Influence of Slab Structure on the Performance of Bamboo Based Concrete Formwork

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To reduce the density of bamboo-based concrete formwork on the premise of meeting the performance requirements, the bamboo was first treated by cold plasma, and then by increasing the distance between the adjacent bamboo strips of the radial bamboo curtain in the middle layer, the internal porosity was increased. The production of lightened bamboo based concrete formwork, which meets China's forestry industry standards, was achieved. Four groups of bamboo-based concrete formworks with different slab structures were designed. The key results showed that slab structures have an extremely significant effect on the density, MOR, MOE, IB, and TS of the bamboo-based concrete formwork. A group of optimal slab structures was obtained by comparing their physical and mechanical properties (1st and 9th floor-phenolic resin impregnated paper, 2nd and 8th floor-bamboo mat, 3rd and 7th floor-tangential bamboo curtain, 4th and 6th floor-radial spaced bamboo curtain). Based on the required physical and mechanical properties, its density was 0.62 g·cm^{-3}, which was 27.1% lower than that of traditional bamboo plywood template (0.85 g·cm^{-3}) circulating on the current market. This lightened BBCF can save raw materials, facilitate transportation and reduce labor intensity in the application process so that it will be widely used in building construction.

Keywords: Bamboo; Bamboo based concrete formwork (BBCF); Slab structure; Physical and mechanical properties

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INTRODUCTION

Bamboo is used worldwide as a sustainable, cost-effective, and ecologically responsible alternative building material (Flander and Rovers 2009). Because of the unique growth characteristics, ecological functions, and economic value of bamboo, the development of bamboo resources will make a great contribution to the economic advancements of mountain areas under the background of increasing attention to the global environment. Bamboo is a forest species with ecological, economic, and social benefits (Zhao *et al.* 2012). It has many advantages as a building material (Xiao *et al.* 2013; Sharma *et al.* 2015). Bamboo grows rapidly, taking only 4 to 6 years to grow into useful timber. Additionally, it is a sustainable resource with rapid regeneration. Bamboo has similar mechanical properties and physicochemical properties to wood. Bamboo is rich in flora, wildly distributed, and highly adaptable, and it is easy to breed, plant, process, and use (Gu *et al.* 2010). China possesses the largest bamboo resource in the world, ranking first in the world in terms of species, area, volume, output, and export volume (Li *et al.* 2016). China's annual output of bamboo is 1.539 billion individual pieces, which is equivalent to about 23 million square meters of timber. The management of bamboo forests has significantly reduced deforestation.

Concrete formwork made of bamboo material has high bending strength and stiffness, easy demolding, large document, convenient assembly, high construction efficiency, excellent technical quality, and economic benefits (Xu *et al.* 2012). It has become a development trend to replace the traditional metal formwork with bamboo based concrete formwork (BBCF) and it can reduce the consumption of non-renewable resources as well.

BBCF plays an important role in formwork engineering because of its excellent performance and ecological advantages. As an important construction procedure in the creation of cast-in-place reinforced concrete, formwork engineering directly affects the quality and efficiency of construction engineering, and the characteristics of formwork materials also affect the development of formwork construction technology (Ye and Shi 2007). At present, the density of the traditional bamboo plywood formwork circulating in the market is about 0.85 to 1.0 $g\cdot cm^{-3}$, which is significantly higher than that of the common wood plywood formwork at about 0.6 $g\cdot cm^{-3}$ (Wang and Chen 1994; Kim *et al.* 2011). This leads to an increase in transportation cost and labor intensity in the application process, and to a certain extent, it also inhibits the industrial development of BBCF. The construction market calls for lightweight BBCF, so development trends have mirrored that need (Wu 2000). Therefore, the overall aim is to find ways to improve the strength to weight ratio. And the current goal is to reduce the density to close to wood based concrete formwork while meeting China’s industry standards.

