Influence of Alkali Treatment on Properties of Bamboo Portland Cement Particle Board

Canbin Yin and Xingong Li*

ABSTRACT: Bamboo contains water-soluble saccharides and carboxylic acid which have an anticoagulation effect on Portland cement; the anticoagulation ingredients can directly influence the adaptability of the Portland cement and bamboo shavings and finally influence the mechanical properties of bamboo Portland cement particle board. In order to improve the adaptability of bamboo and the Portland cement, bamboo shavings are pretreated with 1% NaOH solution, 2% NaOH solution, or 3% NaOH solution. High-performance liquid chromatography is adopted to analyze the influences of treatment based on different concentrations of NaOH solutions on the content of water-soluble saccharides and carboxylic acid in the bamboo shavings, and a Fourier infrared spectrometer and an X-ray diffractometer are utilized to analyze the characteristic peak changes and crystallization property changes, respectively, of the chemical ingredients of the bamboo shavings before and after the three types of pretreatment. This paper discusses the effects of treatment based on different concentrations of NaOH solutions in eliminating water-soluble saccharides and carboxylic acid in the bamboo shavings, details the preparation of bamboo Portland cement particle board by use of the bamboo shavings before and after pretreatment, and reports the influences and mechanisms of NaOH pretreatment on properties of the bamboo Portland cement particle board. Research indicates that the mechanical properties of the Portland cement particle board prepared from bamboo shavings treated with 3% NaOH solution exceed the requirements of qualified products and superior products specified in the Standard GB/T24312-2009.

1. INTRODUCTION

Bamboo Portland cement particle board is an inorganic artificial board prepared by using Portland cement as a cementing material and adopting bamboo shavings as a reinforcing and toughening material. The result 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 so on.1,2 The mechanical properties of the bamboo Portland cement particle board are closely related to the self-strength of the bamboo shavings, the hydration reaction extent of the Portland cement, and the binding interfaces of the bamboo shavings and hydration products. The bamboo has poor adaptability with Portland cement. Compared with wood, bamboo 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 interfaces3,4 of the Portland cement, so that effective reduction in the content of anticoagulation ingredients in the bamboo is quite important for preparation of bamboo Portland cement particle board. Compared with other pretreatment methods, the low-concentration alkali treatment method has the advantages that the self-strength of bamboo can not be reduced; furthermore, the content of water-soluble saccharides and carboxylic acid in bamboo can be effectively reduced,5,6 and the adaptability of bamboo and Portland cement can be effectively improved. In this paper, bamboo shavings are pretreated with different concentrations of NaOH solutions. High-performance liquid chromatography is adopted to analyze the influence of pretreatment on the contents of water-soluble saccharides and carboxylic acid in the bamboo shavings, and a Fourier infrared spectrometer and an X-ray diffractometer are utilized to analyze the characteristic peak changes and crystallization property changes, respectively, of chemical ingredients of the bamboo shavings before and after pretreatment. This paper discusses the effects of treatment with NaOH solutions in eliminating water-soluble saccharides and carboxylic acid in the bamboo, reports the preparation of bamboo Portland cement particle board by use of the pretreated bamboo shavings, and presents the research influences and mechanisms of pretreatment based on different concentrations of NaOH solutions on the properties of the bamboo Portland cement particle board.
2. EXPERIMENTAL SECTION

2.1. Experimental Materials. Bamboo shavings were purchased from Hunan Taohua River Industrial Limited Company, water content 10%, length 10−30 mm, width 1−6 mm, thickness 0.2−0.4 mm. Portland cement, RS2.5, was purchased from Zhucheng City Yangchun Cement Limited Company. Natrium hydroxydatum (NaOH), commercially pure, was purchased from Changsha Pingchuan Chemical Technology Co., Ltd.

