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Physical and mechanical properties of composites made from bamboo and woody wastes in Taiwan

Min Jay Chung[1] and Sheng Yang Wang[2,3*]

Abstract

This study investigated the physical and mechanical properties of six groups of bamboo–wood composites (BWC) made from bamboo and wood wastes, which are produced from the industry processing in Taiwan. Results obtained from non-destructive testing (NDT) indicated that the boards made with 100% bamboo residues (Group B) revealed higher ultrasonic-wave velocity (V_u) and tap tone sound velocity (V_t) than other BWC boards. Both V_u and V_t of composite boards were proportional to the ratio of bamboo residues contains. Three-layer composites made with bamboo/wood/bamboo residues at 1:2:1 ratio (Group B/2W/B) had the highest specific strength as well as modulus of elasticity (MOE) and modulus of rupture (MOR) among all the composites. B/2W/B composite board had structural characteristics similar to those of medium-density fiberboards (MDF) and particleboards; thus, it might have better compression resistance than other types of boards. B/2W/B composite board also had the highest screw holding strength (SHS); next was the boards composed entirely of woody wastes (Group W). The results obtained from analysis of water absorption rate (WA%) show a positive correlation with porous bamboo contents; meanwhile, wood chips have higher water-absorption swelling rate than bamboo residues. Hence, it showed greater change in thickness swelling coefficient (TS%) and volume swelling coefficient (*S*%).

Keywords: Bamboo residues, Wood wastes, Non-destructive testing, Dimensional stability, Physical properties, Mechanical properties

Introduction

In Taiwan, the agricultural and forestry wastes can be mainly divided into wastes from "woody plants" and "herbaceous plants". Literature pointed out that agricultural and forestry waste residues are estimated to be approximately 2 million metric tons per year, including residues produced from bamboo or woody processing [1]. The current status for treating these wastes is incinerated, buried, or used as the boiler burning material directly. Considering the environmental protection and sustainable development issues, the concept of the circular economy is becoming a notable topic. Recycling and reusing the wastes could contribute to reduce the greenhouse gases generation and ensure more effective and comprehensive utilization of these lignocellulosic materials. Moreover, according to the circular economy model "resources → products → wastes → recycling", these processing wastes should be recycled and reused as resources to create economic and social benefits [2]. Moreover, Taiwan has more than 60% of the rich forest resources. To achieve sustainable forest management and plantation development, thinning is an important operation intending of forestry. Hence, nowadays, growing attention is focusing on the timber resources generated by thinning in Taiwan [3].

Logs left from thinning are mostly of small and medium diameters. In general, the utilization rate of raw wood ranges between 30 and 40%, implying that 60–70% of the raw wood would end up as slabs and residues during processing [4]. Furthermore, makino

*Correspondence: taiwanfir@dragon.nchu.edu.tw
[2] Department of Forestry, National Chung-Hsing University, No. 145, Xingda Road, Taichung 402, Taiwan
Full list of author information is available at the end of the article

bamboo culm (*Phyllostachys makinoi*) is one of the most important bamboo resources in Taiwan. Owing to good mechanical and processing properties of makino bamboo, it has been widely used as construction and furniture materials [5]. Unfortunately, the similar situation for bamboo processing, it leaves lots of residues as woody wastes and have not been fully utilized. Indeed, without systematic recycling and reusing bamboo and woody wastes will increase the processing costs of waste disposal or cause a negative impact on the environment [5]. Besides, recycling and reusing bamboo and timber residues contribute to realize the ideal of circular economy. Bamboo and wood are renewable resources; they are precious, and thus merit conservation and attention to avoid waste. To enhance utilization of wood and bamboo processing residues is an emerging issue for the forest products researchers [6]. Related studies including manufacturing biodegradable composites are made of bamboo processing wastes [7], agricultural and forestry wastes made into gypsum composites [8], and recycling of wood wastes to produce energy-saving wood-based boards for floor heating systems [2].

In the other hand, non-destructive testing (NDT) has been extensively applied to strength assessment of wood products. Ross and Pellerin found a good correlation between modulus of elasticity (MOE) predicted by acoustic wave and wood-based composites bending determined by the longitudinal speed of stress wave transmission [9]. Yang et al. [10] also used NDT with ultrasonic wave to evaluate the quality of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin and demonstrated that it is a useful technology for analyzing the mechanical strength of particleboard. Moreover, the forest industry has devoted efforts to manufacturing artificial boards with good strength performance using waste materials from wood and bamboo processing [3]. In this study, bamboo-wood composites (BWC) were made with wood and makino bamboo residues obtained at their processing sites. These wastes were chemically treated and mechanically processed, then glued and hot-pressed into BWCs with varying proportions of bamboo and wood mixed or layered in different designs. Besides, both ultrasonic testing technique and tap tone method were performed to examine the physical and mechanical properties of WBC boards. Finally, compression ratio, density distribution, strength characteristics, specific strength, screw retention, and dimensional stability of BWCs were also analyzed. Results obtained in this study might provide the useful information for future related forestry and processing industries.

