ISSN impresa 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 2024 (26): 28, 1-12

DOI: 10.22320/s0718221x/2024.28

INFLUENCE OF PRETREATMENT ON PROPERTIES OF BAMBOO PORTLAND CEMENT PARTICLE BOARD

Canbin Yin[1,2]

https://orcid.org/0000-0001-7630-5861

Xingong Li[1,♠]

https://orcid.org/0000-0003-1387-4199

ABSTRACT

Bamboo contains water-soluble saccharides and carboxylic acid which have an anticoagulation effect on Portland cement, and the anticoagulation ingredients can directly influence the hydration reaction extent. Hydration product varieties and hydration product-bamboo shaving binding interfaces of the Portland cement, and finally the mechanical properties of bamboo cement particle boards. In this paper, bamboo shavings are pretreated by carbonizing treatment, hydro-thermal treatment and alkali treatment; high performance liquid chromatography is adopted to analyze the influences of three different pretreatment methods on contents of water-soluble saccharides and carboxylic acid in the bamboo shavings; a Fourier infrared spectrometer and an X-ray diffractometer are respectively utilized to analyze the characteristic peak changes and crystallization property changes of chemical ingredients of the bamboo shavings before and after the three types of pretreatment. This paper discusses effects of three types of pretreatment methods in eliminating water-soluble saccharides and carboxylic acid in the bamboo shavings. Bamboo Portland cement particle boards was prepared using bamboo shavings, which are pretreated in three ways, and influences and mechanisms of different pretreatment methods on properties of the bamboo Portland cement particle boards were studied. Research indicates that the mechanical properties of the Portland cement particle board prepared from bamboo shavings pretreated with 3 % NaOH solution are superior to requirements of qualified products and superior products specified in the Standard.

Keywords: Alkali treatment, bamboo portland cement particle board, bamboo, carbonizing treatment, hydro-thermal treatment.

INTRODUCTION

The bamboo Portland cement particle board is an inorganic artificial board prepared by using Portland cement as a base material and adopting wood, bamboo or straw shavings as reinforcing and toughening materials, so that it has excellent properties such as high strength, water-proof property and antiflaming property, and it is widely applied in the fields of building wall materials, outdoor furniture materials and the like (Cabral *et al.* 2018). Bamboo has the characteristics of high strength, high toughness, good rigidity, high processability and the like, and the bamboo Portland cement particle board prepared by utilizing the bamboo shavings as the reinforcing material has overall performances superior to those of other similar products. The strength of the bamboo shavings, the hydration reaction extent of the Portland cement and the binding interfaces of the bam-

[1]Central South University of Forestry and Technology. College of Materials Science and Engineering. Department of wood science and furniture engineering. Changsha, China.

[2]Hunan City University. College of Civil Engineering. Department of engineering cost. Yiyang, China.

[♠]Corresponding author: lxgwood2021@163.com

Received: 15.03.2022 Accepted: 16.10.2023

boo shavings and hydration products are premises for forming the mechanical strength of the bamboo Portland cement particle board. Compared with wood, bamboos contain more water-soluble saccharides and carboxylic acid which have an anticoagulation effect on Portland cement, and the anticoagulation ingredients can directly influence the hydration reaction extent, hydration product varieties and hydration product-bamboo shaving binding interfaces (Shen *et al.* 2007) of the Portland cement particle board, so that effective reduction in the content of anticoagulation ingredients in the bamboos is quite important for preparation of bamboo Portland cement particle boards. The water-soluble saccharides and carboxylic acid in the bamboos can be reduced to different extents by virtue of carbonizing treatment, hydro-thermal treatment, and alkali treatment. In this paper, bamboo shavings are pretreated by utilizing three methods, namely carbonizing treatment (Zeng *et al.* 2006), hydro-thermal treatment and alkali treatment (Zhang *et al*. 2010, Xu *et al*. 2005), high-performance liquid chromatography is adopted to analyze the influences of three different pretreatment methods on contents of water-soluble saccharides and carboxylic acid in the bamboo shavings; a Fourier infrared spectrometer and an X-ray diffractometer are respectively utilized to analyze the characteristic peak changes and crystallization property changes of chemical ingredients of the bamboo shavings before and after the three types of pretreatment. This paper discusses effects of three pretreatment methods in eliminating water-soluble saccharides and carboxylic acid in the bamboo shavings, and bamboo Portland cement particle boards was prepared by use of the bamboo shavings subjected to three types of pretreatment, and influences and mechanisms of different pretreatment methods on performances of the bamboo Portland cement particle boards were researched.

MATERIALS AND METHODS

Experimental materials

Bamboo shavings, purchased from Hunan Taohua River Industrial Limited Company (water content: 10 %; length: 10 mm - 30 mm; width: 1 mm - 6 mm, thickness: 0,2 mm - 0,4 mm). Portland cement, R52,5, purchased from Zhucheng City Yangchun Cement Limited Company. NaOH solution (3 %), commercially pure, purchased from Changsha Pingchuan Chemical Technology Co., Ltd.

