast, the water permeability of bamboo in basic red solution was lower than that in brilliant crocein solution when the concentration was lower (1% and 3%). As the concentration increased up to 5%, the water permeability of bamboo in brilliant crocein solution was higher than that in basic red solution. Regardless whether in basic red or

brilliant crocein solution, with the same concentration, the water permeability of flattened bamboo was higher in comparison to that of unflattened bamboo.

#### Adhesion of waterborne coating film on the flattened bamboo

Figure 11 shows the images of coated samples and coating films after the cross-cut test. After the cross-cut test, a little coating film had flaked along the edges and at the intersections of the cuts on both the outer layer and inner layer of the flattened bamboo (Fig. 11a, b). It indicated that the adhesion classification of the waterborne coating on both the outer layer and inner layer was 2. Figure 11c, d show the coating film off from the samples; there was



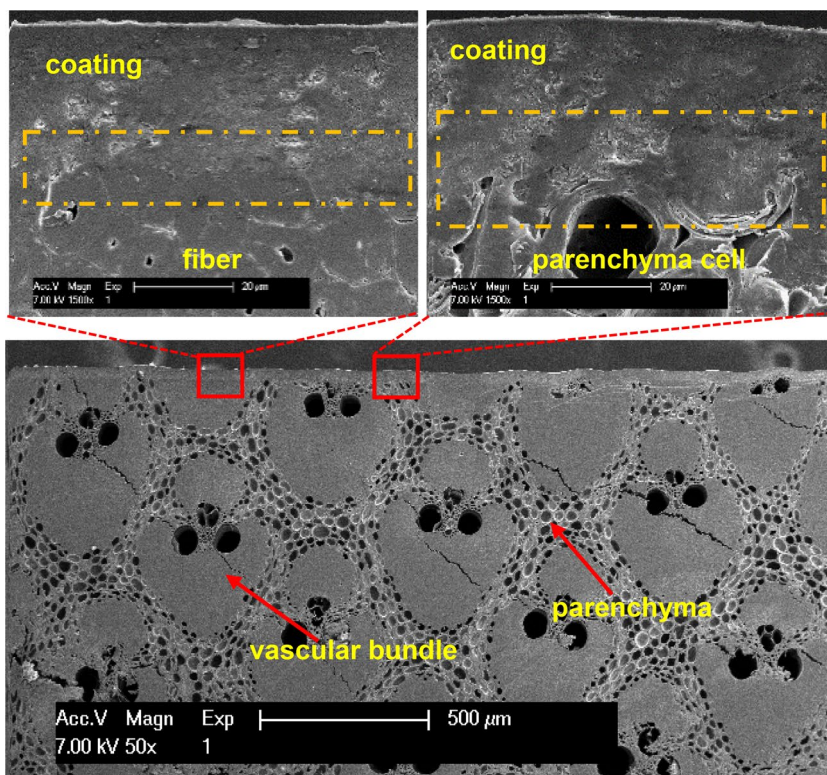
**Fig. 11** Images of coated samples and films after cross-cut test (**a** coated outer layer, **b** coated inner layer, **c** coating film off from the outer layer, **d** coating film off from the inner layer)

a slightly more bamboo tissue on the coating film from the outer layer than from the inner layer. It might suggest that the interface between the outer layer and coating was different from that between the coating and inner layer.