Materials and methods

Bamboo–wood composites (BWC)

3–5 cm long *P. makinoi* residues were collected from the bamboo processing waste (including bamboo epidermis) at the Zhushan Industrial Park in Nan-Tou County, Taiwan. The bamboo residues were pre-treated with an alkaline solution containing 2% potassium hydroxide (KOH) at 100 °C for 30 min and then oven-dried at 80 ± 2 °C to constant weight. Woody wastes were collected from residues of *Taiwania cryptomerioides*, *Cunninghamia lanceolate* and *Cryptomeria japonica* after thinning in October 2014. The ages of trees were 25–35 years growing in the Experimental Forest of National Taiwan University in Nan-Tou County, Taiwan. The woody residues were shredded using a towable wood chipper (Type: TC 24; Goodkym Technology Co., Ltd.) into chips of three sizes. That is, 50% of chips are < 16 mesh, 40% are 7 mesh, and 10% are > 4 mesh. Besides, the average density of bamboo residues and woody residues was 0.69 and 0.32 g/cm^3, respectively.

Pretreated and mechanically processed chips of bamboo and woody residues were placed unidirectional in a 450 × 450 × 12 mm (length × width × thickness) iron frame, then glued and hot-pressed to form a 1.0 g/cm^3 target density of the board. The adhesive used in this study was water-soluble urea formaldehyde (UF) resin (Wood Glue Industrial Co., Ltd. Tainan) with a 63.6% solid content (pH: 6.25; viscosity: 120 cps; degree of hydration: 1.8; amount of free formaldehyde: 0.85%). The weight of raw materials and glue followed the specifications for particleboard manufacturing according to Chinese National Standards (CNS) 2215 [11]. Hot pressing was conducted under curing temperature of 120 °C at 150 kgf/cm^2 for 12 min, followed by 10-min cooling. Before the experiments, all specimens were conditioned in a controlled environment with temperature at 20 °C and relative humidity (RH) at 65% for 2 weeks. Table 1 summarizes the constituents, layering designs and composition ratios of the six groups of experimental BWC

Table 1 Constituents, layering designs and composition ratios of experimental BWCs

Groups of specimens ($n = 9$)	Constituents	Ratio
W	Wood	1
B	Bamboo	1
BW	Bamboo and wood	1:1
B/W/B	Bamboo/wood/bamboo	1:1:1
W/B/W	Wood/bamboo/wood	1:1:1
B/2W/B	Bamboo/wood/bamboo	1:2:1

Bamboo: *P. makinoi* waste; wood: tree bark/sap wood waste boards, each group with nine specimens ($n = 9$). Figure 1 demonstrated the manufacturing process of the BWCs.

Non-destructive evaluation

Ultrasonic-wave velocity (V_u) and dynamic modulus of elasticity ($DMOE_u$)

NDT was conducted to evaluate the ultrasonic-wave velocity (V_u) and dynamic modulus of elasticity ($DMOE_u$) using a portable ultrasonic non-destructive testing device (Sylvatest Duo, Saint Sulpice, Switzerland) at a frequency of 22 kHz. Specimens were placed between the transmitting and receiving transducers ($n = 9$), and the travel time of the ultrasonic wave (transmission time) was recorded. The specimens were of size 240 × 50 × 12 mm (length × width × thickness). The V_u and $DMOE_u$ were calculated by Eqs. 1 and 2, respectively.

$$V_u = \frac{L}{t}, \tag{1}$$

where V_u is the ultrasonic transmission speed (m/s), L is the distance from sound wave penetration, length of specimen (m) and t is the duration of sound waves penetrating specimen (s).

$$DMOE_u = V_u^2 \rho, \tag{2}$$

where $DMOE_u$ is the ultrasound dynamic elastic modulus, V_u is the ultrasonic transmission speed (m/s) and ρ is the density of specimen (kg/m^3).

Tap tone sound velocity (V_t) and dynamic modulus of elasticity ($DMOE_t$)

Another NDT testing was conducted to evaluate V_t and $DMOE_t$ using a tap tone analyzer (Multi-purpose FFT analyser CF-5220, Ono Sokki). Supported at the center by a piece of foam, the BWC specimen was hit on one end with a hard-rubber hammer. The tap tone was transmitted from the hit end and received by the microphone placed at the other end. The instantaneously generated sound waveform was decomposed into a spectrum using the Fast Fourier Transform (FFT) as accurate measurement of the natural vibration frequency. The specimens were of size 240 × 50 × 12 mm (length × width × thickness). The V_t and $DMOE_t$ were calculated by Eqs. 3 and 4, respectively.

$$V_t(\mathrm{m/s}) = 2\,FL, \tag{3}$$

$$DMOE_t = V_t^2 \rho, \tag{4}$$

where V_t is the longitudinal sound velocity (m/s), L is the length of specimen (m), F is the natural frequency (Hz) and ρ is the density of specimen (kg/m^3).