Experimental equipment and instrument

Electronic thermostatic drier box (101A), Shanghai Experiment Instrument Factory; multifunctional pulverizer (2500Y), Yongkang City Boou Hardware Product Limited Company; artificial board single-layer hot press (Y33-50), Pingxiang Jiuzhou Precise Press Limited Company; Waters244-type high-performance liquid chromatograph, American Waters Company; chromatographic column: Diamonsil C18 (250 mm x 4,6 mm); Waters486 differential detector, M510 pump, six-way valve sample injector, Zhejiang University 2000 chromatographic work station; X-ray diffractometer (XD-2), purchased from Beijing pgeneral Co., Ltd; Fourier transform infrared spectrometer (IRAffinity-1), purchased from Shimadzu Corporation; all-purpose mechanical tester (DCS-R-100), purchased from Shimadzu Corporation; scanning electron microscope (MIRA3LMH), purchased from TESCAN China, Ltd.

Experimental methods

Bamboo shaving pretreatment

Portland cement belongs to an alkaline inorganic cementing material. The water-soluble saccharides and carboxylic acid in bamboos have a strong anticoagulation effect on Portland cement hydration reaction (Yu *et al.* 2004). Research indicates that hydro-thermal treatment and alkali treatment can effectively eliminate the anticoagulation ingredients in bamboos, so that the adaptability of the bamboos and Portland cement can be improved (Han 2014). The higher the hydro-thermal treatment temperature is, the better the effect of eliminating the anticoagulation ingredients in bamboos is. High-temperature carbonizing treatment also can effectively eliminate the carboxylic acids in bamboos, however high-temperature effect can destroy the hemicellulose in bamboo cytoderm, and further the strength of bamboo shavings is reduced, so that the critical temperature of high-temperature carbonizing treatment is 200 DEG C (Wu *et al.* 2014). Based on the above research, this paper adopts three pretreatment methods (carbonizing treatment, hydro-thermal treatment and alkali treatment) and systematically researches the influences of three pretreatment methods on the properties of the bamboo Portland cement particle board.

Carbonizing treatment: feeding the bamboo shavings into a carbonizing kiln, and performing carbonizing treatment at a temperature of 200 ºC for 10 h so as to prepare carbonized bamboo shavings.

Hydro-thermal treatment: adding the bamboo shavings into a temperature-adjustable boiling tank filled with tap water (the mass ratio of the bamboo shavings to the tap water is 1:20), and performing treatment at a temperature of 100 ºC for 120 min; rinsing the treated bamboo shavings with tap water for five times; then feeding the bamboo shavings into an electronic thermostatic drier box, and drying the bamboo shavings to constant weight for standby at a temperature of 103 ºC.

Alkali treatment: preparing a 3 % NaOH solution, soaking the bamboo shavings with the NaOH solution for 24 h (the mass ratio of the bamboo shavings to the NaOH solution is 1:20), then filtering out the bamboo shavings with a filter screen, and repeatedly rinsing the bamboo shavings with tap water until the solution is neutral; and then feeding the bamboo shavings into the electronic thermostatic drier box, and drying the bamboo shavings to constant weight for standby at a temperature of 103 ºC.

Bamboo powder preparation

Respectively pulverizing untreated bamboo shavings, carbonized bamboo shavings, hydrothermal-treated bamboo shavings and the alkali-treated bamboo shavings by use of a multifunctional pulverizer; then screening out bamboo powder with a 200-mesh vibrating screen, wherein the bamboo powder is used for high-performance liquid chromatography, Fourier transform Infrared spectroscopy and X-ray diffraction analysis.

Preparation of bamboo cement particle boards

A semi-dry method is adopted to press bamboo cement particle boards. The board specification is 400 mm x 400 mm x12 mm; the density design is 1200 kg/m^3; the mass ratio of the Portland cement to bamboo particle boards is 3:1; the mass ratio of the Portland cement to water is 0,5. The preparation steps are as follows: respectively weighing the bamboo shavings subjected to three different types of pretreatment and water, mixing and stirring the bamboo shavings and water for 2 min, further adding the weighed Portland cement, and then stirring for 5 min until the materials are uniformly mixed; then manually and uniformly paving the mixture on a steel shim; paving three board blanks once, stacking the three board blanks and the steel shim on a mode locking rack, and feeding the board blanks, the steel shim and the mode locking rack into a cold press, and performing cold-pressing mold locking, wherein the thickness of the board blanks is controlled by a thickness gauge, and the pressing pressure is 5,0 MPa; feeding the board blanks subjected to mold locking into a curing box, and performing thermal curing for 12 h, wherein the curing box is controlled with water vapor, and the temperature is controlled at a temperature of 60 ºC - 80 ºC; after thermal curing, performing pressure relief so as to obtain bamboo cement particle board semi-finished products; stacking the bamboo cement particle board semi-finished products, and naturally curing the semi-finished products for 28 days, thereby obtaining finished products; then feeding the finished products into a dryer, and drying the finished products at a temperature of 70 ºC - 90 ºC until the moisture content is about 10 % for detection.

