Properties and Application of Kraft Pulp Prepared from Waste Bamboo Powder

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As a by-product of bamboo processing, bamboo powder is incinerated or buried due to its ineffective utilization, which contributes to pollution. The large amount of waste bamboo powder generated during the processing of bamboo products cannot be effectively utilized. Meanwhile, multiple recycling leads to the loss of fiber quality of corrugated cardboard (OCC) pulp, reducing the mechanical properties of paper. In an effort to obtain high value from waste bamboo powder, this study pulped it using the kraft process. Scanning electron microscope (SEM) observations showed that the surface of bamboo fiber had more cracks, which made bamboo fiber have better air permeability. The permeability of bamboo paper was 146% that of the OCC. X-ray diffraction (XRD) analysis showed that the crystallinity of bamboo pulp was 133% that of the OCC pulp. The results of physical testing of paper showed that the tensile strength of bamboo paper was 116% that of the OCC. The tear strength of bamboo paper was 61.7% that of the OCC, and the bursting strength of bamboo paper was 59.1% that of the OCC. Based on the above results, bamboo powder can be used as raw material for making OCC pulp.

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INTRODUCTION

Paper is a green packaging material, but it requires a lot of plant fibers (Hubbe 2014a). China's forest resources are relatively scarce, and the per capita forest area is less than 1/4 of the world average (Liu *et al*. 2021a; Yang *et al*. 2012). An increase in pulp and paperboard consumption coupled with stricter environmental and sustainability regulations have prompted the development of additional natural materials for pulp and papermaking (Lucia *et al*. 2007; Iroegbu and Ray *et al*. 2021). Saving paper has become a social consensus. The packing market is one of the fastest growing markets, which means the demand for consumer packing is high, and it is necessary to use more economical and environmentally friendly materials (Ferrer *et al*. 2017). At the same time, recycling and reuse is a feature of future packaging materials, which meets the concept of sustainable development to conserve natural resources (Hubbe 2014b).

At present, the recovery rate of old corrugated containerboard (OCC) in China is less than 50%, which is much less than other developed countries. After the recovery of OCC, the performance declines greatly, which limits its applications. Economically, the recycled OCC needs to be pulped, possibly deinked, screened and passed through a hydrocyclone cleaner system to remove debris before papermaking (Chen *et al*. 2019a). Bamboo powder does not need to be crushed and deinked, which is more environmentally friendly and energy-saving. Moreover, as one of the wastes generated in the production and processing of bamboo products (Iroegbu and Ray *et al*. 2021), its recycling price is lower than that of OCC, and the economic feasibility is higher.

Zhejiang is a high-volume bamboo-producing province. While bamboo brings certain economic benefits to Zhejiang, it also produces a large amount of bamboo processing waste (Chen *et al*. 2019b). Bamboo powder is often treated as garbage, polluting the environment and wasting resources.

Bamboo is abundant in Zhejiang province. Bamboo powder is used as raw material for pulping in this experiment. Through the component analysis of bamboo powder, it was confirmed that bamboo powder can be used as raw material for pulp and paper making. In addition, the micro-morphology of bamboo fiber was observed, and the cooking method was determined according to the physical and chemical properties of bamboo fiber (Huang and Fei 2017). All raw material were pulped by kraft process. The obtained bamboo pulp was made into paper handsheets. The bamboo paper and OCC were tested for various physical properties and performance under the same conditions

EXPERIMENTAL

Materials

Bamboo powder was obtained from moso bamboo product production and processing waste (Quzhou, Zhejiang). The OCC was taken from packaging cartons. The cooking agents were NaOH and Na_2S, both purchased from Shanghai Lingfeng Chemical Reagent Co., Ltd. (Shanghai, China).

Pulping

After tearing the OCC into small pieces, it was soaked in water for 24 h, then placed in the hydraulic pulper. The beating pressure was adjusted to disperse the fibers evenly (Fig. 1). The weight of raw materials used in pulping was based on oven-dried fibers. The cooking process recipe is shown in Table 1.

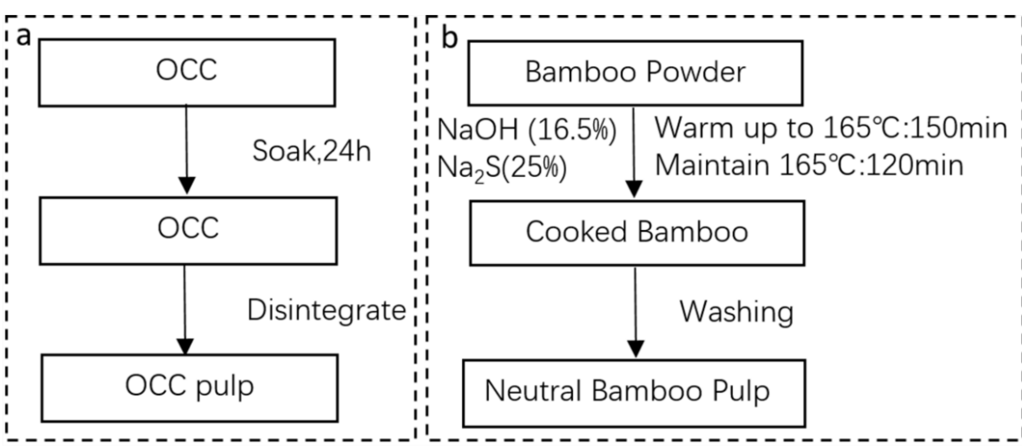

Fig. 1. Operation flow chart: a: Flow chart of OCC pulp preparation; b: Flow chart of bamboo pulp preparation