In this paper, modification of bamboo by cold plasma and optimization of BBCF structure are used to prepare lightweight BBCF with a density that is obviously lower than that of traditional BBCF. Due to the poor wettability of inner of bamboo and outer of bamboo to water and adhesive, they are often been removed in the actual production of BBCF, which leads to a significant decline in the utilization rate of bamboo. With the rapid development of plasma technology in recent years, it has been widely used in the modification of bamboo. Cold plasma treatment can clean and etch the surface of bamboo, increase the content of oxygen-containing functional groups such as O - H, C = O and COOH, so as to improve the wettability of bamboo surface (Wang *et al.* 2016; Wu *et al.* 2017). Cold plasma treatment can also improve the adhesive property of phenolic resin to bamboo (Bao *et al.* 2014). The wettability of wood and bamboo was improved by different cold plasma treatment gas, treatment power and treatment time (Wu *et al.* 2017; Peng *et al.* 2018). Through the orthogonal test, investigating various of cold plasma modification factors affecting the static strength of BBCF (Duan and Du 2017).

In this paper, the internal pores were increased by increasing the distance between the adjacent bamboo strips of the radial bamboo curtain in the middle layer, so as to reduce the density of the BBCF. Finally, the production of lightweight BBCF can be achieved, not only reducing the amount of bamboo needed and promoting the efficient use of bamboo, but also cutting down the cost of material transportation and improving the economic efficiency effectively.

In this study, four kinds of composite structures (A, B, C, and D) were designed, and the influence of composite structure on the physical and mechanical properties of BBCF is considered. The slab structure with the lowest density was obtained under the condition of meeting China's forestry industry standard LY/T 1574 (2000).

EXPERIMENTAL

Test Material

Impregnated paper that had been prepared with phenolic resin (0.15 mm), bamboo mat (1.4 mm), tangential bamboo curtain (2.0 mm), and radial bamboo curtain (2.0 mm) were all supplied by Fujian Heqichang Bamboo Co., Ltd. (Sanming, China). The cutting size was 400 mm × 400 mm, and the moisture content was about 6% (moisture content of bamboo before dipping). The bamboo strips weaving the bamboo mat and tangential bamboo curtain were relatively wide (about 20 mm), and the adjacent bamboo strips were closely arranged in order to ensure the flatness of the lightweight BBCF. The radial bamboo curtain is divided into two parts: the radial bamboo curtain arranged closely (no gap between adjacent bamboo strips) and the radial bamboo curtain arranged in intervals (the interval between adjacent bamboo strips was 2.5 mm), and the width of bamboo strips was 8 mm. To ensure that the surface of the prepared bamboo-based concrete formwork would be smooth and glossy, the bamboo mats used were closely aligned to the bamboo curtain, or in other words, there was no gap between the adjacent bamboo strips.

Phenol-formaldehyde (PF) adhesive was supplied by Fujian Heqichang Bamboo Co., Ltd.. Its basic properties are shown in Table 1.

Table 1. The Fundamental Parameters of Phenol-Formaldehyde Adhesive (20 °C)

Liquid	Viscosity (s)	Solid content (%)	pH
PF	89.0	28.0	11.7

Test Methods

The bamboo was treated with cold plasma so that the strength requirements were met after slab structure adjustment. Cold plasma treatment can clean and etch the surface of bamboo, and it can increase the content of oxygen-containing functional groups such as O-H, C=O, and COOH, so as to improve the wettability of the bamboo surface.