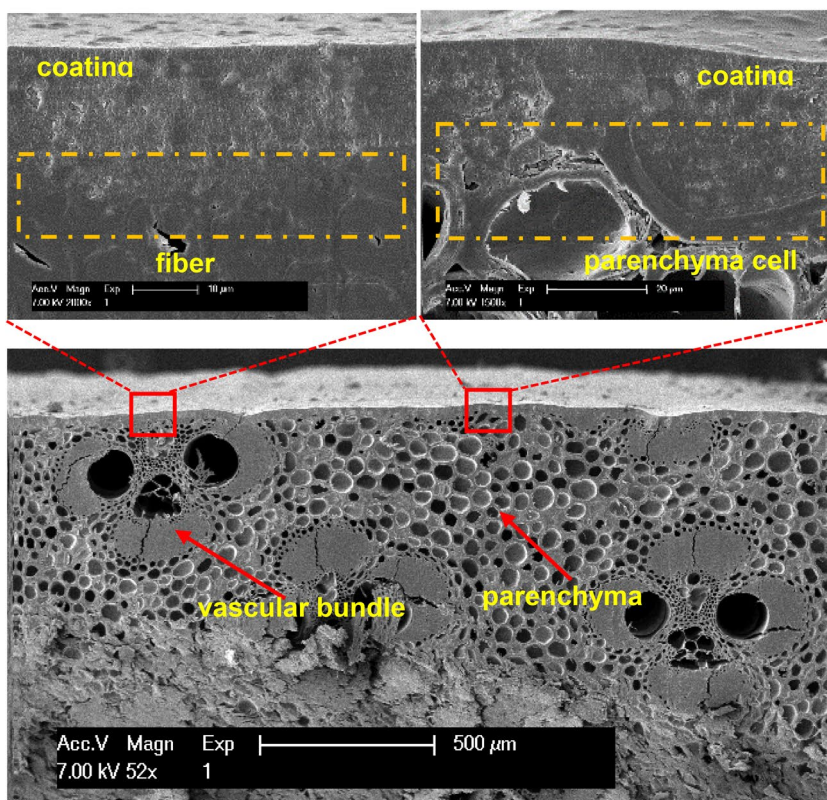
Furthermore, as the shape of bamboo culm was tubular, the adhesion cannot be measured with the cross-cut test, and the interface between bamboo and coating was observed compared with that between flattened bamboo and coating in Fig. 12. For both bamboo and flattened bamboo, there were two kinds of interface: one was the interface between fiber and coating, and the other was the interface between parenchyma cell and coating. The interface between fiber and coating was greater in the outer layer because there were a large number of vascular bundles (Fig. 11a, c). But in the inner layer, the interface between parenchyma cell and

the coating was more dominant because of the presence of a large amount of parenchyma there (Fig. 11b, d). Even in some areas of the inner layer, there was no interface between fiber and coating, but only interface between parenchyma cell and coating (Fig. 12d). From the FE-SEM observation, in flattened bamboo, the interface between fiber and coating was similar to that in bamboo, whereas the interface between parenchyma cell and coating was very different in the two substrates. The interface between parenchyma cell and coating included the interface between the outer surface of parenchyma cell and coating, and between the inner surface and coating. The parenchyma cell in flattened bamboo was compressed and the starch was extracted, and the cell lumen decreased and the cell shape changed. When coated, the interface between parenchyma cell and coating in flattened bamboo was very