2.2. Experimental Equipment and Instruments. The equipment used included the following: electronic thermostat 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 Juzhou Precise Press Limited Company; Waters 244-type high-performance liquid chromatograph, American Waters Company; chromatographic column: Diamonsil C18(250 × 4.6 mm); Waters 486 differential detector, M510 pump, six-way valve sample injector, Zhejiang University 2000 chromatographic workstation; X-ray diffractometer (XD-2), purchased from Beijing ppeneral Co., Ltd.; Fourier transform infrared spectrometer (IRAFinity-1), purchased from Shimadzu Corporation; all-purpose mechanical tester (DCS-R-100), purchased from Shimadzu Corporation; scanning electron microscope (MIR-A3LMH), purchased from TESCO China, Ltd.

2.3. Experimental Methods. 2.3.1. Alkaline Pretreatment for Bamboo Shavings. The preparation of the 1% NaOH solution, 2% NaOH solution, and 3% NaOH solution was as follows: soaking the bamboo shavings with the NaOH solutions for 24 h (the mass ratio of the bamboo shavings to the NaOH solution is 1:20); filtering out the bamboo shavings with a filter screen, and repeatedly rinsing the bamboo shavings with tap water until the solution is neutral; feeding the bamboo shavings into the electronic thermostatic drier box, and drying the bamboo shavings to constant weight for use at a temperature of 103 °C.

2.3.2. Preparation of Bamboo Portland Cement Particle Board. A semidry method is adopted to press bamboo Portland cement particle board. The board specification is 400 × 400 × 12 mm, and the density design is 1200 kg/m³; the mass ratio of the Portland cement to bamboo shavings is 3:1, and the mass ratio of the Portland cement to water is 0.5. The preparation steps are as follows: separately 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 fully and 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 mold locking rack; feeding the board blanks, the steel shim, and the mold locking rack into a cold press; performing cold-pressing mold locking, wherein the thickness of the board blanks is controlled with 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 12h, wherein the curing box is controlled with water vapor and the temperature is controlled at a temperature of 60−80 °C; after thermal curing, performing pressure relief so as to obtain bamboo Portland cement particle board seminished products; stacking the bamboo Portland cement particle board seminished products and naturally curing the seminished products for 28 d, thereby obtaining finished products; then feeding the finished products into a dryer and drying the finished products at a temperature of 70−90 °C until the moisture content is about 10% for measurement.

2.4. Detection and Representation. Detection of water-soluble saccharides and organic acid followed these steps: detecting the water-soluble saccharides and organic acid in bamboo powder (200 mesh and below) by use of a high-performance liquid chromatograph, wherein the mobile phase is 0.05 mol/L H₂SO₄(V:V), the temperature is 55 °C, 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, guaranteed methyl alcohol is filtered with a 0.51 μm filtration membrane, and phosphoric acid is guaranteed; separately weighing 5 g of bamboo powder samples, adding redistilled water, soaking the bamboo powder samples at 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 of supernate, separately performing high-performance liquid chromatography detection, and analysis of the 3 parts of supernate under the above chromatographic conditions so as to obtain a chromatogram of free saccharides and free organic acids; repeating sample feeding three times; calculating peak areas of respective peaks by use of an area normalization method and calculating their content by use of an external reference method.

Fourier transform infrared spectroscopy (FTIR) detection was performed as follows: 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 4000−400 cm⁻¹, the resolution ratio is 2 cm⁻¹, and the scanning times is 32 times; and repeating the above steps once.

For the X-ray diffractometer (XRD) detection, test analysis was conducted on crystallization properties of the untreated bamboo powder and pretreated bamboo powder, wherein the test conditions are as follows: the Cu Kα target λ is 0.154 nm, the voltage is 40 kV, the electric current is 35 mA, the scanning speed 2θ is 8°/min, and 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 (Standards GB/T24312-2009).

Scanning electron microscopy (SEM) test: metal spraying fracture appearance of the test pieces was observed by use of an MIRA3LMH-type scanning electron microscope, wherein the test pressure is 0.8 MPa and the test voltage is 15 kV.