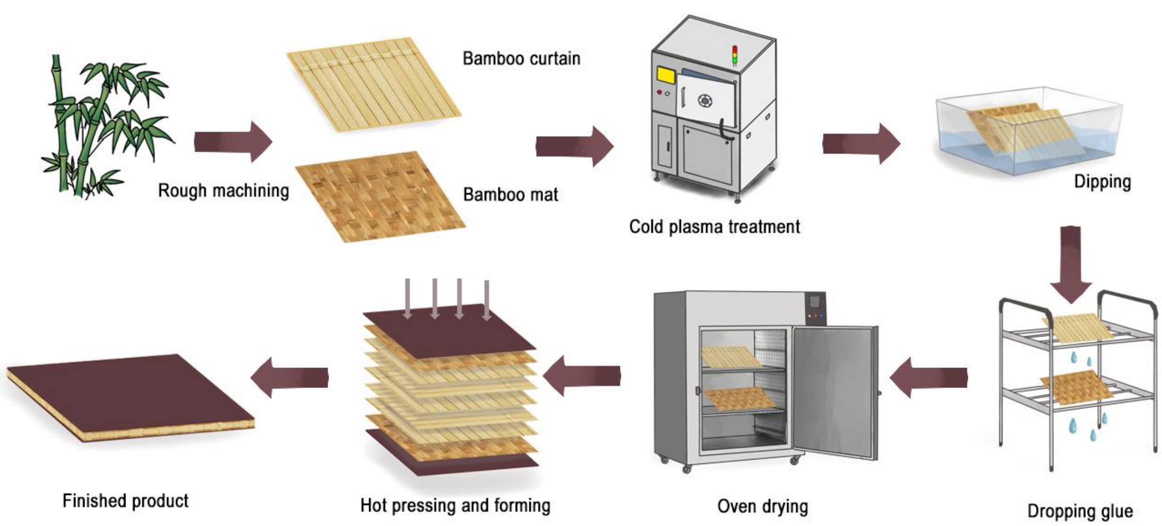

Fig. 1. Flow chart of experiment process

The bamboo mat, bamboo curtain, and closely arranged and spaced radial bamboo curtain were put into the cold plasma processor, and the bamboo material was modified by using a based concrete template during the cold plasma modification process (treatment gas O2, treatment power 160 W, and treatment time 90 s) optimized by the orthogonal test (Thompson 2006; Karahancer *et al.* 2014; Sheng *et al.* 2018). This is the result of previous experiments. The modified bamboo mat and curtain in the prepared glue solution were immersed for 15 min and 5 min, respectively. Afterwards, the bamboo mat and curtain were placed on the prepared iron frame platform to drop glue (3 min). The bamboo mat and curtain were subsequently placed in a 55 °C drying kiln to dry to 12% moisture content. Finally, the bamboo mat and curtain were combined using the method indicated in Fig. 2 and Table 2. The process is depicted in Fig. 1.

The slab structures of four different BBCFs (A, B, C, and D) are all 9 layers, and the thickness of the final product was 12 mm. The difference is in the radial bamboo curtains in the 4th, 5th, and 6th layers, which are divided into close arrangement (no gap between adjacent bamboo strips) and interval arrangement (the interval between adjacent bamboo strips is about 2.5 mm).

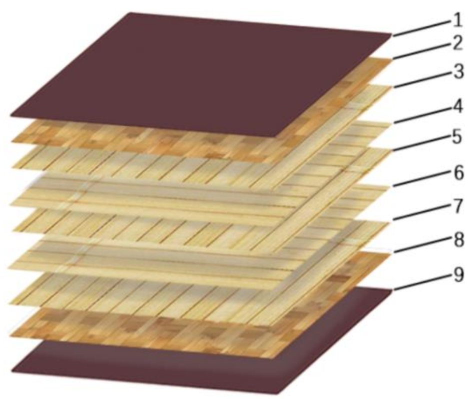

Fig. 2. Slab structure of bamboo-based concrete formwork

Table 2. Details of Four Different Slab Structures

Layer Type	1 and 9	2 and 8	3 and 7	4 and 6	5
A	1,9-phenolic resin impregnated paper, 2,8-bamboo mat, and 3,7-tangential bamboo curtain			radial closely arranged bamboo curtain	radial closely arranged bamboo curtain
B				radial closely arranged bamboo curtain	radial spaced bamboo curtain
C				radial spaced bamboo curtain	radial closely arranged bamboo curtain
D				radial spaced bamboo curtain	radial spaced bamboo curtain

Hot-pressing was performed after the forming was completed. The whole process was carried out in the universal test press. During the hot-pressing process, the upper and lower plates of the hot press were always kept at the hot-pressing temperature. The hot press was closed immediately and pressurized to the maximum pressure required by the process. At the same time, the hot-pressing time (T_1) was calculated. The hot pressing process curve is shown in Fig. 3, and the hot pressing parameters are shown in Table 3.