Detection and representation

Detection of water-soluble saccharides and carboxylic acid: detecting the water-soluble saccharides and carboxylic acid in bamboo powder by use of a high-performance liquid chromatograph, wherein the mobile phase is 0,05 mol/L H_2SO_4 (V:V), with the temperature is 55 ºC and the flow velocity is 0,01 mL/min. Redistilled water is adopted and filtered with a 0,45 μm filtration membrane. Acetonitrile is chromatographically pure. Methyl alcohol is superior pure filtered with a 0,51μm filtration membrane, and phosphoric acid is guaranteed; respectively weighing5g bamboo powder samples, adding redistilled water, soaking the bamboo powder samples at a room temperature for 24 h, feeding the soaked bamboo powder samples into a centrifuge, and performing centrifugal treatment on the soaked bamboo powder samples for 25 min at a revolution speed of 4000 rpm; taking 3 parts of 20 μL supernate, respectively performing high-performance liquid chromatography detection and analysis on the 3 parts of supernate under the above chromatographic condition so as to obtain a chromatogram of free saccharides and free organic acids, repeating sample feeding for three times, calculating peak areas of respective peaks by use of an area normalization method, and calculating their contents by use of an external reference method.

Fourier transform infrared spectroscopy (FTIR) detection: during detection, scanning surfaces of bamboo powder and analyzing surface functional groups of the untreated bamboo powder and pretreated bamboo powder by use of a potassium bromide pellet technique and a Fourier transform infrared spectrometer, wherein the scanning range is 4000 cm^{-1} - 400 cm^{-1}, with the resolution ratio is 2 cm^{-1} and the scanning times is 32 times; and repeating the above steps once.

X-ray diffractometer (XRD) detection: performing test analysis on crystallization properties of the untreated bamboo powder and pretreated bamboo powder, wherein the test conditions are as follows: the CuKα target λ is 0,154 nm; the voltage is 40 kV; the electric current is 35 mA; the scanning speed 2θ is 8°/min; the scanning range is 5°～45°.

Detection of mechanical properties: detecting the MOR, modulus of elasticity (MOE), internal bond strength (IB) and 24 h water absorption thickness swelling rate (TS) and the like of test pieces according to the national standards of cement particle boards GB/T24312-2009 (2009).

Scanning electron microscope (SEM) test: observing metal spraying fracture appearances of the test pieces by use of an MIRA3LMH-type scanning electron microscope, wherein the test pressure is 0,8 MPa, and the test voltage is 15 KV.

RESULTS AND ANALYSIS

Fourier transform infrared spectroscopy analysis on untreated and pretreated bamboos

Main chemical compositions of bamboos mainly include three natural high-molecular compounds, namely cellulose, hemicellulose and lignose. The bamboo cellulose, which is a macromolecule polysaccharide consisting of glucose, is a main ingredient of bamboo cytoderm; the bamboo hemicellulose, which is a heterogeneous polymer consisting of different monosaccharides, is combined to the surface of the cellulose, and the hemicellulose and the cellulose are mutually connected and enwound to form a network structure of mutually connecting bamboo cells, which is beneficial to formation of bamboo strength. The lignose as an aromatic superpolymer can form a fiber support with an effect of reinforcing wood fibers. The cellulose, hemicellulose and lignose in the bamboos have a certain effect on the mechanical strength of the bamboos. The infrared sensitive group of bamboo cellulose is hydroxy (-OH), and the hydroxy (-OH) is also the infrared sensitive group of bamboo hemicellulose. The infrared spectroscopy of lignose is more complex than those of the cellulose and the hemicellulose, and the infrared sensitive groups of the lignose include methoxy group, methoxy group (C=O), benzene ring (C=C-OH) and the like (Chu *et al*. 2016).

It can be seen from Figure 1 that infrared characteristic peaks of the untreated and pretreated bamboo shavings are basically consistent, and it indicates that new chemical bond isn't produced by bamboos subjected to different types of pretreatment, so that no new characteristic peak is produced in a spectrogram. Band peaks at 897 cm^{-1}, 2900 cm^{-1} and 3304 $cm^{-1}$are characteristic peaks of the bamboo cellulose; compared with untreated bamboo shavings, three characteristic peaks near 897 cm^{-1}, 2900 cm^{-1} and 3304 cm^{-1} of the bamboo shavings subjected to alkali treatment and hydro-thermal treatment are almost unchanged, but the characteristic peak near 897 cm^{-1} of the carbonized bamboo shavings is weakened to a certain extent, so that it indicates that in terms of three types of pretreatment, carbonizing treatment causes certain damage on part of cellulose of the bamboo shavings. Bamboo cellulose is possibly damaged and decomposed to generate substances such as carbon dioxide, carbon monoxide and a small quantity of acetic acid. Band peaks at 1021 $cm^{-1}$and 1506 cm^{-1} are characteristic peaks of the lignose. Compared with untreated bamboo shavings, the characteristic peaks at 1021 $cm^{-1}$and 1506 cm^{-1} of the bamboo shavings subjected to three types of pretreatment are almost unchanged, so that it indicates that three types of pretreatment cause no damage on the bamboo lignose. Acetyl and carbonyl stretch vibration peaks near 1730 $cm^{-1}$are characteristic peaks of the hemicellulose. The characteristic peaks near 1730 cm^{-1} of the carbonized bamboo shavings are obviously weakened, however the characteristic peaks near 1730 cm^{-1} of the bamboo shavings subjected to alkali treatment and hydro-thermal treatment have no obvious change. It indicates that carbonizing treatment causes more obvious damage on the bamboo hemicellulose.