3. RESULTS

3.1. High-Performance Liquid Chromatography of Bamboo Treated with Different Concentrations of Alkali. Table 1 shows varieties and contents of water-soluble saccharides and organic carboxylic acids in the bamboo shavings treated with different concentrations of alkali. It can be seen from Table 1 that no formic acid and acetic acid can be detected from the bamboo shavings subjected to alkali treatment, but different contents of water-soluble saccharides exist in the bamboo shavings. The contents of water-soluble
different concentrations of NaOH solutions does not cause obvious damage on cellulose, lignin, and hemicellulose in the bamboo shavings. Thus, it can be seen that treatment based on alkali with concentration less than or equal to 3% can not cause changes in the cytoderm chemical ingredients in bamboo shavings, and the self-strength of the bamboo shavings also has no change.

3.3. X-ray Diffraction Analysis of Bamboo Treated with Different Concentrations of Alkali. Figure 2 is an X-ray diffraction pattern of bamboo shavings treated with different concentrations of alkali

![Figure 2](image)

Figure 2. X-ray diffraction pattern of bamboo shavings treated with different concentrations of alkali

Table 1. Content of Water-Soluble Saccharides and Carboxylic Acid in the Bamboo Shavings Treated with Different Concentrations of Alkali

|            | water-soluble saccharides (g/100 g) | formic acid (mg/100 g) | acetic acid (mg/100 g) |
|------------|-------------------------------------|------------------------|------------------------|
| untreated  | 7.225                               | 293.4                  | 830.7                  |
| 1% alkali treatment | 4.390                          | 0                      | 0                      |
| 2% alkali treatment | 4.308                          | 0                      | 0                      |
| 3% alkali treatment | 2.428                          | 0                      | 0                      |

Table 2. Mechanical Properties of Bamboo Portland Cement Particle Board Treated with Different Concentrations of Alkali

|            | static bending strength (MPa) | elasticity modulus (MPa) | internal bond strength (MPa) | thickness swelling rate of 24 h of water absorption (%) |
|------------|------------------------------|--------------------------|-----------------------------|------------------------------------------------------|
| untreated  | 4.60                         | 1300                     | 0.18                        | 2.1                                                 |
| 1%NaOH treatment | 7.24                         | 2456                     | 0.19                        | 2.1                                                 |
| 2%NaOH treatment | 8.90                         | 3015                     | 0.24                        | 1.8                                                 |
| 3%NaOH treatment | 10.3                         | 3402                     | 0.51                        | 1.5                                                 |
| GB/T 16048 qualified product | ≥9                          | ≥3000                    | ≥0.3                        | ≤2                                                  |
| GB/T 16048 superior product | ≥10                         | ≥3000                    | ≥0.5                        | ≤2                                                  |