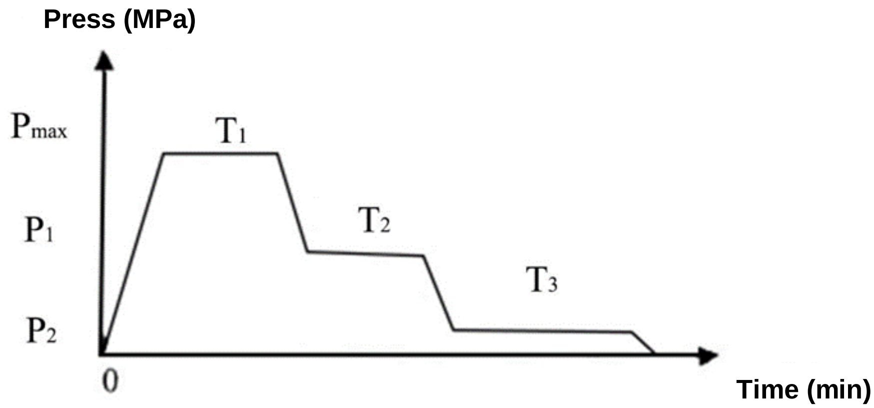

Fig. 3. Curve of technology of hot-pressing. P_{max}, hot-pressing pressure; T_1, hot pressing time; P_1, equilibrium pressure 0.5 MPa; T_2, balanced working hours 3 min; P_2, equilibrium pressure 0.1 MPa; T_3, balanced working hours 10 min

Table 3. Basic Parameters of Hot Pressing

Pressure (MPa)			Hot-Pressing Temperature	Time (min)			Moisture Content of Bamboo (%)
P_{max}	P_1	P_2	(°C)	T_1	T_2	T_3	
3.0	0.5	0.1	140	12	3	10	12

After the four kinds of BBCFs (A, B, C, and D) prepared in the experiment were stored for 4 days, the physical and mechanical properties (density, static bending strength, and MOE) were tested according to the national standard GB/T 17657 (2013).

MOR is the pressure strength that BBCF can bear when it is bent to fracture. It is an index reflecting the bending failure resistance of the bamboo-based formwork itself. The bending failure resistance is stronger when the MOR value is higher (Shen *et al.* 2004). The BBCFs with different slab structures were tested for the static bending strength in the longitudinal and transverse directions. The slab direction is the same as the central layer direction. MOE refers to the difficulty of elastic deformation of BBCF. A larger value indicates a more difficult formwork deformation (Jiang 1995). The MOE was tested for dry longitudinal and transverse directions.

The 24 h thickness expansion rate of water absorption (TS) is an important index reflecting the water resistance and dimensional stability of the BBCF. A smaller value indicates better water resistance and dimensional stability of the formwork (Fu *et al.* 2015). Internal bond strength (IB) can reflect the bonding quality between the BBCF fibers, and the low strength (< 1.0 MPa) can cause the formwork to crack and delamination (Zhu *et al.* 2011). The immersion peeling strength refers to the degree of peeling and peeling of the adhesive layer of BBCF after immersion and drying (Li *et al.* 2011). Therefore, both the internal bond strength and the immersion peel strength can reflect the bonding performance of the BBCF well. The internal bond strength and type II dip peel test of four kinds of BBCFs with different blank structures were tested in accordance with GB/T 17657 (2013), and the results are shown in Table 11 and Fig. 8. The compression ratio of bamboo-based formwork is 8.4%.

Table 4. Equipment Used

Device name	Model	Manufacturer / Supplier
Plasma treatment system	OKSUN-PR60L	Shenzhen Aokunxin Technology Co., Ltd. (Shenzhen, China)
Universal test press	BY302X2/15	Suzhou Xinxieli Machine Manufacturing Co., Ltd. (Suzhou, China)
DHG series heating and drying oven	DHG–9223A	Shanghai Jinghong Experimental Equipment Co., Ltd. (Shanghai, China)
Microcomputer controlled electronic universal testing machine	CWT6104	Shenzhen Xinsansi Measurement Technology Co., Ltd, (Shenzhen, China)
Bamboo moisture content tester	VC2GA	Shenzhen Shengli Instrument Co., Ltd. (Shenzhen, China)
Manual feed woodworking circular saw	MJ104A	Shanghai Woodworking Machinery Factory (Shanghai, China)

Instruments and Equipment

The main instruments and equipment used in the four kinds of slab structure optimization tests of lightweight BBCF are shown in Table 4.