Mechanical strength analysis

The mechanical strength of BWC boards was examined using the American Society Testing and Materials (ASTM) D-1037 [12]. The static bending test was carried out using a universal-type testing machine (Shimadzu UH-10A, Tokyo, Japan) according to the center-loading method for specimens. A concentrated bending load was applied at the center with a span 15 times the thickness of the specimen.

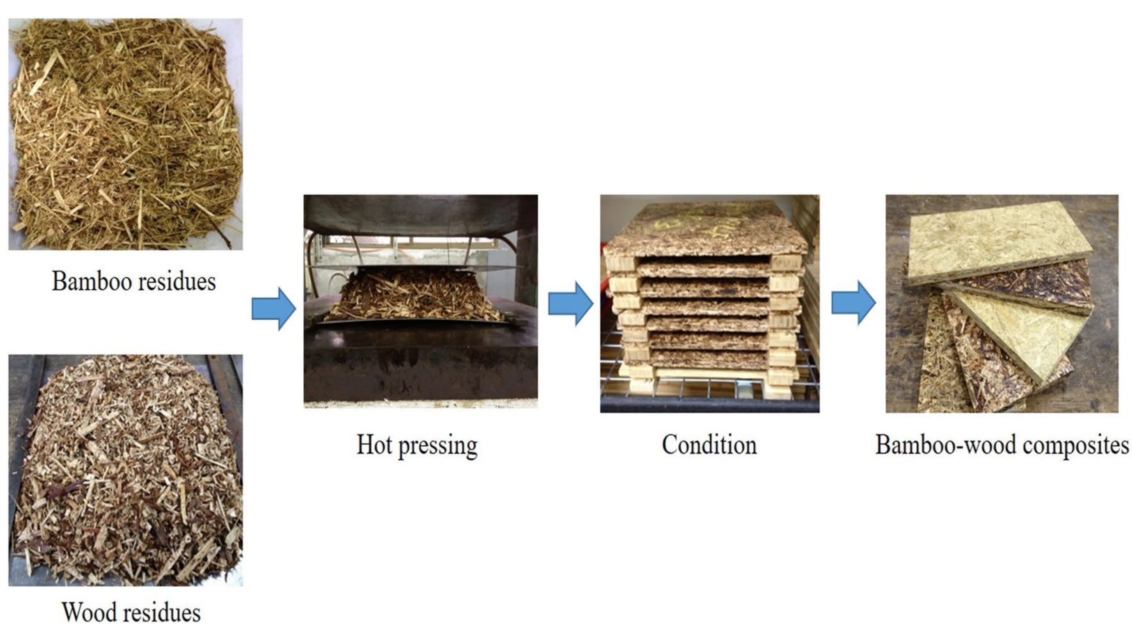

Fig. 1 The manufacturing process of BWCs

Both modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated from load–deflection curves using Eqs. 5 and 6, respectively.

$$\text{MOR (MPa)} = \frac{3P_{\max}L}{2bh^2} \times 100, \quad (5)$$

$$\text{MOE (MPa)} = \frac{P_pL^3}{4\delta bh^3} \times 100, \quad (6)$$

where $P_{\max}$ is the maximum load (*N*), *L* is the span (mm), *b* is the width of specimen (mm), *h* is the thickness of specimen (mm), *P*p is the difference between upper limit load and lower limit load in proportional limit (*N*) and δ is the amount of bending deformation (mm) of *P*p relative to center of span.

Density distribution analysis

BWC specimens for analysis of density distribution ($n=9$). The specimens were 450 × 450 × 12 mm (length × width × thickness), divided into 9 pieces. The dimensions of each piece were 150 × 150 × 2.0 mm (length × width × thickness). The density of each pieces was calculated according to its weight and volume measured. Variance analysis of 9 density values of each BWC specimen was descripted to illustrate the density distribution.

Nail withdrawal resistance analysis

According to the test for particle boards (CNS 2215) [11], the BWC boards were placed in a controlled environment with 65% RH for 3 weeks. The specimens size was 100 × 50 × 12 mm (length × width × thickness). Wood screws size was 2.7 × 16.0 mm (diameter × length), which were drilled vertically into the BWC boards to a depth of 11.0 mm and then pulled up vertically at 2.0 mm/min. The maximum pull loading was measured, and the average of three measurements was taken as the nail withdrawal resistance.