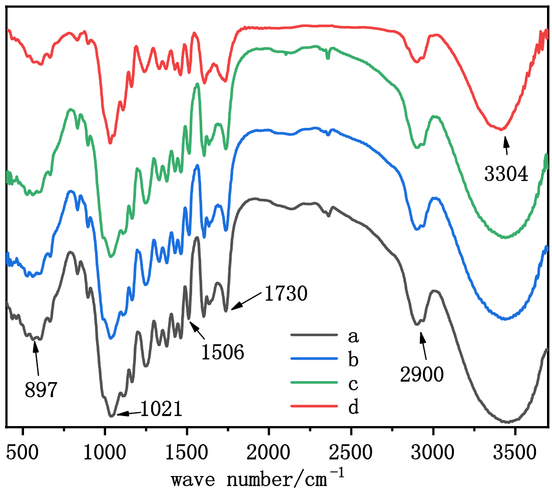

Figure 1: Infra-red spectrogram of untreated and pretreated bamboo shavings. (a) Untreated; (b) alkali treatment; (c) hydro-thermal treatment; (d) carbonizing treatment.

Carbonizing treatment causes certain damage on part of cellulose of the bamboo shavings and more obvious damage on the hemicellulose, and it can influence the strength of bamboo shavings and further influence the effect of bamboos in reinforcing cement particle boards; the damaged hemicellulose is further saccharified to generate water-soluble saccharides (Tian and Wang 2001) such as oligosaccharide, xylose, arabinose, galactose and mannose, so that the content of water-soluble saccharides with anticoagulation effect on the Portland cement in bamboo shavings is increased, and thus the cement hydration reaction and mechanical properties of cement particle boards during a cement particle board forming process are influenced.

X-ray Diffraction analysis on untreated and pretreated bamboos

It can be seen from the X-ray diffraction spectrogram of bamboo in Figure 2 that the 101 peak, 002 peak and 004 peak near 2θ=16,05°,21,5°, 34,5° are characteristic diffraction peaks of bamboo cellulose. These peaks (especially the 002 peak) reflect the crystalline structure (Li *et al.* 2012, Chu *et al.* 2017) of bamboo cytodermcellulose. The bamboo cytoderm cellulose consists of a crystalline region and an amorphous region which are gradually transitional. The mass or volume percent of the crystalline region in the cellulose is an important index for measuring the cellulose crystalline degree, and it is named as cellulose crystallinity (Yang *et al.* 2010, Sun *et al.* 2011). It can be seen from Figure 2 that compared with the untreated bamboo shavings, the bamboo shavings subjected to the three types of pretreatment have various degrees of changes in peak height and peak width of characteristic diffraction peaks (the 101 peak, 002 peak and 004 peak, especially the 002 peak) of bamboo cytodermcellulose, wherein the characteristic diffraction peaks (002 peaks) of cellulose cytoderm of the bamboos subjected to alkali treatment and the bamboos subjected to hydro-thermal treatment have less peak height changes, and the characteristic diffraction peaks (002 peaks) of cellulose cytoderm of the carbonized bamboos have great peak height changes, so that it indicates that the crystallinity of bamboo cytoderm cellulose is obviously increased due to carbonizing treatment. It is because that the alkali treatment and hydro-thermal treatment cause less damage on part of hemicellulose in bamboo cytodem, whereas carbonizing treatment causes great damage on the hemicellulose in the bamboo cytodem, so that hydroxy (-OH) of microfilaments in amorphous regions of the bamboo cytodemcellulose are exposed and combined with microfilaments on the surfaces of crystalline regions of the bamboo cytodemcellulose to form hydrogen bonds, thereby achieving a result that the microfilaments in the amorphous regions approach to the crystalline regions and are sequentially arranged. This result is consistent with that of Fourier transform infrared spectroscopy.

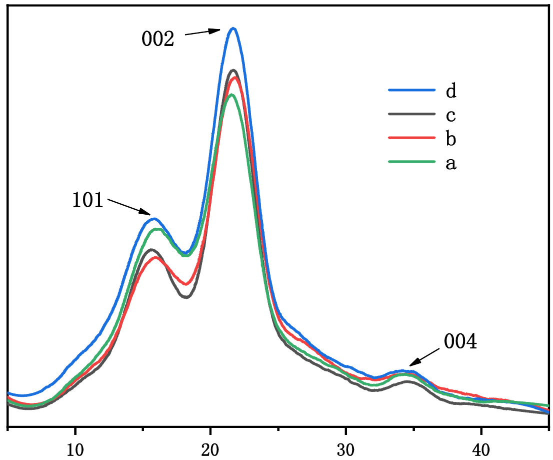

Figure 2: X-ray diffraction pattern of untreated and pretreated bamboo shavings. (a) Untreated; (b) alkali treatment; (c) hydro-thermal treatment; (d) carbonizing treatment.