RESULTS AND DISCUSSION

Influence of Slab Structure on Density of BBCF

The density results are shown in Fig. 4 and Table 5. The results had a significance level of α=0.01. According to the table, results showed that F0.01(3,12) = 5.95, and because F=144.057 > 5.95, the influence of different slab structures on the density of BBCF was significant.

Figure 4 and Table 5 show that with the increase in the number of radial spaced bamboo curtains, the density of BBCF decreased with time. Comparing BBCF density with the density of 0.85 $g \cdot cm^{-3}$ on the market, the density of A, B, C, and D decreased by 9.41%, 16.47%, 22.35%, and 27.06%, respectively, which significantly reduced the density of the BBCFs and achieved the goal of lightening.

The main reason for the density decrease was that the radial spaced bamboo curtain gradually replaced the radial closely arranged bamboo curtain on the 4^{th}, 5^{th}, and 6^{th} layers, thereby increasing the porosity of the slab and reducing the amount of bamboo and the density of the slab with the same volume.

Table 5. Variance Analysis of the density of Bamboo-Based Concrete Formwork

Factor	SS	DF	MS	F	Significance
Between Groups	0.048	3	0.016	144.057	**
Within groups	0.001	12	0.001		
Total	0.049	15			

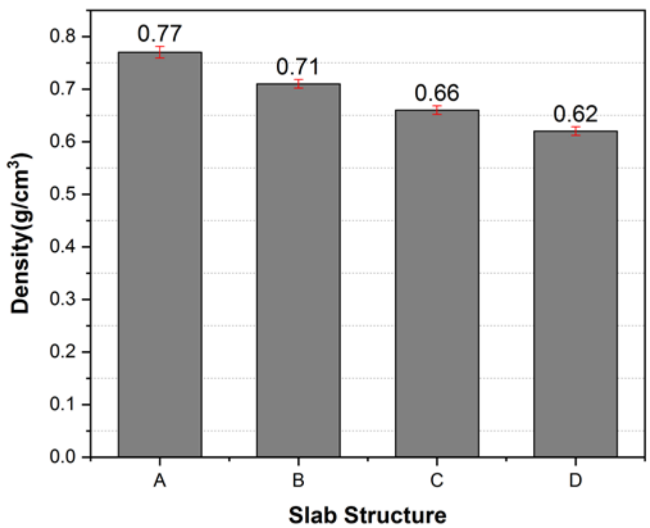

Fig. 4. Density of four kinds of slab structure. Mean values (n = 4) ± standard deviations

Influence of Slab Structure on MOR of BBCF

The MOR results are shown in Fig. 5, Table 6, and Table 7, at a significance level α=0.01. From Table 1 it can be determined that $F_{0.01}(3,12) = 5.95$, and because F = 25.210 > 5.95 and F = 42.703 > 5.95, the influence of different slab structures on the MOR of BBCF is significant.

From Tables 6 and 7, and Fig. 5, it is evident that with the increase in the number of radial spaced bamboo curtains, the MOR of BBCF decreased from 107.9 MPa (A) and 91.6 MPa (B) to 98.5 MPa (C) and 75.9 MPa (D).

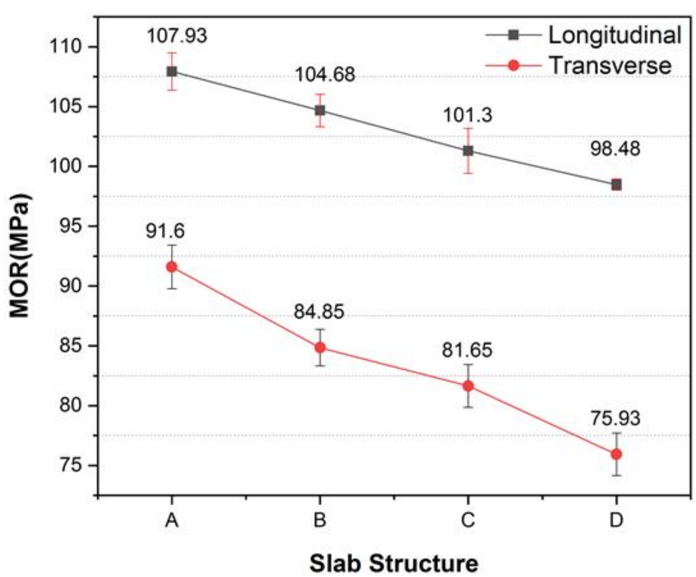

Fig. 5. Effect of the structure on the MOR of bamboo-based concrete formwork. Mean values (n = 4) ± standard deviations