Dimensional stability

The BWC boards were tested using the ASTM D-1037 [12] to determine water absorption (WA), thickness swelling (TS), and volumetric swelling (*S*). Initial thickness at the middle of the test specimen was measured with a micrometer. Then, all specimens were placed in parallel 30 mm under water and soaked for 2 and 24 h before the thickness was measured again. WA, TS, and S were determined using Eqs. 7–9, respectively.

$$\text{WA}(\%) = \frac{W_w - W_o}{W_o} \times 100, \quad (7)$$

where W_w is the weight of saturated state and W_o is the weight of oven-dried state.

$$\text{TS}(\%) = \frac{T_w - T_o}{T_o} \times 100, \quad (8)$$

where T_w is the thickness of saturated state and T_o is the thickness of oven-dried state.

$$S(\%) = \frac{V_w - V_o}{V_o} \times 100, \quad (9)$$

where V_w is the volume of saturated state and V_o is the volume of oven-dried state.

Analysis of variance

All multiple comparisons of physical and mechanical properties were subjected to Tukey's test and analysis of variance (ANOVA). Significant differences between mean values of control and experimental specimens were determined using the Duncan's multiple range test.

Results and Discussion

Non-destructive evaluation

Ultrasonic-wave velocity (V_u) and dynamic modulus of elasticity (DMOE$_u$)

The average density, compression ratio, density distribution, V_u, and DMOE$_u$ of six groups are listed in Table 2. The range of average density of the BWC boards was

Table 2 Average density, compression ratio, density distribution, V_u, and DMOE$_u$ of six groups of BWCs

Groups of specimens ($n=9$)	Density (g/cm^3)	Compression ratio	Density distribution	V_u (m/s)	DMOE$_u$ (GPa)
W	1.01 (0.12)^a	3.06	a	2141 (91)^d	4.17 (0.24)^c
B	0.99 (0.23)^a	1.32	a	2579 (92)^a	5.92 (0.60)^a
BW	0.98 (0.16)^a	1.83	a	2310 (68)^c	4.69 (0.27)^b
B/W/B	1.02 (0.18)^a	1.68	a	2550 (95)^a	5.98 (0.61)^a
W/B/W	1.00 (0.21)^a	2.16	a	2144 (93)^d	4.14 (0.28)^c
B/2W/B	1.01 (0.15)^a	1.89	a	2413 (93)^b	5.30 (0.68)^{ab}

Results are mean ± SD, $n=9$; numbers followed by different letters (a–d) are statistically different at the probability level of $p<0.05$ according to Tukey's test and ANOVA between 0.98 and 1.02 g/cm^3; there was no significant difference in density among the experimental boards ($p > 0.05$). For density distribution analysis, it also shows no significant difference between 9 density values of each BWC specimens. Boards made with woody wastes alone (Group W; 2141 m/s) or of higher proportion woody material (Group W/B/W; 2144 m/s) have lower V_u. In contrast, V_u is higher in boards made with bamboo residues of higher proportion bamboo residues, indicating a positive linear relationship between bamboo content and V_u. That is, the higher density tissue the bamboo has, the higher the V_u; composite boards made entirely with bamboo have the highest V_u (Group B; 2579 m/s). The boards with higher V_u comprised mainly bamboo residues could be attributed to the slender shape of bamboo residues, which facilitates faster transmission of ultrasonic wave. Our findings were similar to the results ($V_u = 2065–2482$ m/s) obtained by Yang et al. [10] for the particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin of the similar densities as those in this study (0.8 g/cm^3).

Similar trend can be observed for $DMOE_u$ of the six groups of BWC boards. As shown in Table 2, boards containing higher proportions of bamboo residues had similar $DMOE_u$ with no significant difference (5.92, 5.98 and 5.30 GPa for Groups B, B/W/B, and B/2W/B, respectively; $p < 0.05$). However, they had significantly higher $DMOE_u$ than boards comprising greater amount of wood wastes (4.17 and 4.14 GPa for Groups W and W/B/W, respectively; $p > 0.05$). The bamboo residues ratio in the manufacture of BWC are difference between these six groups. Slender bamboo fiber contributed to faster transmission of ultrasonic wave as it has a higher density tissue, leading to higher $DMOE_u$. Besides, Table 2 also revealed that values of $DMOE_u$ and compression ratio roughly show an inverse relationship.

Longitudinal acoustic velocity (V_t) and dynamic modulus of elasticity ($DMOE_t$)

Figure 2 shows the longitudinal acoustic velocity (V_t) and dynamic modulus of elasticity ($DMOE_t$) of the six groups. BWC boards made of 100% bamboo residues had the highest V_t (Group B; 2756 m/s), while those comprising 100% woody residues had the lowest V_t (Group W, 1976 m/s). The other four types of BWC boards had V_t in the order of B/W/B (2578 m/s) > B/2W/B (2368 m/s) > W/B/W (2251 m/s) > BW (2138 m/s). These results indicated that BWC boards comprising alternate layers of chips with higher proportion of bamboo residues had higher V_t, thus implying that V_t of BWC is proportional to the bamboo contents. Again, the $DMOE_t$ showed the same trend with V_t. BWC boards made of 100% bamboo residues have the highest $DMOE_t$ (B, 6.76 GPa), while those comprising 100% wood slabs have the lowest $DMOE_t$ (W, 3.55 GPa). The other four types of BWC boards have $DMOE_t$ in the order of B/W/B (6.12 GPa) > B/2W/B (5.10 GPa) > W/B/W (4.56 GPa) > BW (4.02 GPa). Similarly, these results indicated that BWC boards comprising layered chips with higher proportion of bamboo residues have higher $DMOE_t$ for its higher density tissue, thus revealing a linear relationship between $DMOE_t$ and bamboo content.