High merformance liquid chromatography and preteated bamboos

Table 1 shows varieties and contents of water-soluble saccharides and organic carboxylic acids in the untreated and pretreated bamboo shavings. It can been seen from Table 1 that the content of water-soluble saccharides in the carbonized bamboo shavings increases instead of decreasing. The content of water-soluble saccharides in the carbonized bamboo shavings is increased by 22,9 % from the 7,225 g / 100g of untreated bamboo shavings to 8,879 g / 100 g. It is possibly because that during the carbonizing treatment process, the hemicellulose in bamboo shavings is damaged under high-temperature and high-humidity conditions and subjected to saccharification and conversion reaction so as to generate water-soluble saccharides such as oligosaccharide, xylose, arabinose, galactose and mannose. The contents of formic acid and acetic acids in the carbonized bamboo shavings decrease obviously, which is caused due to the reason that the formic acid and acetic acid in bamboo shavings and substances such as less acetic acid generated by decomposition of cellulose in the bamboo shavings volatilize due to a high temperature in a carbonizing process; the contents of water-soluble saccharides and acetic acid in the bamboo shavings subjected to hydro-thermal treatment are obviously less than those of untreated bamboo shavings, and no formic acid is not detected. It is caused due to the reason that the water-soluble saccharides and acetic acid in the bamboo shavings subjected to hydro-thermal treatment are partially dissolved out. In addition, formic acid is a volatile carboxylic acid, and it can rapidly volatilize during the hydro-thermal treatment process, so that formic acid ingredient isn't detected; the content of water-soluble saccharides in bamboo shavings subjected to alkali treatment is obviously less than that of untreated bamboo shavings, which is caused due to the reason that the water-soluble saccharides in the bamboo shavings are partially dissolved out in the NaOH solution. Meanwhile, formic acid and acetic acid ingredients aren't detected from the bamboo shavings subjected to alkali treatment, which is because that formic acid and acetic acid ingredients in the bamboo shavings and NaOH in aqueous alkali are subjected to an acid-base reaction.

Table 1: Contents of water-soluble saccharides and carboxylic acid in the untreated and pretreated bamboo shavings.

	Water-soluble saccharides (g/100g)	Formic acid (mg/100g)	Acetic acid (mg/100g)
Untreating	7,225	293,4	830,7
Carbonizing treatment	8,879	90,84	119,1
Hydro-thermal treatment	2,422	0	45,32
Alkali treatment	2,428	0	0

In terms of contents of water-soluble saccharides, formic acid and acetic acid in the bamboo shavings subjected to three types of pretreatment, the bamboo shavings subjected to alkali treatment have least ingredients with an anticoagulation effect on Portland cement, then the bamboo shavings subjected to hydro-thermal treatment have more ingredients with an anticoagulation effect on Portland cement, and the bamboo shavings subjected to carbonizing treatment have most ingredients with an anticoagulation effect on Portland cement. Therefore, alkali treatment may be the most beneficial pretreatment method for mechanical properties of bamboo cement particle boards.

Analysis on mechanical properties of untreated and pretreated bamboo cement particle boards

The strength of the bamboo shavings, the hydration reaction extent of the Portland cement and the binding interfaces of the bamboo shavings and hydration products are premises (Juengera and Jennings 2002) for forming the mechanical strength of the bamboo Portland cement particle board. The content of anticoagulation ingredients such as water-soluble saccharides and organic carboxylic acid in the pretreated bamboo shavings can directly influence the hydration reaction extent of the Portland cement and the binding interfaces of the hydration products and the bamboo shavings. When the content of anticoagulation ingredients is less than the critical value, it hasn't obvious influence on the hydration reaction extent of the Portland cement and the binding interfaces of the hydration products and the bamboo shavings. Therefore, the content of anticoagulation ingredients in the pretreated bamboo shavings and the strength of the bamboo shavings are key factors of influencing the mechanical properties of the cement particle board.

Table 2 compares the mechanical properties of cement particle boards prepared by three different pretreatment methods with values of the cement particle board standard GB/T24312-2009 (2009). It can be seen from the Table 2 that the mechanical property indexes of the cement particle board prepared from carbonized bamboo shavings do not meet the qualified product requirements specified in the cement particle board standard. It is because that carbonizing treatment does not effectively reduce the contents of anticoagulation ingredients such as water-soluble saccharides and organic carboxylic acid in the bamboo shavings, meanwhile, carbonizing treatment also damages the strength of the bamboo shavings to a certain extent. The mechanical property indexes of the cement particle board prepared from the bamboo shavings subjected to hydro-thermal treatment are superior to those of the cement particle board prepared from carbonized bamboo shavings, but still do not meet the qualified product requirements specified in the cement particle board standard, which is because that even though hydro-thermal treatment does not damages the strength of bamboo shavings, but hydro-thermal treatment does not effectively reduce the contents of anticoagulation ingredients, such as water-soluble saccharides and organic carboxylic acid in the bamboo shavings. The mechanical property indexes of the cement particle board prepared from the bamboo shavings treated with the NaOH solution not only meet the qualified product requirements specified in the cement particle board standard, but also meet the superior product requirements. According to analysis, reasons are following two aspects: firstly, the content of ingredients such as water-soluble saccharides, formic acid and acetic acid, which have an anticoagulation effect on Portland cementin the bamboo shavings is decreased to be less than the 'anticoagulation' critical value by alkali treatment, so that the adaptability of the bamboos and Portland cement is improved; secondly, alkali treatment does not damage the cellulose, hemicellulose and lignin in the bamboos (it is consistent with results of infrared spectroscopy analysis and X-ray diffraction analysis), the strength of bamboo shavings is also not damaged, and the bamboo shavings achieve a favorable reinforcing effect on particle boards. Therefore, a method of preparing qualified bamboo cement particle boards from bamboo shavings treated with the NaOH solution is practicable.