The main reason for the decrease was that the radial spaced bamboo curtain gradually replaced the radial closely arranged bamboo curtain on the 4th, 5th, and 6th layers. It increases the porosity of the slab and reduces the density of the slab with the same volume. This leads to a reduction in the amount of bamboo that can withstand bending and the bending resistance of the slab decreases gradually.

According to Fig. 5, the MOR (parallel and perpendicular) of BBCF for the D-type were the lowest, which was 98.5 and 75.9 MPa, respectively, bigger than 90 MPa and 60 MPa, respectively. The MOR results for type D still comply with the requirements of China's forestry industry standard LY/T 1574-2000. Therefore, the MOR of four types of BBCFs designed in this study can satisfy the requirements.

Table 6. Variance Analysis of the MOR (Parallel) of Bamboo-Based Concrete Formwork

Factor	SS	DF	MS	F	Significance
Between Groups	201.567	3	67.189	25.210	**
Within groups	31.983	12	2.665		
Total	233.550	15			

Table 7. Variance Analysis of the MOR (Perpendicular) of Bamboo-Based Concrete Formwork

Factor	SS	DF	MS	F	Significance
Between Groups	512.942	3	170.981	42.703	**
Within groups	48.047	12	4.004		
Total	560.989	15			

Influence of Slab Structure on MOE of BBCF

The results are shown in Fig. 6, Table 8, and Table 9 at significance levels of α=0.05 and α=0.01. As shown in the table, $F_{0.05}(3,12) = 3.49$ and $F_{0.01}(3,12) = 5.95$. Because $F = 4.467 > 3.49$ and $F = 31.932 > 5.95$, the influence of different slab structures on the longitudinal MOE of BBCF was significant, and on the transverse MOE of BBCF the influence was extremely significant.

From Tables 8 and 9, and Fig. 6, it is observed that with the increase in the layers of the radial spaced bamboo curtain instead of the radial closely arranged bamboo curtain, the longitudinal and transverse MOE of BBCF gradually decreased from 8280 and 6660 MPa to 7820 and 6130 MPa, respectively. The main reason is that the radial spaced bamboo curtain gradually replaced the radial closely arranged bamboo curtain on the 4th, 5th, and 6th layers. The porosity inside the slab and the distance between the bamboo strips was increased, and the pores were mostly "rectangular," so the deformation resistance was reduced, leading to a gradual reduction in the MOE.

According to Fig. 6, the MOE (parallel and perpendicular) of BBCF for type D specimens were the lowest, at 7820 and 6130 MPa, respectively. As those figures are higher than the standard of 7500 MPa and 5500 MPa, respectively, it still meets the requirements of China's forestry industry standard LY / T 1574-2000 for MOE. Therefore, the MOE of four types of BBCFs designed in this study can satisfy the requirements.

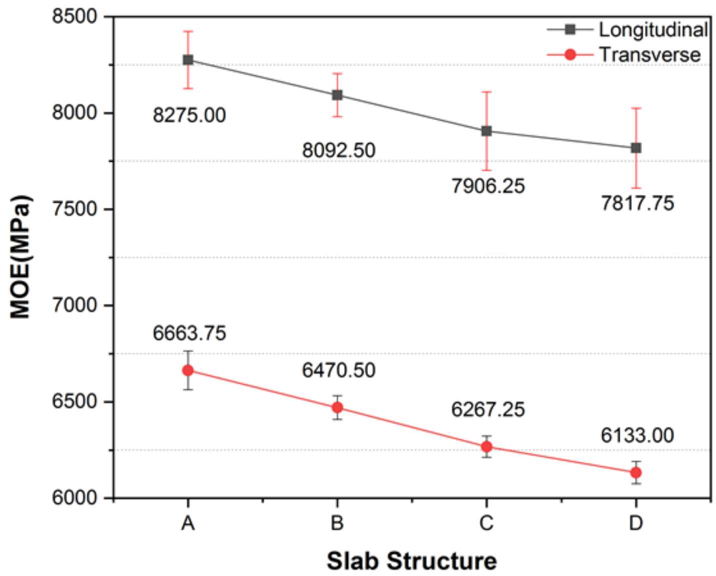

Fig. 6. Effects of the structure on the MOE of bamboo-based concrete formwork
Mean values (n = 4) ± standard deviations.