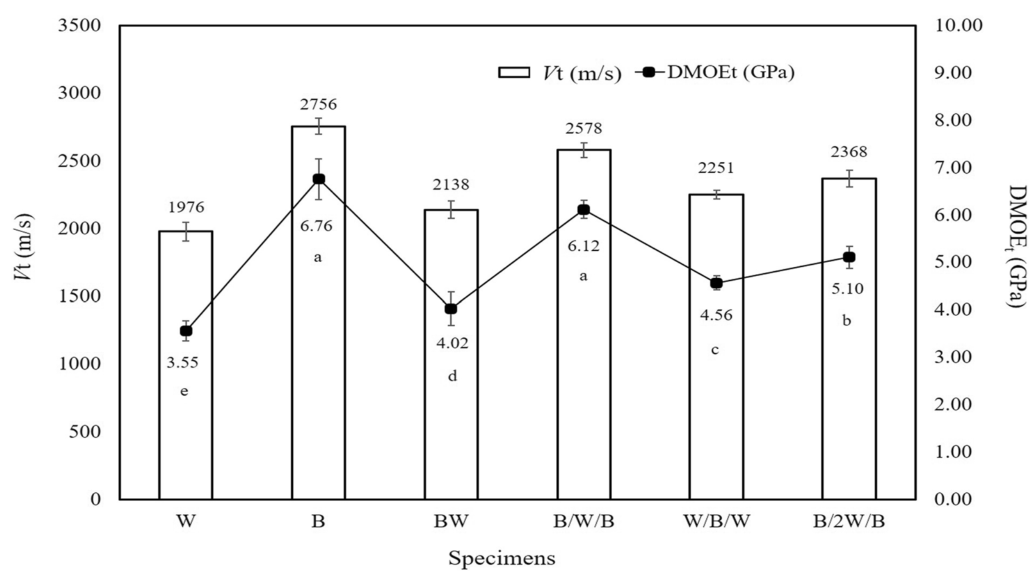

Fig. 2 Longitudinal acoustic velocity and dynamic modulus of elasticity of six groups of BWCs (results are mean ± SD, $n = 9$; numbers followed by different letters (a–e) are statistically different at the probability level of $p < 0.05$ according to Tukey's test and ANOVA)

Table 3 Correlation of $DMOE_u$ and $DMOE_t$ with MOE of six groups of experimental BWCs

Groups of specimens ($n=9$)	R^2 values ($DMOE_u$/MOE)	R^2 values ($DMOE_t$/MOE)
W	0.89	0.92
B	0.81	0.91
BW	0.67	0.89
B/W/B	0.57	0.72
W/B/W	0.58	0.70
B/2W/B	0.61	0.71

Furthermore, the correlation of $DMOE_u$ and $DMOE_t$, with MOE within different types of BWC boards was analyzed in this study. As shown in Table 3, the coefficient of determination (R^2) of $DMOE_u$/MOE is lower than that of $DMOE_t$/MOE, indicating that the R^2 values calculated using DMOE and MOE obtained by the tap tone method are higher than ultrasonic measurement. Moreover, Groups W (100%) and B (100% bamboo) had higher R^2 values compared with other BWC boards. The results implied that boards made by single and denser material caused faster and easier transmission through the relatively simple and higher density medium, while boards of mixed composition might slow down transmission through the more complex medium.

Mechanical strength analysis

Figure 3 presented the specific strength of the experimental BWC boards. Higher strength was observed in layered boards with the top and bottom layers made of bamboo residue and the middle layer composed of wood chip (24.81 for B/2W/B; 21.67 for B/W/B). For single-layer boards, those made of bamboo residues alone (B) had the highest specific strength, i.e. 20.63; while those composed entirely of wood waste (W) had the lowest specific strength (16.48). As shown in Fig. 3, the strength of the board will be affected by bamboo content and layered structure.