Table 1. Kraft Process Conditions

Active alkali rate (%)	Sulfidity (%)	Max. Temperature (℃)	Heating Time (min.)	Cooking Time (min.)	Liquor-to-Biomass Ratio ($L.kg^{-1}$)	Dry Mass of Chips (g)
16.5	25	165	120	150	5:1	300

Fiber Quality Analyzer (FQA)

The fiber length, width, coarseness, kink angle, curl index and other indexes were measured by fiber quality analyzer (Techpap, Grenoble, France). These values can be used to identify fiber raw materials, control refining conditions, predict pulp coating, and identify pulping the process, among other things.

Papermaking Method

The bamboo pulp (unbeaten) after 10,000 rpm was loosened and made into hand sheets with a paper former (TD10-200, Tongda Light Industry, Xianyang, China). The temperature of the extractor was set at 105 °C, the drying time was 5 min. The basis weight of the bamboo paper was 120 g/m^2. The performance of the hand-copied tablets was tested after equilibrating the moisture for 24 h in a constant temperature and humidity environment. The OCC pulp was made into paper by the same method.

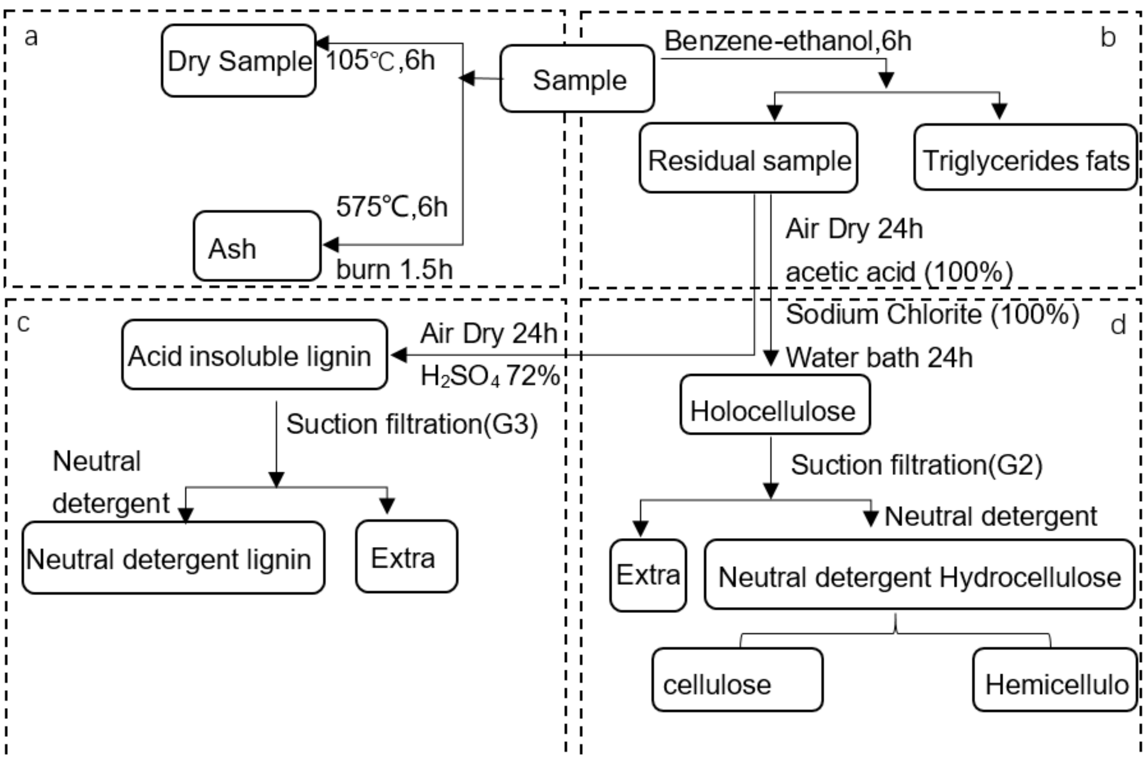

Fig. 2. Flow chart of composition extraction. a: Flow chart of quantitative analysis method of moisture and ash; b: Flow chart of quantitative analysis method of phenyl alcohol extract; c: Flow chart of quantitative analysis method of lignin; d: Flow chart of quantitative analysis method of total cellulose

Analysis of Bamboo Powder, Bamboo Pulp, OCC Pulp Composition, and Fiber Morphology

According to test methods GB/T2677.2 (2011), GB/T462 (2008), GB/T742 (2018), GB/T2677.10 (1995), GB/T2677.8 (1994), GB/T747 (2003), and GB/T2677.6 (1994), the moisture, ash, total cellulose, acid-insoluble lignin, and alcohol-benzene solubility of bamboo powder, bamboo pulp, and OCC pulp were detected. A component test flow chart is shown in Fig. 2.

The moisture content of each pulp sample was measured, and the dry weight (*D*) was calculated according to Eq. 1,

$$D = m \times (1 - W) \quad (1)$$

where *m* is the mass (g) and *W* is the water content.