Table 8. Variance Analysis of the MOE (Parallel) of Bamboo-Based Concrete Formwork

Factor	SS	DF	MS	F	Significance
Between Groups	496369.3	3	165456.4	4.467	*
Within groups	476438.5	12	39703.2		
Total	972807.8	15			

Table 9. Variance Analysis of the MOE (Perpendicular) of Bamboo-Based Concrete Formwork

Factor	SS	DF	MS	F	Significance
Between Groups	649493.3	3	216497.8	31.932	**
Within groups	81358.5	12	6779.9		
Total	730851.8	15			

Influence of Slab Structure on TS of BBCF

The TS results are shown in Fig. 7, at a significance level α=0.05. According to the table, F0.05 (3,12) = 3.49, and because F = 4.908 > 3.49, the influence of different slab structures on the TS of BBCF was significant.

As shown in Table 10 and Fig. 7, with the increase in layers of the radial spaced bamboo curtain instead of the radial closely arranged bamboo curtain, the longitudinal and transverse TS of BBCF gradually decreased from 3.4% to 2.0% .The main reason is that the radial spaced bamboo curtain gradually replaced the radial closely arranged bamboo curtain on the 4th, 5th, and 6th layers. The amount of bamboo material used to prepare the BBCF was reduced. The cell structure that can absorb water was reduced when the formwork was in a humid environment. Moreover, the groove type pores in the slab are conducive to water drainage and reduce the internal stress caused by the water absorption expansion of bamboo. Therefore, the TS of D-type BBCF was the lowest, that is, its water resistance was the best. Figure 7 shows that the TS of A-type BBCF are the highest, with a value of 3.4%, less than 5.0%. It still meets the requirements of China's forestry industry standard LY/T 1574 (2000), so the TS of the four types of BBCF designed can meet the requirements (Wen *et al.* 2009).

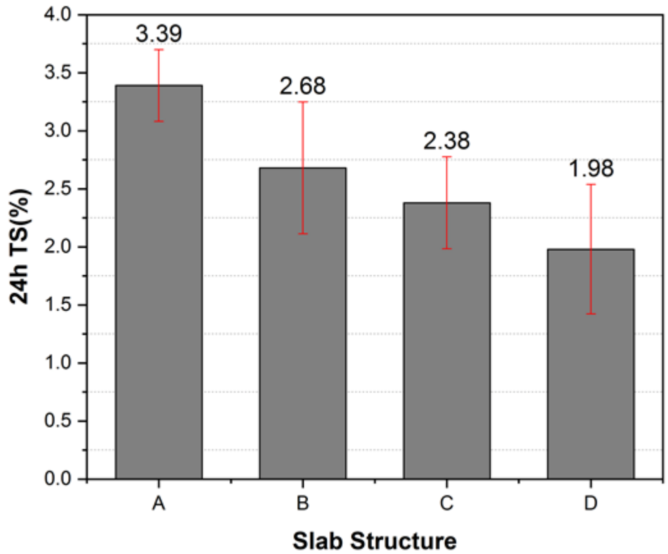

Fig. 7. Effect of the structure on the 24h TS of bamboo-based concrete formwork. Mean values (n = 4) ± standard deviations

Table 10. Variance Analysis of the 24h TS of Bamboo-Based Concrete Formwork

Factor	SS	DF	MS	F	Significance
Between Groups	4.347	3	1.449	4.908	*
Within groups	3.542	12	0.295		
Total	7.889	15			

Influence of Slab Structure on IB of BBCF

The IB results are shown in Fig. 8, Table 11, and Table 12 at a significance level α=0.01. Based on the table, F0.01(3,12) = 5.59, and because F = 36.756 > 5.59, the influence of different slab structures on the TS of BBCF was extremely significant.