Figure 1. Infrared spectrogram of bamboo shavings treated with different concentrations of alkali.
properties of cement particle board before and after NaOH solution treatment with values of the cement particle board standard (GB/T24312-2009). Table 2 shows that the mechanical property indexes of the cement particle board prepared from bamboo shavings treated with the NaOH solution are obviously superior to those of the cement particle board prepared from bamboo shavings which are not treated with the NaOH solution; especially the mechanical property indexes of the cement particle board prepared from bamboo shavings treated with the 3% NaOH solution not only meet the qualified product values specified in the cement particle board standard (GB/T24312-2009) but also meet the superior product requirements. However, the mechanical property indexes of the cement particle board prepared from bamboo shavings treated with 1% NaOH solution and 2% NaOH solution do not meet the qualified product values or superior product values specified in the cement particle board standard (GB/T24312-2009). This indicates that 1% NaOH solution treatment and 2% NaOH solution treatment have limited effect in improving the adaptability of bamboo and Portland cement; however, the 3% NaOH solution treatment has an obvious effect in improving the adaptability of bamboo and Portland cement. The reasons for the above results are as follows: The Fourier transform infrared spectroscopy and X-ray diffraction analysis for bamboo before and after alkali treatment show that although bamboo pretreatment based on the 1%NaOH solution, 2%NaOH solution, and 3%NaOH solution does not obviously damage the cellulose, lignin, and hemicellulose in the bamboo cytoderm, NaOH in the NaOH solution can be subjected to an acid–base neutralization reaction with the formic acid and acetic acid in bamboo shavings, so that the formic acid and acetic acid in the bamboo shavings are eliminated. Meanwhile, the high-performance liquid chromatography of bamboo before and after alkali treatment shows that because of alkali treatment, part of the water-soluble saccharides can be dissolved out from the bamboo shavings. The higher the alkali concentration is, the higher the saccharide dissolution amount is. The bamboo cytoderm is not damaged, the self-strength of bamboo is not reduced, and a favorable effect for strengthening and toughening cement particle board is achieved. In addition, because of the elimination of formic acid and acetic acid and the dissolution of part of the water-soluble saccharides, the adaptability of bamboo and Portland cement and the binding interfaces of the bamboo and Portland cement hydration products are improved to a certain extent. Therefore, the bamboo Portland cement particle board prepared from bamboo shavings treated with 3% NaOH solution has superior mechanical properties. The comparison between standard values and the mechanical properties of bamboo Portland cement particle board before and after alkali treatment shows that a method of preparing qualified bamboo Portland cement particle board from bamboo shavings treated with the 3% NaOH solution is practicable.

3.5. Scanning Electron Microscopy Analysis of Bamboo Portland Cement Particle Board Treated with Different Concentrations of Alkali. The main ingredients of Portland cement are tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetra calcium aluminoferrite, and the main hydration products of Portland cement include C–S–H gel, Ca(OH)$_2$, trisulfur calcium sulfoaluminate hydrates (ettringite and Aft), and monosulfur calcium sulfoaluminate hydrates (AFm). The C–S–H gel is of an irregular cotton shape, a needle-column shape, a rod shape, a fiber shape, a coralline shape, and so on and plays a leading role in developing the strength of hydration products; Ca(OH)$_2$ is a hexagonal tabular crystal; Aft formed in the initial stage of hydration is of a rod shape with two straight nonsplit ends; irregular plate-shaped AFm grows up in a cluster or flower shape so as to finally become hexagonal plate-shaped.

Figure 3 is a scanning electron microscopy image of bamboo Portland cement particle board treated with different concentrations of alkali. Figure 3a,b,c shows that different amounts of hydration products of Portland cement in the cement particle board prepared from bamboo shavings subjected to alkali treatment are of an irregular cotton shape, a coralline shape, a needle-column shape, a rod shape, and a plate shape. It is speculated that C–S–H, Aft, Ca(OH)$_2$, and AFm are generated because of the hydration reaction of Portland cement in the cement particle board. This shows that the hydration reaction of the Portland cement in the cement particle board prepared from bamboo shavings subjected to alkali treatment is full, and a great amount of hydration products are generated. It also shows that along with concentration increase of NaOH solution, the amount of hydration products (C–S–H and Aft) with characteristics of irregular cotton shape, coralline shape, needle-column shape, and rod shape increases; the amount of plate-shaped hydration products Ca(OH)$_2$ and AFm decreases; and the compactness of the hydration products also increases gradually. In terms of the hydration products of the cement particle board prepared from bamboo shavings treated with 3% NaOH solution, the hydration products (C–S–H and Aft) with characteristics of irregular cotton shape, coralline shape, needle-column shape, and rod shape are greatest in amount and highest in compactness, and various hydration products are distributed in an interwoven manner. This is possibly because the amount of water-soluble saccharides in the bamboo shavings treated with 3% NaOH solution is the lowest (Table 1), causing the weakest anticoagulation effect on the Portland cement. However, it also can be seen from Figure 3d that the interface gluing condition of the bamboo shavings and Portland cement
Hydration products is very good. There are fewer cracks between the bamboo shavings and hydration products, the bamboo shavings can effectively transfer breaking stress and achieve a favorable effect in strengthening the board, and the bamboo Portland cement particle board can show excellent mechanical properties. This result is consistent with the mechanical property analysis results of bamboo Portland cement particle board treated with different concentrations of alkali. Table 2 shows that the mechanical property indexes of the cement particle board prepared from the bamboo shavings treated with the 3% NaOH solution not only meet the qualified production values specified in the cement particle board standard (GB/T24312-2009) but also meet the superior product requirements. Therefore, by virtue of treating bamboo shavings with 3% NaOH solution, the adaptability of the bamboo and Portland cement can be well improved; furthermore, the gluing interface of the bamboo and Portland cement is improved, and a method of preparing qualified bamboo Portland cement particle board from bamboo shavings treated with the 3% NaOH solution is practicable.