Knowing the dry weight of the sample, the yield (*Y*) was calculated according to Eq. 2,

$$Y_{BJ} = \frac{D_{BP}}{D_{BJ}} \times 100\% \quad (2)$$

where *m* is the mass (g) and *W* is the water content, D_{BP} is dry weight of bamboo powder, and D_{BJ} is dry weight of bamboo pulp.

Scanning Electron Microscopy (SEM)

The fiber morphology of OCC pulp and bamboo pulp was observed with a scanning electron microscope (SEM SU1510, Hitachi, Tokyo, Japan) operating at an accelerating voltage of 15 kV. The samples were gold-plated using a vacuum sputter coater (MSP-2S/MSP-Mini; IXRF, Inc., Austin, TX, USA) prior to observation.

Fourier-transform Infrared (FT-IR) Spectroscopy

FTIR spectra were recorded on a Shimadzu 8400S spectrophotometer (Kyoto, Japan). The number of scans was 32, and the resolution was 4 cm^{-1}. Spectra were acquired in projection mode in the range of 500 to 4000^{-1} cm.

X-Ray Diffraction (XRD)

The crystallinity of bamboo powder, bamboo pulp, and OOC pulp can be calculated by XRD pattern. The XRD test parameters were Cu target, tube pressure/tube flow of 40 kV/20 mA, scanning speed of 4°/min, scanning step size of 0.04°, and 2θ=5° to 80° (Rigaku; Kuraray CO.LTO Tokyo, Japan).

The relative crystallinity was expressed as follows (Segal *et al*. 1959),

$$Crl = \frac{I_{002} - I_{AM}}{I_{002}} \times 100\% \quad (3)$$

where I_{002} is the extreme intensity of the lattice diffraction angle near 2θ = 22° (002), and I_{AM} is the scattering intensity of non-crystalline background diffraction near 2θ = 18°.

Determination of Paper Properties

The basis weight of paper was operated according to GB/T451.2 (1989). A paper sample of 100 cm^2 was obtained with a circular quantitative sampler (PN-SC100, Pinxiang, Hangzhou, China) and weighed on a precision electronic balance (XY, Lucky Electronics, Changzhou, China).

The tensile strength of paper was tested according to GB/T12914 (2008). The paper sample had a width of 15mm and length of 90 mm. The test speed was 15 mm/min ± 3.75 mm/min (WZL-B, Qingtong Boke, Hangzhou, China).

The bursting strength of paper was tested according to GB/T454 (2002) with a circular paper sample. The air pressure was adjusted to 0.2 to 0.3 MPa, and the corresponding quantitative value was entered in the settings (PN-BSM160F, Pinxiang, Hangzhou, China).

The tear strength of the paper was tested according to GB/T455 (2022). The paper sample dimensions were 63 mm × 50 mm, and the pendulum was raised to the initial position and fixed with the release mechanism of the pendulum (SLY-1000, Qingtong Boke, Hangzhou, China).

A multi-point sampling test was carried out on each sample using an air permeability tester, with a test area of 20 cm^2 and a test pressure of 200 Pa (FX3300IX, textest, Switzerland).

The beating degree of bamboo pulp and OOC pulp was determined by using a Shaw Berkeley beating tester (SDJ-100, Qingtong Boke, Hangzhou, China).

RESULTS AND DISCUSSION

Chemical Composition Analysis

The chemical composition of bamboo is an important factor for judging whether it can become a high-quality papermaking raw material, and it is also an important basis for rationally utilizing the fiber and specifying the technical conditions of the pulping process. The chemical components of the bamboo powder are shown in Table 2.

Table 2. Chemical Composition

Raw Material	Moisture (%)	Ash (%)	Holocellulose (%)	Acid-insoluble Lignin (%)	Acid-soluble Lignin (%)	Benzene-Alcohol Extract (%)
Bamboo powder	9.46	1.99	60.30	22.65	1.13	6.00
Bamboo pulp	7.25	1.45	90.20	0.51	0.03	0.64
OCC pulp	6.27	12.72	68.50	13.10	0.66	1.84

The ash content of bamboo powder was 1.995%. In the pulping process, the high ash content affects the recovery of alkali (Seo *et al*. 2017). Therefore, when using bamboo as a raw material for papermaking, care should be taken to avoid “silicon interference,” which adversely affects alkali recovery. The extracts mainly include soluble sugars, proteins, amino acids, fats, resins, essential oils, tannins, pigments, *etc*. The composition is very complex. These substances have different solubility in different solvents due to different polarity, acidity, alkalinity, and molecular weight. The alcohol-benzene solubility of bamboo powder was 6%, and the total lignin content was 23.8%. However, the alcohol-benzene solubility of bamboo pulp was only 0.64%, and the lignin content was as low as 0.54%. The orientation of most of the lignin and fibers in the parenchyma cells of bamboo powder was weakened after alkaline treatment, which was due to the stronger interaction between lignin and xylan in the fibers (Zhu *et al*. 2022a).