The analyzed results of MOE and MOR for BWC are shown in Fig. 4, it consistence of the specific strength evaluation. BWC boards made with wood alone had the lowest MOE (1.92 GPa) and MOR (15.00 MPa), revealing the poor strength property. It is because wood wastes contain comparatively less cellulose content than bamboo residues, and our related studies also demonstrated that cellulose is the main component of cell wall which affects both physical and mechanical properties [13, 14]. Hence, in contrast, Group B had comparatively higher MOE (2.68 GPa) and MOR (18.36 MPa, respectively), while Group BW comprising equal proportion of bamboo and wood wastes had MOE and MOR (2.28 GPa and 17.10 MPa, respectively) roughly between Groups W and B. As for the groups with layered structure, their MOE and MOR were in the order of B/2W/B (3.35 GPa and 22.58 MPa, respectively) > B/W/B (3.01 GPa and 19.94 MPa, respectively) > W/B/W (2.16 GPa and 16.20 MPa, respectively). Such layered structure is similar to that the cross-sectional structure of medium-density

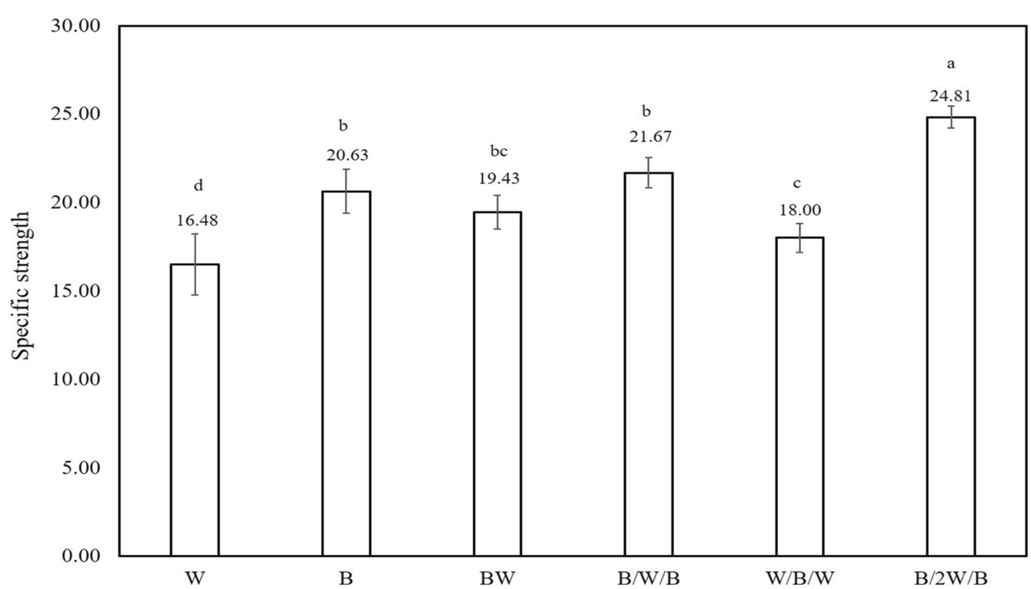

Fig. 3 Specific strength of BWCs (results are mean ± SD, $n=9$; numbers followed by different letters (a–d) are statistically different at the probability level of $p<0.05$ according to Tukey's test and ANOVA)

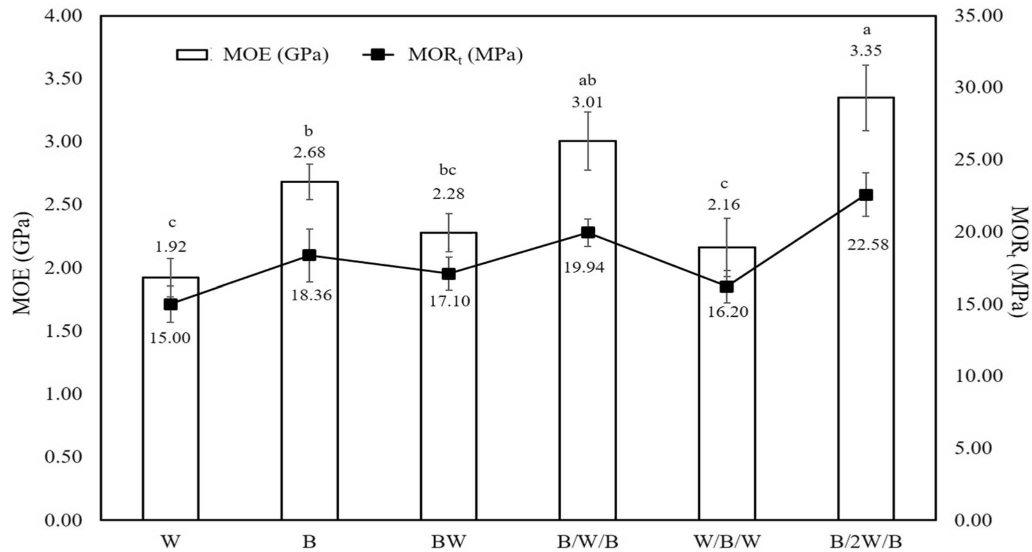

Fig. 4 MOE and MOR of BWCs (results are mean ± SD, *n* = 9; numbers followed by different letters (a–c) are statistically different at the probability level of $p < 0.05$ according to Tukey's test and ANOVA)