4. CONCLUSION

Hydration products of Portland cement mainly include C–S–H, Aft, Ca(OH)₂, and AFm, and the main strength is determined by C–S–H. The study discovers that the hydration product (C–S–H) with coralloidal and flocculent characteristics is generated by the cement particle board prepared from bamboo shavings treated with 3% NaOH solution, and it is highest in amount and greatest in compactness; various hydration products are distributed in an interwoven shape.

(1) By virtue of treatment based on three concentrations of NaOH solutions, the formic acid and acetic acid in the bamboo shavings can be completely eliminated, and meanwhile, the water-soluble saccharides in the bamboo particle board are partially dissolved out. The water-soluble saccharide dissolution rate, which is caused by treatment based on 3% NaOH solution, is highest.

(2) By virtue of treatment based on three concentrations of NaOH solutions, no obvious damage to ingredients such as cellulose, hemicellulose, and lignin in the bamboo cytoderm can be found, and no damage to the mechanical properties of bamboo is caused.

(3) By virtue of treatment based on three concentrations of NaOH solutions, the adaptability of bamboo and Portland cement and the mechanical properties of the bamboo Portland cement particle board are improved to a certain extent, and the higher the concentration is, the more obvious the effect is. The mechanical properties of the cement particle board prepared from the bamboo shavings treated with the 3% NaOH solution not only exceed the qualified production requirements specified in the cement particle board standard (GB/T24312-2009) but also exceed the superior product requirements specified in the standard (GB/T24312-2009).

Author

Canbin Yin — College of Materials Science and Engineering, Central South University of Forestry and Technology, Changsha 410004, PR China; Hunan City University, Yiyang 413000, PR China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c01142

Funding

This work was supported by the National Natural Science Foundation of China (grant number: 32171882); the Science and Technology Innovation Program of Hunan Province (grant number: 2021RC4062) for funding projects; the Postgraduate Scientific Research Innovation Project of Hunan Province (project name: Research on Adaptability of Bamboo and Portland Cement); and the Scientific Innovation Fund for Postgraduates of Central South University of Forestry and Technology (project name: Research on Adaptability of Bamboo and Portland Cement).

Notes

The authors declare no competing financial interest.

References

[1] Cabral, M. R.; Nakani, E. Y.; Marmol, G.; Palacios, J.; Godbout, S.; Lagace, R.; Savastano, H.; Fiorelli, J. Potential of Jerusalem Artichoke stalks to produce cement-bonded particleboards. Ind. Crops Prod. 2018, 122, 214–222.

[2] Wang, L.; Chen, S.-S.; Tsang, D.-C.-W.; et al. Value-added recycling of construction waste wood into noise and thermal insulating cement-bonded particleboards. Constr. Build. Mater. 2016, 125, 316–325.

[3] Tang, Z.-J.; Guan, C.; Wu, S. Study on Influence of Bamboo Shaving High-temperature treatment on Hydration Heat and Bending Property of Cement Particle Board. J. Northwest. For. Coll. 2019, 34 (5), 195–201.