Table 2: Mechanical properties of bamboo particle boards subjected to different types of pretreatment.

		Static bending intensity (MPa)	Elasticity modulus (MPa)	Internal bond strength (MPa)	Thickness swelling rate of 24h water absorption (%)
Untreating		4,60	1300	0,18	2,1
Carbonizing treatment		4,87	1340	0,13	2,4
Hydro-thermal treatment		8,45	2850	0,25	1,8
NaOH treatment		10,3	3402	0,51	1,5
GB/T24312-2009	qualified product	⩾9	⩾3000	⩾0,3	⩽2
	superior product	⩾10	⩾3000	⩾0,5	⩽2

Analysis on microstructures of untreated and pretreated bamboo shavings

Figure 3 is a scanning electron microscope graph of untreated and pretreated bamboo shavings. The untreated bamboo shavings have smooth surfaces (Figure 3a) and favorable fasciculate shape. The surfaces of pretreated bamboo shavings become rougher, wherein the surface changes of the alkali-treated bamboo shavings are the most obvious (Figure 3b), the surface changes of bamboo shavings subjected to hydro-thermal treatment take the second plate (Figure 3c), and the surface changes of the carbonized bamboo shavings are relatively small (Figure 3d). This maybe because that during the pretreatment processes, the water-soluble saccharides, formic acid, acetic acids and the like in bamboo shavings are dissolved out from the surfaces of bamboo shavings. The higher the dissolution quantity is, the rougher the surfaces of bamboo shavings are (this is consistent with the water-soluble saccharide and carboxylic acid content analysis results of untreated and pretreated bamboo shavings in Table 1). Meanwhile, it can be seen from Figure 3 that the pretreated bamboo shavings still remain in a favorable fasciculate shape, therefore it shows that the self-strength of bamboo shavings is not damaged by the tree pretreatment methods. The three pretreatment methods, especially the alkali treatment, can effectively reduce the anticoagulation' ingredients in bamboo shavings; the hydration reaction of Portland cement in the bamboo Portland cement particle board is more sufficient, and the board strength is higher. In addition, the surfaces of alkali-treated bamboo shavings become rougher, and this is beneficial to improvement of the mechanical insertion force between bamboo shavings and cement hydration products, so that the board strength is further improved (this is consistent with the mechanical property analysis results of untreated and pretreated bamboo shavings).

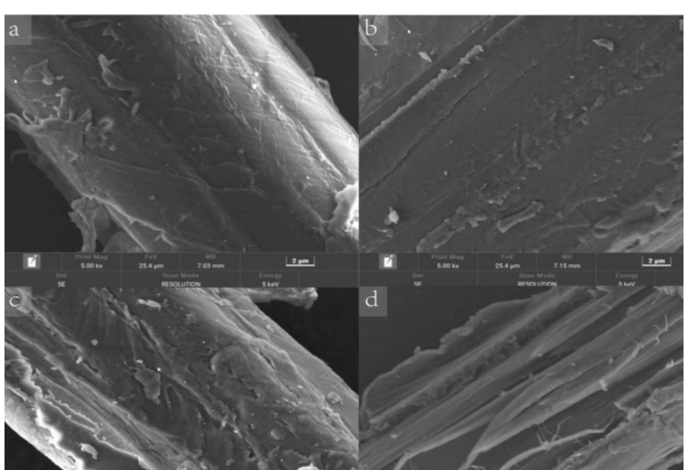

Figure 3: Scanning electron microscope graph of untreated and pretreated bamboo shavings. (a) Untreated (b) Carbonizing treatment (c) Hydro-thermal treatment (d) Alkali treatment.

Analysis on microstructures of untreated and pretreated bamboo cement particle boards