If all the lignin is completely removed, then part of the cellulose will be damaged, which will reduce the pulp yield and affect the paper-forming properties. If the raw material is pulped by kraft process using a lower alkalinity, then it can a higher quality and molecular mass of the cellulose. The alkalinity of the cooking process adopted by Liu *et al*. (2021) exceeded 20%. Taking Liu *et al.* (2021a,b) as a reference, in order to retain more fiber, this study adopted 16.5% basicity for sulfate pulping (Wang *et al.* 2010; Xu *et al.* 2016; Yue *et al*. 2017; Aprianis *et al.* 2020; Liu *et al*. 2021a,b; Zhu *et al*. 2022).

Cellulose is the most important chemical component of plant fiber and the most basic chemical component of paper. The cellulose content of the raw material is the basic basis for evaluating the pulp and paper value (Yao and Wei 2021). Retaining a high hemicellulose content can improve the paper-forming properties and increase the pulp yield (Rocky and Thompson 2018). Cellulose and hemicellulose are collectively called holocellulose and are important indicators to measure the pulping extent of fiber raw materials. The higher content of holocellulose indicates a higher pulp yield (Zhang and Yang 2006). The lignin content is an important basis for formulating reasonable cooking and bleaching process conditions. A higher content of lignin results in more difficult cooking conditions, as well as more chemicals consumed. As shown in Table 2, the holocellulose content of bamboo was 60.3%, and the lignin content of bamboo was 22.6%. Thus, the chemical composition of bamboo meets the quality requirements of the paper industry for pulp and is a good raw material for papermaking.

The holocellulose content of bamboo pulp per unit mass was 90.2%, and the content of holocellulose per unit mass of OCC pulp was 68.6%. Thus, the cellulose content of bamboo pulp was higher than that of OCC pulp under the same weight. The paper sheets were formed by combining cellulose fibers with each other by through hydrogen bonds. The bamboo paper had a higher cellulose content, and the connection between fibers was tighter, which to a certain extent compensated for the reduction of paper strength due to the fragmentation of fiber morphology (Malachowska *et al.* 2019).

The water content and weight of bamboo slurry were 84.5% and 540 g, respectively. Combined with the amount of raw materials, the yield of bamboo pulp can be calculated according to Eqs. 1 and 2. The yield of bamboo pulp was 31.4%.

Microstructure Analysis (SEM)

Scanning electron microscopy was used to analyze the surface morphology of fibers, including their surface roughness and degree of fiber damage (Rocky and Thompson 2018).

As the raw material of bamboo pulp was in powder form, the arrangement of bamboo fibers in Fig. 4 is irregular, and the morphology of some fibers is broken. The apparent fiber damage was caused by external mechanical action. Such fiber damage will affect the physical properties of paper (Zhang *et al*. 2022).

Bamboo pulp fibers are densely distributed, twisted, and generally arranged longitudinally. The surface of bamboo fiber is rough, and there are a lot of small cracks. These fine lines are like capillary tubes, so that bamboo fiber can absorb or evaporate water from the air better. The fiber distribution of OOC pulp was not as dense as bamboo pulp. The degree of fibrillation was low. Thus, multiple reuse will reduce the retention efficiency of the fiber and affect the morphology of the fiber itself. The bonding strength between fibers has been found to be positively correlated with the roughness of the fiber surface (Tripathi *et al*. 2018).

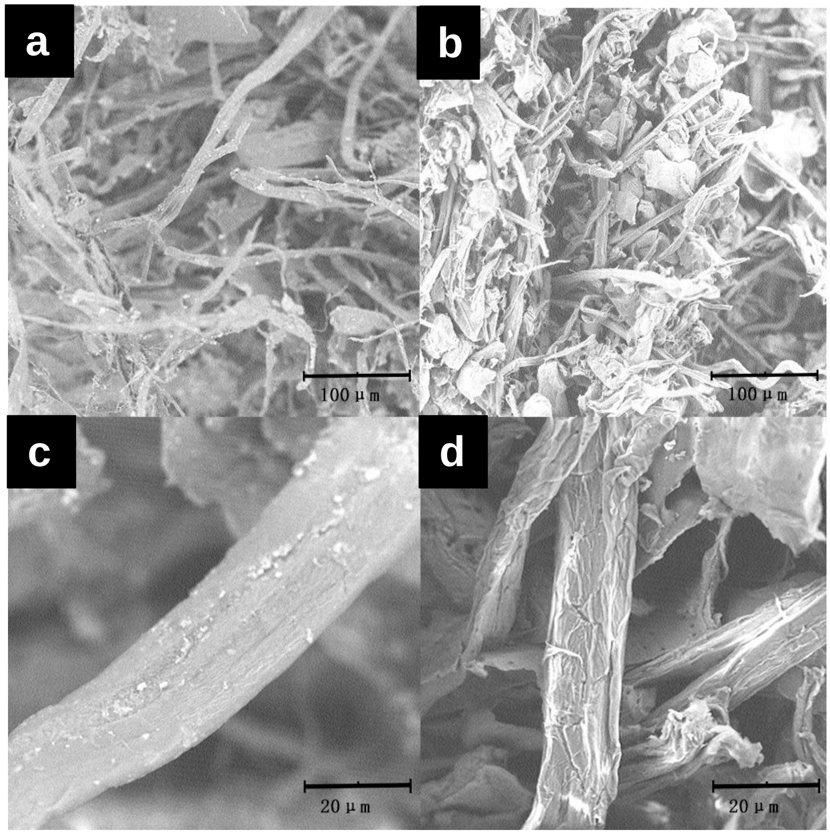

Fig. 3. Image of bamboo fiber and OCC fiber. a) OOC at 500× magnification, b) bamboo pulp at 3500× magnification, c) OOC at 3500× magnification, d) bamboo pulp at 3500× magnification