[4] Shen, W.-G.; Zhou, M.-K. Research on Influence Mechanism of Saccharose on Cement Hydration Process. J. Build. Mater. 2007, 10 (5), 566–572.

[5] Zhang, X.-Q.; Han, J.-Q.; Zhou, D.-Y. Influence of Wheat Straw Pretreatment Method on Straw-inorganic Gel Composite Material. J. Northeast. For. Univ. 2010, 38 (2), 45–46.

[6] Xu, X.; Lu, A.-Q.; Chen, J. Research on domestic and Abroad Plant Fiber Reinforced Cement Based Composite Materials. Cellul. Sci. Technol. 2005, 13 (4), 60–64.

[7] Chu, J.; Ma, L.; Zhang, Z.-H. Fourier Transform Infrared Spectroscopy for Chemical Compositions of Thermally-treated Bamboos. Spectrosc. Spectr. Anal. 2016, 36 (11), 3557–3562.

[8] Tian, X.-J.; Wang, C. Research on Separation of Hemicellulose Hydrolysis Products. J. Sichuan. Inst. Light. Ind. Chem. Technol. 2001, 14 (2), 63–65.

[9] Li, X.-G.; Zheng, X.; Wu, Y.-Q. Regulation and Control of Bamboo Fiber/Polyglylic Acid Composite Interface. J. Compos. 2012, 29 (4), 94–98.

[10] Chu, J.; Zhang, J.-H.; Ma, L. Analysis on Crystallinity of Pretreated Bamboos. For. Sci. 2017, 53 (2), 100–109.

[11] Yang, S.-M.; Jiang, Z.-H.; Ren, H.-Q. Measurement on Bamboo Cellulose Crystallinity Based on X-ray Diffraction Method. J. Northeast. For. Univ. 2010, 38 (8), 75–77.

[12] Sun, F.-B.; Fei, B.-H.; Jiang, Z.-H. X-ray Spectrum Study on Bamboos Subjected to Gamma-ray Irradiation Treatment[J]. Spectrosc. Spectr. Anal. 2011, 31 (6), 17–19.

[13] Garci Juenger, M.-C.-G.; Jennings, H. M. New insights into the effects of sugar on the hydration and microstructure of cement pastes. Cem. Concr. Res. 2002, 32 (3), 393–399.
(14) Han, S.-W.; Zhong, J.; Ding, W.-J.; et al. Strength, hydration, and microstructure of seawater sea-sand concrete using high-ferrite Portland cement. Constr. Build. Mater. 2021, 295, 123703.

(15) Xue, L.-Y.; Zhang, Z.-H.; Wang, H. Hydration mechanisms and durability of hybrid alkaline cements: A review. Constr. Build. Mater. Part. A 2021, 266, 121039.

(16) Asasutjarit, C.; Charoenvai, S.; Hirunlabh, J.; Khedari, J. Materials and mechanical properties of pretreated coir-based green composites. Composites Part B 2009, 40, 633–637.

(17) Yang, L.; Yan, Y.; Hu, Z.-H.; Xie, X.-L. Utilization of phosphate fertilizer industry waste for belite-ferroaluminate cement production. Constr. Build. Mater. 2013, 38, 8–13.

(18) Onuaguluchi, O.; Banthia, N. Plant-based natural fibre reinforced cement composites: A review. Cem. Concr. Compos. 2016, 68, 96–108.

(19) Chakraborty, S.; Kundu, S.-P.; Roy, A.; Basak, R.-K.; Adhikari, B.; Majumder, S. B. Improvement of the mechanical properties of jute fibre reinforced cement mortar: A statistical approach. Constr. Build. Mater. 2013, 38, 776–784.

(20) Zhao, J.; Yao, Y.; Cui, Q.; Wang, X.-M. Optimization of processing variables and mechanical properties in rubber-wood particles reinforced cement based composites manufacturing technology. Composites Part B 2013, 50, 193–201.