By virtue of sufficient hydration reaction of Portland cement, hydration products such as tobermorite (C-S-H), calcium hydroxide (CH), ettringite (AFt) and mono-sulfur calcium sulfo aluminate hydrates (AFm) are generated, wherein C-S-H is an ingredient (Han *et al.* 2021, Xue *et al*. 2021) which plays a leading role in developing the strength of hydration products. Figure 4 is a scanning electron microscope graph of damaged fracture microstructures of cement particle boards prepared by untreated and pretreated bamboo shavings. Figure 4a shows that cement particle boards prepared from Carbonized bamboo shavings also show some scattered slab-like crystals in the damaged section, which may also be a small amount of slab-like $Ca(OH)_2$ and AFm generated by the hydration reaction of silicate cement, but still no hydration products with obvious characteristics of C-S-H and Aft are seen, which is because the glycation reaction of the charcoal treatment process produces more water-soluble sugars with "blocking" effect, which hinders the hydration reaction process of silicate cement. Figure 4b shows that different amounts of irregular flocculent, coralloidal and rod-like hydration products also occur to the fracture of the cement particle board prepared from bamboo shavings subjected to hydro-thermal treatment, it is speculated that C-S-H and Aft are produced by virtue of hydration reaction of Portland cement in the cement particle board, but nearly no blocky $Ca(OH)_2$ and Afm can be discovered. Compared with carbonizing treatment results, hydro-thermal treatment results are as follows: the hydration reaction extent of the cement particle board prepared from bamboo shavings subjected to hydro-thermal treatment is higher. The C-S-H ingredient with a leading role of developing the strength of hydration products is generated, and the mechanical properties of the cement particle board are improved (Table 2). It is possibly because that the content of 'anticoagulation' ingredients such as water-soluble saccharides and carboxylic acids in bamboo shavings is greatly decreased by hydro-thermal treatment (Table 1). Figure 4c shows that irregular flocculent, coralloidal, elongated columnar and rod-like hydration products, which are uniformly interwoven and grown, occur to the Portland cement of the cement particle board prepared from bamboo shavings subjected to alkali treatment, wherein hydration products such as C-S-H and Aft play a leading role in developing the strength of hydration products, and the hydration products are exquisite and increased in compactness and has an internal network structure (Figure 4c). Compared with carbonizing treatment results and hydro-thermal treatment results, the alkali treatment results are as follows: the hydration reaction of Portland cement in the cement particle board prepared from bamboo shavings subjected to alkali treatment is more complete and more sufficient. This is because the alkali-treated bamboo shavings have the lowest water-soluble sugar content (Table 1), the weakest "blocking" effect on silicate cement, the best compatibility between bamboo shavings and silicate cement, good interfacial bonding between bamboo shavings and silicate cement hydration products, bamboo shavings can effectively transfer the damage stress, and can play a good reinforcing role in the boards. Therefore, the bamboo cement particle boards can show favorable mechanical properties (Table 2), and the mechanical property indexes not only meet the qualified product values specified in the GB/T24312-2009 (2009), but also meet the requirements of superior products. It can be shown that a method of preparing qualified bamboo cement particle boards from bamboo shavings treated with 3 % NaOH solution is practicable.

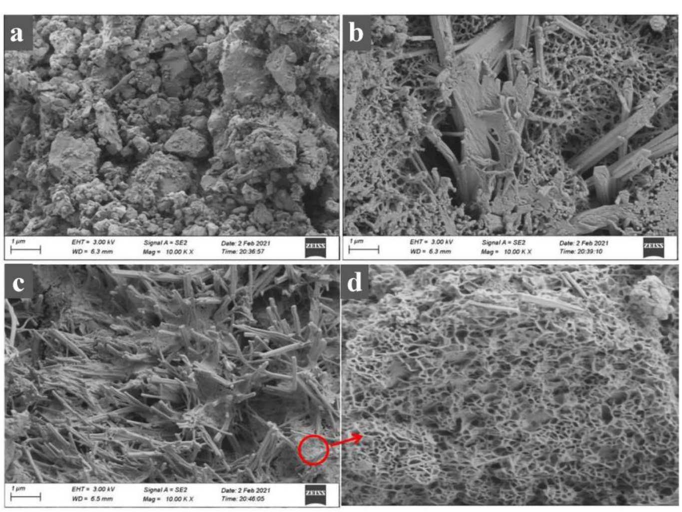

Figure 4: SEM of bamboo cement particle board (a) Bamboo cement particle board subjected to carbonizing treatment, (b) Bamboo cement particle board subjected to hydro-thermal treatment, (c) Bamboo cement particle board subjected to alkali treatment, (d) Partial enlarged image of bamboo cement particle board subjected to alkali treatment.

CONCLUSIONS

Carbonizing treatment can obviously decrease the content of formic acid and acetic acid in bamboos but can cause saccharification and conversion reaction of the bamboos, therefore the content of water-soluble saccharides is increased. Carbonizing treatment cannot obviously improve the adaptability of bamboos and Portland cement, and it also causes damage on the self strength of bamboo shavings. The bamboo cement particle boards prepared from carbonized bamboo shavings do not meet the qualified product requirements specified in the GB/T24312-2009 (2009).

(1) Hydro-thermal treatment can eliminate all formic acid and part of acetic acid in the bamboos, and most of water-soluble saccharides in the bamboo is dissolved out. Therefore, hydro-thermal treatment can improve the adaptability of bamboos and Portland cement and the mechanical properties of bamboo cement particle boards to a certain extent. However, the mechanical properties of bamboo cement particle boards prepared from the bamboo shavings subjected to hydro-thermal treatment also do not meet the qualified product requirements specified in the Standards GB/T24312-2009 (2009).

Alkali treatment (3 % NaOH solution) can eliminate all formic acid and acetic acid in the bamboos, and part of water-soluble saccharides in the bamboo particle board is dissolved out. Alkali treatment (3 % NaOH solution) treatment can obviously improve the adaptability of bamboos and Portland cement and the mechanical properties of bamboo cement particle boards. The mechanical properties of bamboo cement particle boards prepared from the bamboo shavings subjected to NaOH solution treatment exceed the qualified product requirements and superior product requirements specified in the Standards GB/T24312-2009 (2009).

Authorship contributions

C. Y.: Data curation, investigation, writing-original draft. X. L.: Conceptualization, resources, supervision, validation, writing-review & editing.

Acknowledgements

This study was financially supported by the National Natural Science Foundation of China (no. 32171882), the Post- graduate Scientific Research Innovation Project of Hunan Province (project name: Research on Adaptability of Bamboo and Portland Cement), and the Scientific Innovation Fund for Post-graduates of Central South University of Forestry and Technology (project name: Research on Adaptability of Bamboo and Portland Cement).