With the increase in layers of the radial spaced bamboo curtain instead of the radial closely arranged bamboo curtain, the longitudinal and transverse IB of BBCF gradually decreased from 2.73 to 2.09 MPa. The main reason for the decrease was that the radial spaced bamboo curtain gradually replaced the radial closely arranged bamboo curtain on the 4^{th}, 5^{th}, and 6^{th} layers. It results in the decrease of the contact area between the adjacent layers of bamboo curtains. The stress on the unit area of bamboo increased when the transverse tension of the formwork was fixed, which made the bonding interface easier to damage and decreased the IB. Figure 8 shows that the IB of D-type BBCF is the lowest with a value of 2.09 MPa, and it can be seen from Table 11 that the four kinds of BBCF had no peeling phenomenon in the class II immersion peeling test, which meets the requirements of China's forestry industry standard LY/T 1574 (2000) on the bonding performance. Therefore, the four BBCF specimen types designed can meet the requirements.

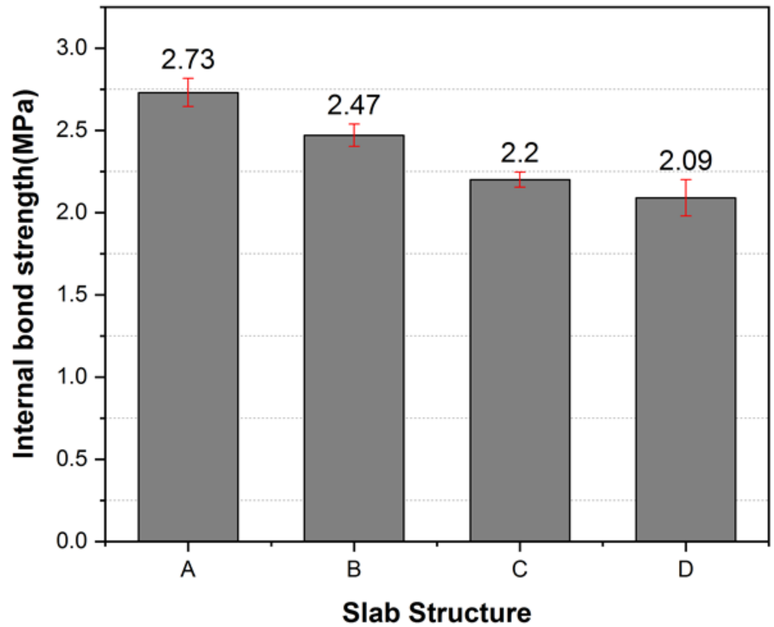

Fig. 8. Effect of the structure on the IB of bamboo-based concrete formwork. Mean values (n = 4) ± standard deviations

Table 11. Immersion Strength of Bamboo-Based Concrete Formwork

	A	B	C	D
Dipping peeling property	Non stripping	Non stripping	Non stripping	Non stripping

Table 12. Variance Analysis of the IB of Bamboo-Based Concrete Formwork

Factor	SS	DF	MS	F	Significance
Between Groups	0.962	3	0.321	36.756	**
Within groups	0.105	12	0.009		
Total	1.067	15			

CONCLUSIONS

1. Four types of slab structures A, B, C, and D exhibited extremely significant effects on the density, MOR, MOE, and IB of the bamboo-based concrete formwork, as well as the TS. The influence of slab structure on the performance of the bamboo based concrete formwork cannot be ignored. When the density of bamboo based concrete formwork decreases, its MOR, MOE, TS, and adhesive property all decrease.
2. The main physical and mechanical properties of the four kinds of bamboo-based concrete formworks prepared in this study are in line with the requirements of China's forestry industry standard LY/ T 1574-2000. The density is obviously reduced, but the purpose of lightening is achieved.
3. The density of bamboo based concrete formwork prepared by D-slab structure (1st and

9th floor-phenolic resin impregnated paper, 2nd and 8th floor-bamboo mat, 3rd and 7th floor-tangential bamboo curtain, 4th and 6th floor-radial spaced bamboo curtain) was 27.1% lower than that of bamboo based concrete formwork ($0.85 g\cdot cm^{-3}$) on the market, and the light-weight effect was obvious. The goal of reducing the density to close to the wood based concrete formwork was achieved.

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