FT-IR Spectra

The infrared spectral characteristics of bamboo powder, bamboo pulp, and OOC pulp were obtained by Fourier infrared spectroscopy. Since all fiber samples were theoretically cellulosic materials, the infrared spectra were similar. However, the chemical compositions of bamboo pulp fiber and bamboo powder fiber were not the same after cooking, and the corresponding infrared spectra were different. The components of bamboo pulp, bamboo powder, and OCC pulp were mainly cellulose, hemicellulose, and lignin. The infrared spectra in Fig. 4 reflect these three components. The obvious broad peak at the wavelength of 3429 cm^{-1} was attributed to the hydroxyl group(Li and Tan 2022). The stretching vibration peak position of the hydroxyl group in OCC slurry was at the wavelength of 3440 cm^{-1}. There were absorbance peaks at the wavelengths of 2918 cm^{-1}, 2925 cm^{-1}, 2975 cm^{-1}, and 2916 cm^{-1}, which correspond to the stretching of C-H in methyl ($-CH_3$) and methylene ($-CH_2$) vibration peaks (Fan *et al*. 2020). The peaks near wavelength of 1629 and 1641 cm^{-1} are the stretching vibration peaks of C=C in the benzene ring. The absorbance peak near 1254 cm^{-1} is generated by the in-plane bending vibration of O-H; the peak near wavelength of 1049 cm^{-1} can be attributed to primary alcohols stretching vibration peaks of C-O. The wavelength of 1510 cm^{-1} is the characteristic peak of the aromatic ring skeleton vibration in lignin, but the vibration peak of bamboo pulp is weaker than that of bamboo powder, which means that the lignin aromatic ring skeleton in bamboo pulp is destroyed after cooking. The wavelength of 898 cm^{-1} is the vibration peak of the guaiac-based (G-type structure) benzene ring skeleton. In Fig. 4, the vibration peak of bamboo pulp at wavelength of 898 cm^{-1} is weaker than that of bamboo powder, which means that the guaiacyl lignin structure in bamboo pulp was damaged. The 1205 cm^{-1} and 1187 cm^{-1} peaks represent the syringyl group (S-type structure) and p-hydroxybenzene ring skeleton, respectively (Guo 2005). Figure 4 shows that the vibration peak fluctuation of bamboo pulp was weaker than that of bamboo powder, which means that syringyl lignin and p-hydroxybenzene contents in bamboo pulp were lower. The hydroxybenzene replacement skeleton was destroyed (Zhen *et al*. 2016; Zhao *et al*. 2016).

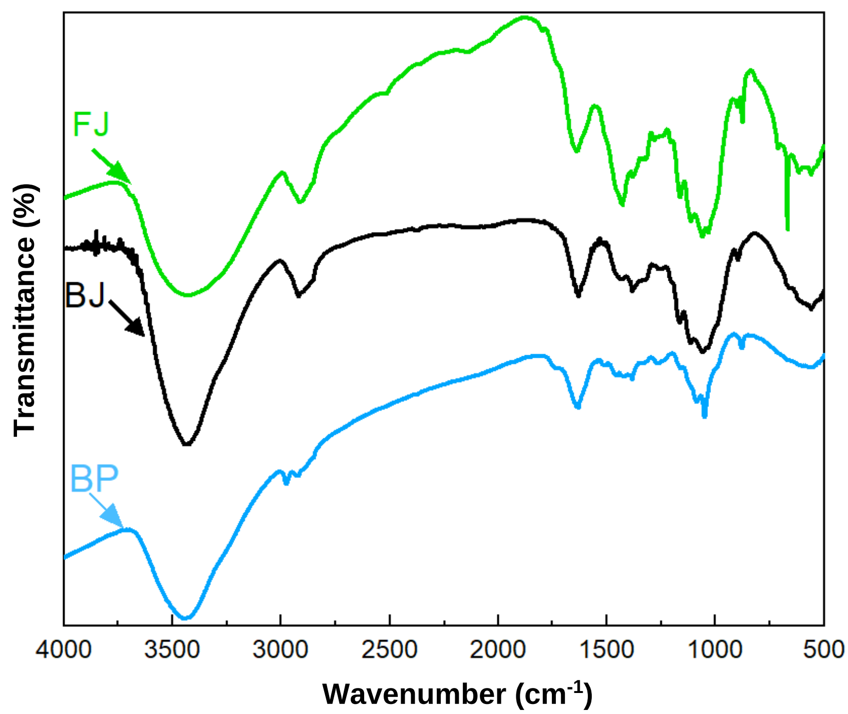

Fig. 4. The FT-IR spectra of bamboo powder, bamboo pulp and OCC pulp. BP: Bamboo Powder; BJ: Bamboo Pulp; FJ: OCC Pulp

Table 2. Infrared Absorbance Assignments

Bamboo Powder Wave Number (cm^{-1})	Bamboo Pulp Wave Number (cm^{-1})	OCC Pulp Wave Number (cm^{-1})	Functional Groups
3421	3423	3440	-OH
2918	2925, 2975	2916	$-CH_3$, $-CH_2$, -CH
1629	1629	1641	Conjugated carbonyl, ester group
1510, 1458	1450	1427	Benzene ring
1265, 1205, 1087, 1049	1245, 1201, 1164, 1058	1060, 1112, 1162	p-Hydroxyphenyl (H), lilac ring (S)
898, 879	896	875	Guaiac based (G) and multiple rings

When combined with the results of component analysis in Table 2, the lignin content of bamboo powder before cooking was 22.6%, and that of bamboo pulp after cooking was 0.51%, which indicates a great reduction in the lignin content. Kraft pulping effectively reduced the lignin content of bamboo, promoted the fiber raw materials to disperse into a single fibers, which were suitable for papermaking.