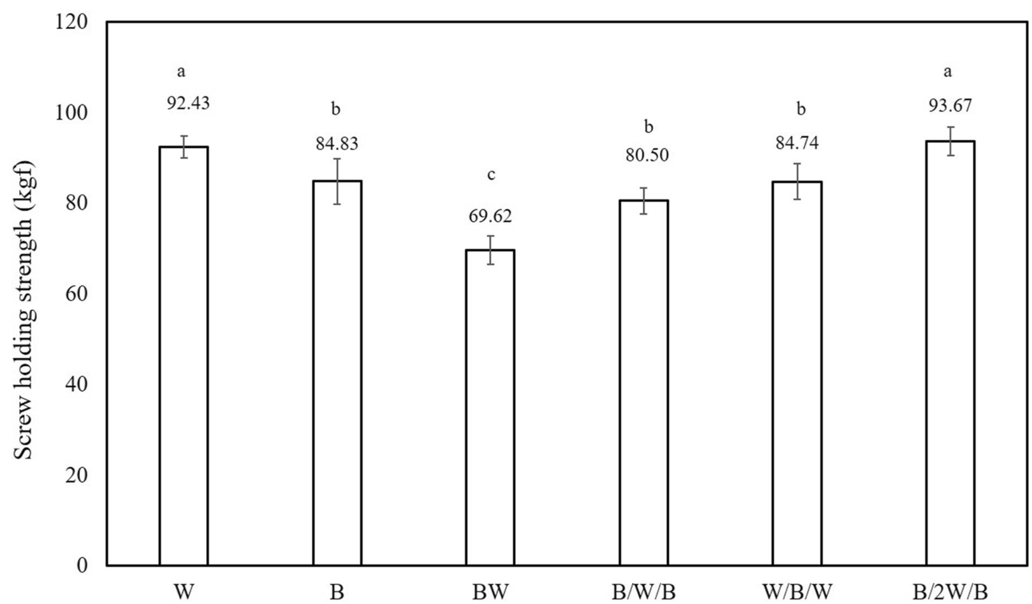

Fig. 5 Screw holding strength of BWCs (results are mean ± SD, *n* = 9; numbers followed by different letters (a–c) are statistically different at the probability level of $p < 0.05$ according to Tukey's test and ANOVA)

fiberboards and particle board which were found to have better compressive strength [15].

Nail withdrawal resistance analysis

Screw holding strength (SHS) is an important evaluation index for joint strength of wood composites. Figure 5 demonstrated the SHS of BWC boards. The CNS 2215 standard for the particleboard's SHS is 35–15 kgf. All six groups of BWC boards SHS were surpassing 51 kgf; among them, B/2W/B had the highest SHS (93.67 kgf), followed by B (92.43 kgf); however, there was no significant difference between B/2W/B and B; the Group BW has the lowest SHS (69.62 kgf). In general, wood has shorter fiber than bamboo, implying that wood wastes

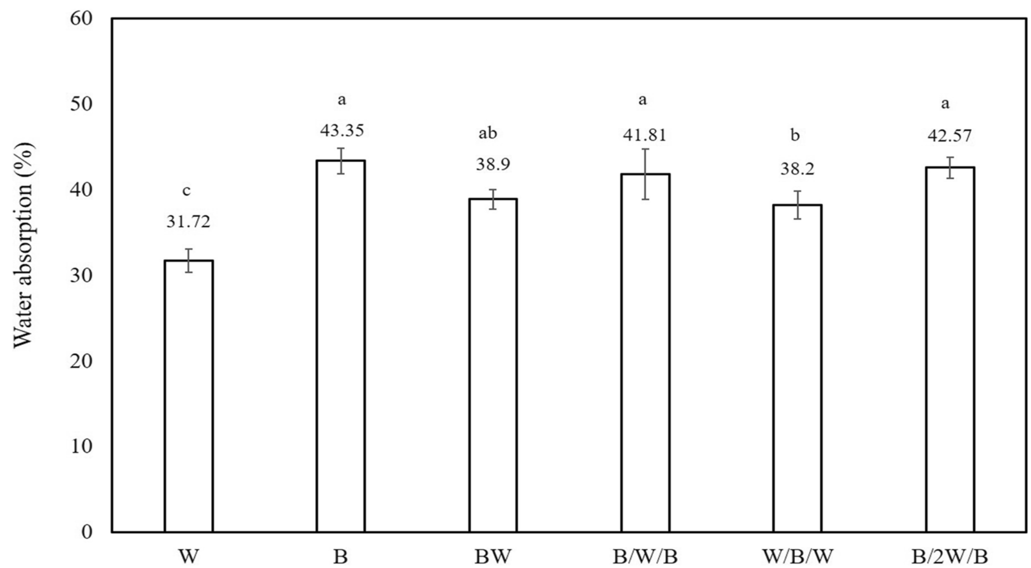

Fig. 6 Water absorption rate of BWCs (results are mean ± SD, $n = 9$; numbers followed by different letters (a–c) are statistically different at the probability level of $p < 0.05$ according to Tukey's test and ANOVA)