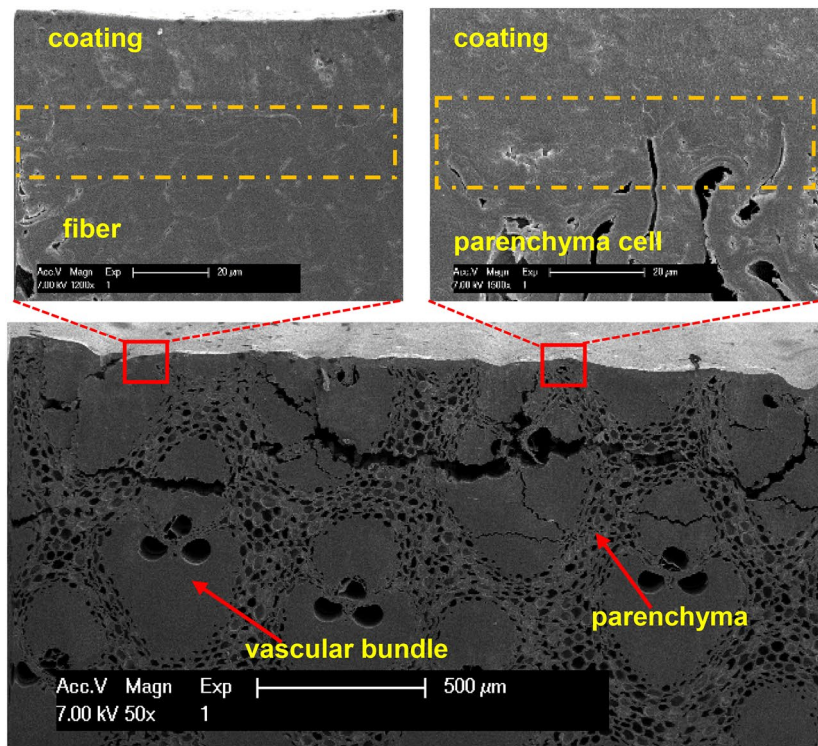
**a** Coating on outer layer of bamboo



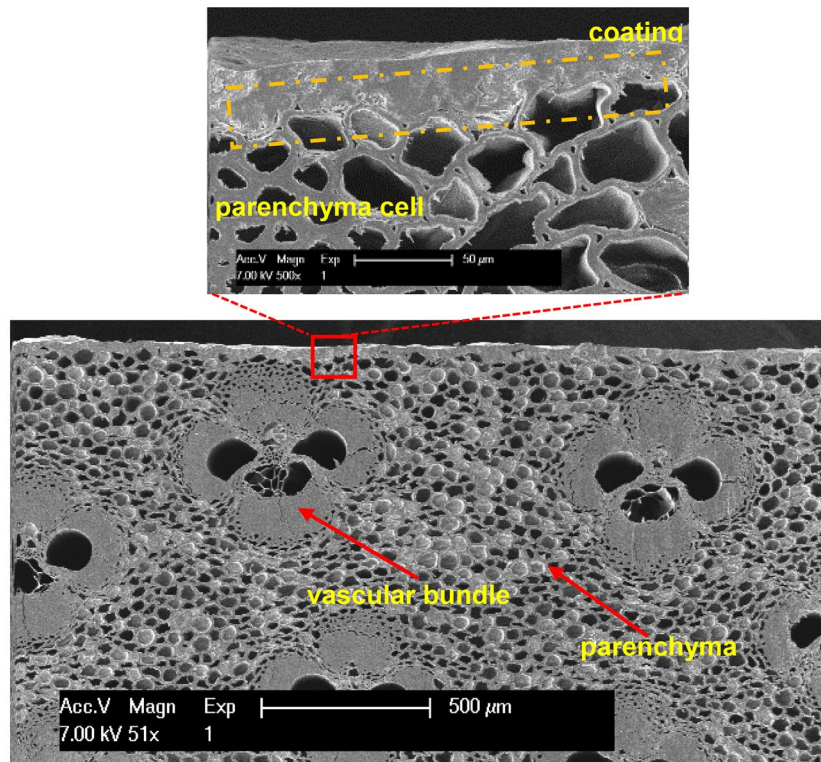
**b** Coating on inner layer of bamboo

**Fig. 12** Interface between the coating and bamboo and flattened bamboo surface





**c** Coating on outer layer of flattened bamboo



**d** Coating on inner layer of flattened bamboo

different from that in bamboo, as shown in Fig. 12b, d. In fact, the interface and the bonding between bamboo and coating are very complicated and very important in the industry and need to be further studied in the future.

## Conclusion

Flattened bamboo was produced for improving the utilization ratio of tubular bamboo culm and widening the applications. In this paper, the flattened bamboo produced with one of the most popular technologies in China was studied. The microstructure, chemical components, water permeability, and the adhesion and interface of waterborne coating on the surface of flattened bamboo were investigated. The results obtained are as follows: (1) the microstructure of flattened bamboo changed significantly, especially the parenchyma cells in which the shape and the lumen, the cell wall, and the starch changed. The chemical components in flattened bamboo were almost unchanged, but the crystallinity index of cellulose slightly decreased. (2) The water permeability of flattened bamboo, as well as that of bamboo, was dependent of the direction: longitudinal direction > tangential direction > radial direction. Whichever the direction, higher water permeability of flattened bamboo was obtained in comparison with bamboo. The water permeability was affected combined with the concentration and the kind of the solution. Flattened bamboo has higher permeability in alkali solution compared with that in acid solution, while that of bamboo depends on the concentration. (3) The adhesion classification of waterborne polyurethane coating on the surface of both outer layer and inner layer of flattened bamboo is two, even though the interfaces between fiber and coating as well as between coating and parenchyma cell were different.

## Abbreviations

BLD: bamboo in the longitudinal direction; BRD: bamboo in the radial direction; BTD: bamboo in the tangential direction; FBLD: flattened bamboo in the longitudinal direction; FBRD: flattened bamboo in the radial direction; FBTD: flattened bamboo in the tangential direction.

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## Authors' contributions

HC performed the SEM examination and was a major contributor to data analysis and writing the manuscript. YZ and XY performed FT-IR and XRD test, and YZ drew part of the images. HJ did the permeability test. TZ partly analyzed the data and wrote the manuscript. GW designed and financed the research. All authors read and approved the final manuscript.

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## Availability of data and materials

All data generated or analyzed during this study are included in this published article.

## Competing interests

The authors declare that they have no competing interests.

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