XRD Characterization

The crystallinity and crystal structure of bamboo powder, bamboo pulp, and OCC pulp were determined by XRD. Cellulose crystallinity is used to characterize the physical and chemical properties of fibers, and it is an important parameter to evaluate fiber quality.

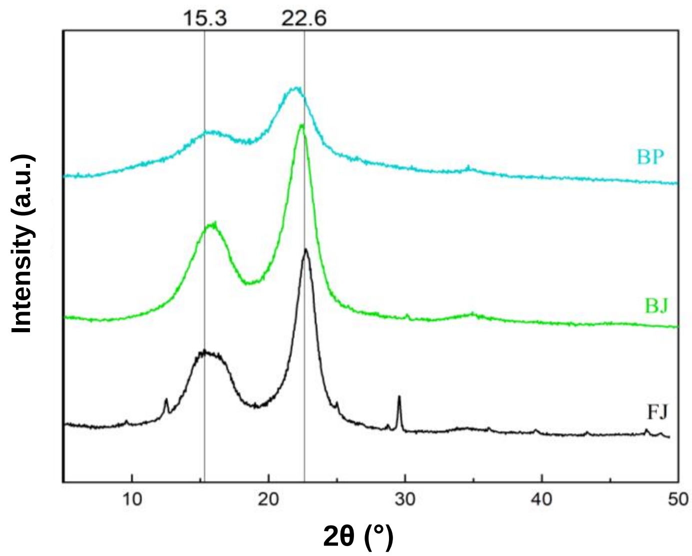

Fig. 5. The XRD of bamboo powder, bamboo pulp, and OCC pulp. BP: Bamboo Powder; BJ: Bamboo Pulp; FJ: OCC Pulp

The phase structure analysis of bamboo powder, bamboo pulp, and OCC pulp is shown in Fig. 5. The prominent peak position of bamboo powder, bamboo pulp, and OCC pulp was 22.08°, 22.36°, and 22.6°, respectively. The diffraction peaks in the crystalline region of the three are characterized by high and sharp peaks, high symmetry, and narrow half-height width; the diffraction peaks in the amorphous region are characterized by low diffraction intensity and a diffuse peak shape width.

I_{002} (2θ=22.7°) is the 002 surface peak intensity, that is, the diffraction intensity of the cellulose crystalline region, and I_{AM} (2θ=18°) is the diffraction intensity of amorphous region. Diffraction peaks appear near the diffraction angles of 2θ=16° (101 plane) and 2θ=22° (002 plane), both of which are characteristic crystalline peaks of cellulose I (Toba *et al*. 2015). Hence, the bamboo powder contained the cellulose I-type structure. No new peaks appeared in the bamboo powder after cooking, but the peak height of the bamboo pulp obtained after cooking increased significantly around 22.2°, indicating that cooking affected the crystalline properties of bamboo powder. As shown in Fig. 5, all the samples had two wide diffraction peaks that centered on the diffraction angles near 15.3° and 22.6°. The relative crystallinity of bamboo powder, bamboo pulp and OCC pulp could be calculated by means of the peak intensity method.

The relative crystallinity of bamboo powder, bamboo pulp, and OCC pulp were 40.6%, 69.6%, and 52.3%, respectively. The crystallinity of bamboo pulp was slightly higher than that of OCC pulp. Cellulose macromolecules are based on β-D-glucose group as a unit structure and are connected by 1,4 glycosidic bonds to form linear polymer compounds (Liu *et al*. 2012). The presence of hydrogen bonds in the macromolecules or between adjacent molecules leads to the formation of a neat crystal structure sequence. Before and after cooking, the crystallinity of cellulose changed. According to Fig. 5, the crystallinity of bamboo pulp increased compared with bamboo powder.

Fiber morphology analysis

Fiber properties include fiber-to-fiber bonding, fiber size, stock preparation, and optimized properties at the chemical addition stage; these factors reflect the basic characteristics of fiber morphology and have a great impact on the physical properties of paper (Zhang *et al*. 2020). The three basic properties of papermaking fibers in fiber length, thickness, and strength are closely related to the performance of paper.

Figure 6 shows that the fiber length of bamboo pulp was mainly distributed between 0.2 and 0.48 mm, and the fiber length of OCC pulp was mainly distributed between 0.48 and 2.71 mm. The fiber of the bamboo powder raw material was broken due to pulverization, resulting in fiber breakage and reduced length.