REFERENCES

Cabral, M.R.; Nakanishi, E.Y.; Mármol, G.; Palacios, J.; Godbout, S.; Lagacé, R.; Savastano, H.Jr.; Fiorelli, J. 2018. Potential of Jerusalem Artichoke stalks to produce cement-bonded particleboards. *Industrial Crops and Products* 122:214-222. https://doi.org/10.1016/j.indcrop.2018.05.054

Chu, J.; Ma, L.; Zhang, J.H. 2016. The Chemical Composition of Bamboo after Heat Pretreatment with Fourier Infrared Spectrum Analysis. *Spectroscopy and Spectral Analysis* 36(11): 3557-3562. http://www.gpxygpfx.com/EN/10.3964/j.issn.1000-0593(2016)11-3557-06

Chu, J.; Zhang, J.H.; Ma, L. 2017. Study of Crystallinity of Pretreated Bamboos. *Forest Science* 53(2): 100-109. https://pubmed.ncbi.nlm.nih.gov/30221888/

GB. 2009. Cement bonded particleboard. GB/T24312-2009. National Standardization Technical Committee plywood: RPC.

Han, S.; Zhong, J.; Ding, W.; Ou, J. 2021. Strength, hydration, and microstructure of seawater sea-sand concrete using high-ferrite Portland cement. *Construction and Building Materials* 295: e123703. https://doi.org/10.1016/j.conbuildmat.2021.123703

Han, Y. 2014. Study on Light Wall Material by Composited with Bamboo and Cement. Fujian Agriculture and Forestry University. Master's thesis

Juengera, M.C.G.; Jennings, H.M. 2002. New insights into the effects of sugar on the hydration and microstructure of cement pastes. *Cement and Concrete Research* 32(3): 393-399. https://doi.org/10.1016/S0008-8846(01)00689-5

Li, X.G.; Zheng, X.; Wu, Y.Q. 2012. Regulation and Control of Bamboo Fiber/Polylactic Acid Composite Interface. *Journal of Composites Science* 29(4): 94-98. https://doi.org/10.13801/j.cnki.fhclxb.2012.04.018

Shen, W.G.; Zhou, M.K. 2007. Research on Influence of Saccharose on Cement Hydration Process. *Journal of Building Materials* 10(5): 566-572. ISSN 1007-9629

Sun, F.B.; Fei, B.H.; Jiang, Z.H.; Yu, Z.X.; Tian, G.L.; Yang, Q.W. 2011. Study on Bamboo Treated with γ Rays by X-Ray Diffraction. *Spectroscopy and Spectral Analysis* 31(6): 1717-1719. http://www.gpxygpfx.com/EN/10.3964/j.issn.1000-0593(2011)06-1717-03

Tian, X.J.; Wang, C. 2001. Research on Separation of Hemicellulose Hydrolysis Products. *Journal of Northeastern University* 14(2): 63-65. ISSN 2096-7543

Wu, B.; Yu, Y.; Qi, J.; Yu, W. 2014. Effects of bamboo bundles treated with fine fluffing and carbonized treatment on the properties of bamboo scrimber. *Journal of Nanjing Forestry University* 38(6): 115-120. https://doi.org/10.3969/j.issn.1000-2006.2014.06.022

Xu, H.; Lu, A.Q.; Chen, J. 2005. Research on domestic and Abroad Plant Fiber Reinforced Cement Based Composite Materials. *Cellulose Science and Technology* 13(4): 60-64. https://doi.org/10.16561/j.cnki.xws.2005.04.011

Xue, L.; Zhang, Z.; Wang, H. 2021. Hydration Mechanisms and Durability of Hybrid Alkaline Cements (HACs): A review. *Construction and Building Materials* 266(Part A): e121039. https://doi.org/10.1016/j.conbuildmat.2020.121039

Yang, S.M.; Jiang, Z.H.; Ren, H.Q.; Fei, B. 2010. Determination of Cellulose Crystallinity of Bamboo Culms with X-ray Diffraction Spectrum. *Journal of Northeastern University* 8: 75-77. https://doi.org/10.13759/j.cnki.dlxb.2010.08.036

Yu, Y.; Yu, X.; Zuo, Q.; Fu, S.; Jiang, Z. 2004. A study of the hydration characteristics of Phyllostachys praecox wood-cement-water mixtures. . *Journal of Zhejiang A & F University* 1: 1-5. ISSN 2095-0756. https://caod.oriprobe.com/articles/6889709/A_study_of_the_hydration_characteristics_of_Phyllostachys_praecox_wood.htm

Zeng, K.B.; Jiang, B.B.; Chen, J.Z. 2006. Dynamics of Bamboo Material Pyrolysis Process. CIESC Journal 57(20): 318-323. ISSN 0438-1157.

Zhang, X.Q.; Han, J.Q.; Zhou, D.Y. 2010. Influence of Wheat Straw Pretreatment Method on Straw-inorganic Gel Composite Material. *Journal of Northwest Forestry College* 38(2): 45-46. https://doi.org/10.13759/j.cnki.dlxb.2010.02.005