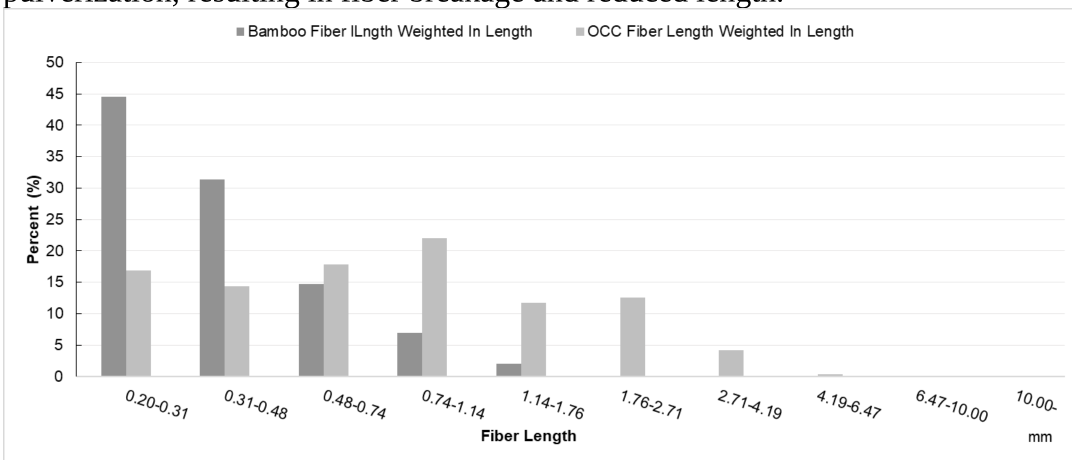

Fig. 6. Bamboo pulp fiber and OCC pulp fiber length (weighted)

Figure 7 shows that the fiber diameters of bamboo pulp and OCC pulp were mainly distributed between 17 and 41 μm, but the number of bamboo pulp fibers in this range was slightly higher than that of OCC fibers. The average diameter of bamboo pulp fibers was slightly higher than that of OCC pulp. Combining the average length distribution of the two fibers, it can be concluded that the aspect ratio of bamboo pulp fibers was smaller than that of OCC fibers, so that the number of bamboo pulp fiber interlacing per unit area was less than the number of fibers interlacing per unit area of OCC pulp. The bonding force between fibers was slightly reduced by the aspect ratio.

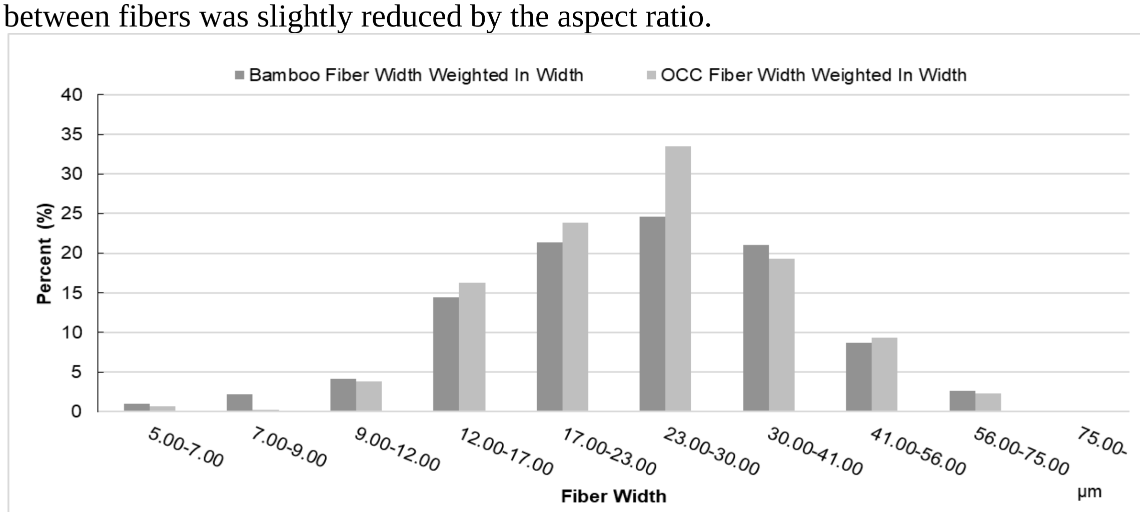

Fig. 7. Width weighted in width of bamboo fiber and OCC fiber. A: Bamboo pulp fiber and OCC pulp fiber width

Table 3 shows that the bamboo pulp fiber roughness was 0.13 mg/m, and the OCC fiber roughness was 0.07 mg/m. The bamboo pulp fiber surface was rougher, and the friction force between fibers was greater than that between OCC pulp fibers. The kink angle of bamboo pulp fibers was 110°, and the kink fibers accounted for 13.60% of the total fibers. The kink angle of OCC pulp fibers was 121°, and the kink fibers accounted for 25.2% of the total fibers. The kink angle of bamboo pulp fiber was slightly smaller than that of OCC pulp, and under the same weight, the kink fiber content of bamboo pulp per square meter was smaller than that of OCC pulp.

As shown in Table 4, the beating degree of bamboo pulp and OOC pulp was 26.5 and 34.2 °SR respectively. The beating degree of bamboo pulp was lower than that of OCC pulp, which means that the water holding capacity of bamboo pulp was weaker. The degree of fiber kink is related to the water retention capacity, and in general, the higher the degree of kink, the higher the water retention capacity. The relationship between kink degree and pulping degree of bamboo pulp and OCC pulp in the table was exactly in line with this phenomenon. In addition, the crimp rate of bamboo pulp fiber was 12.7%, and the crimp value of OCC pulp fiber was 14.4%. The crimp value of bamboo pulp fiber was lower than that of OCC pulp fiber. However, the long fiber proportion of bamboo pulp fiber (4.28%) was higher than that of OCC pulp fiber (3.56%). These results are consistent with the fact that after the OCC pulp is reused for many times, the long fibers become lost. With the increase of the number of reuses, the bonding force between the OCC pulp fibers will become weaker.

Table 3. Paper Physical Property Testing Data

	Coarseness (mg/m)	Kink angle (°)	Kinked fibers (%)	Curl (%)	Rate in Length of Macrofibrils (%)
Bamboo fiber characteristics	0.13	110.00	13.60	12.70	4.30
OCC fiber characteristics	0.07	121.00	25.20	14.40	3.56

Analysis of Physical Properties of Paper

Tensile index is closely related to the strength of paper fibers and the bonding force between fibers(Liu *et al*. 2014). Factors such as the number of hydrogen bonds and the length of the fibers also affect the tensile index of the paper. If the fiber length is larger, then the degree of bonding during papermaking will be higher, which is beneficial to the tensile index of the paper. The beating degree of bamboo pulp is lower than that of OCC pulp, but the tensile strength of bamboo paper is higher than that of OCC pulp, which is a good phenomenon. Bamboo fiber can get good performance even at a low degree of beating. Therefore, it is not necessary to improve the performance of bamboo fiber by beating, which can reduce the production energy consumption. The tear index is related to the length and thickness of the fiber, and paper made of long fibers has a higher tear strength. Bursting strength reflects the maximum pressure that can be uniformly increased per unit area of the tested paper in the vertical direction, and it reflects the ability of the carton to protect the product when it is squeezed during transportation and under static conditions. As shown in Table 4, the average tensile strength of bamboo pulp was slightly higher than that of OCC pulp. After the repeated recycling of OCC pulp, the fibers were inevitably destroyed, and the long fiber content was reduced. Bamboo pulp paper was slightly insufficient.

However, under the same quantitative conditions, the anti-knock index and tear index of OCC pulp were stronger than those of bamboo pulp. This is because the proportion of long fibers in OCC pulp was still more than in bamboo pulp. This conclusion is consistent with the data in the fiber morphology analysis.

Table 4. Paper Physical Property Testing Data

Paper Pulp	Tensile Index (N·m/g)	Bursting Index (kPa·m^2/g)	Tear Index (mN·m^2/g)	Beating Degree/°SR	Air Permeability (mm/s)
Bamboo pulp	4.99	0.30	2.96	26.50	64.82
OCC pulp	4.29	0.50	4.80	34.20	44.28

For chemical pulp, during the recycling process, the fibers undergo hornification, which is manifested as a decrease in water retention value, a decrease in softness, and a decrease in paper tightness.

Air permeability refers to the ability of air to pass through an object when there is a pressure difference between the two sides of the object (Prakash *et al*. 2013a). Air permeability is the rate at which air flows vertically through a sample under specified conditions of sample area, pressure drop, and time. The main factors affecting the air permeability of paper are the selection of raw materials (Prakash and Ramakrishnan 2013b), pulp treatment, and fiber ratio. The air permeability index of paper is an important parameter for paper quality evaluation, especially for special papers such as cigarette paper, filter paper, and fruit bagging paper. Cigarette paper with high air permeability can dilute and reduce the smoke inhaled into the human body and reduce the harm. The experiment was divided into two test groups, each group of three test objects, with a multi-point test method on the same paper sample to obtain the average air permeability of the paper sample. The experimental results are shown in Table 4. The average air permeability of any sample of bamboo pulp paper was higher than that of any sample of waste paper pulp. Bamboo pulp paper has good air permeability, which is determined by the special structure of bamboo fiber itself. The SEM analysis showed that the thickness of bamboo fibers is unevenly distributed, and there are countless micro cracks on the surface of the fibers. These structural characteristics of bamboo fibers are like capillaries that can absorb and evaporate water in an instant, so the air permeability is good.

CONCLUSIONS

1. Waste bamboo powder was used as raw material, and pulping was carried out by the sulfate method. The paper sheets were made by hand at a basis weight of 120 g/m^2. In terms of morphology, bamboo pulp paper fibers were relatively broken, the distribution was tighter, the fiber surface was rough, and there were countless fine cracks. Based on this feature, the bamboo pulp paper with the quantity of 120 g/m^2 had higher air permeability than OCC. The air permeability of bamboo pulp was 146% higher than that of OCC pulp. The fibers of OCC pulp were sparsely dispersed; the fibers themselves were slender, straight, and long. The surface of the fibers was smooth, and the friction between the fibers was weaker than that of bamboo pulp.

2. The tensile strength of bamboo pulp was greater than that of old corrugated container (OCC) pulp. The X-ray diffraction (XRD) pattern showed that the crystallinity of bamboo pulp was higher than that of OCC pulp. This result suggests that because the increase of the intermolecular forces increased, the tensile strength increased, but the elongation at break decreased.

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