have better physical interlocking effect on screws, thus accounting for the higher screw retention in BWC boards with higher wood content. On the other hand, in terms of the morphology of the tissue, although bamboo has longer fiber length and higher bending strength than wood, bamboo lacks the horizontal ray tissue of the cross section. Therefore, bamboo has a good longitudinal splitting property, but the physical interlocking effect of the transverse screw is lower than woody residues. Based on the screw holding strength, it indicated that the morphological characteristic of the material will be more significant than their chemical composition and overall bending strength performance. Lai et al. [16] studied the use of thinned *T. cryptomerioides* wood as oriented strand board (OSB) material and found a high positive correlation between SHS and internal bond (IB) strength. Lin and Huang also reported that better IB strength of high-density particleboards could be attributed to the greater cohesion among the particles as a result of the hot pressing [17]. In other words, IB strength has significant influence on the SHS of BWC boards.

Dimensional stability

Water absorption affects the strength between the board structure and fiber interface, which in turn influences dimensional stability, mechanical, and physical properties. After soaked for 2 h, six experimental boards had no significant difference in water absorption rate (WA%) (data not shown). However, the six experimental boards exhibited the different WA% after soaked 24 h. As shown in Fig. 6, the WA% is the highest in B (43.35%) and the lowest in W (31.72%). The other four types of BWC boards have WA% in the order of B/2W/B (42.57%) > B/W/B (41.81%) > BW (38.9%) > W/B/W (38.2%), indicating that boards with higher content of bamboo residues have higher WA%. Bamboo culms are mainly composed of parenchyma cells and vessels, and form a sponge-like porous natural material on the cross section [14]. Moreover, since the bamboo residues of BWC are mechanically processed into an elongated bamboo residues, the presence of vessel pores in bamboo contributes to its high void ratio, resulting in higher water absorption.

Two other indicators of dimensional stability are TS and *S*. Lignocellulose materials contain richness hydroxyl group in their constituents, which make it extremely susceptible to the influence of temperature and humidity in the external environment to adsorb or remove moisture, thus causing its volume to swell or shrink. This will decrease dimensional stability of wood, which is also a disadvantage when using lignocellulose materials. Moreover, the bonding strength of wood composite panels is inversely related to TS [18]. Table 4 shows the TS% and *S*% of the six experimental groups. Group W had the highest TS% and *S*% while Group B had the lowest TS% and *S*%. Moreover, TS% and *S*% of the other groups were in the order of W/B/W > BW > B/2W/B > B/W/B, indicating that TS% decreases with increasing bamboo residue content, with significant difference among the groups. Our

Table 4 Thickness swelling (TS) and volumetric swelling coefficient (*S*) of six groups of experimental BWCs

Groups of specimens ($n = 9$)	TS%	*S*%
W	16.09 (1.94)^c	18.45 (2.07)
B	11.67 (0.79)^a	13.14 (1.08)
BW	13.85 (0.62)^b	14.67 (0.72)
B/W/B	12.61 (1.17)^{ab}	14.02 (2.05)
W/B/W	15.56 (0.61)^c	17.61 (0.96)
B/2W/B	13.36 (1.74)^b	14.06 (2.44)

Results are mean ± SD, $n = 9$; numbers followed by different letters (a–c) are statistically different at the probability level of $p < 0.05$ according to Tukey's test and ANOVA

results revealed the contrasting trends for WA% with TS% and *S*%. WA% is determined by the change in weight of specimen before and after water absorption. Bamboo is a monocotyledon plant and its fiber can easily adsorb moisture, resulting in higher WA%. Furthermore, wood chips have higher hemicellulose content, lower density tissue, and water-absorption swelling rate than bamboo residues; hence, it showed greater changes in TS% and *S*% than bamboo.

Conclusions

Physical and mechanical properties of six groups of BWCs made from domestic wood and bamboo residues after processing were examined using NDT. Results obtained showed that V_u and V_t of boards made with 100% bamboo residues (B) were higher than those of BWC boards made with mixed materials or pure materials in layers, while boards made with wood slabs alone (W) had the lowest V_u and V_t. These findings revealed a positive relationship of V_u and V_t with bamboo content in BWC boards. Moreover, mechanical strength analysis showed that Group B/2W/B had the best strength property with the highest MOE and MOR; W showed the lowest strength. The layer design with bamboo residues forming the top and bottom as well as wood in between also contributed higher strength. B/2W/B and B have the same highest SHS value due to their higher content of wood with shorter fiber length, which had better physical cladding effect and thus higher screw retention. Finally, WA% of composite was positively related to the content of bamboo residues in the composite boards, while both TS% and *S*% had a negative correlation with bamboo content.

Abbreviations

BWC: bamboo–wood composites; MDF: medium-density fiberboards; MOE: modulus of elasticity; MOR: modulus of rupture; NDT: non-destructive testing; *S*%: volume swelling coefficient; SHF: screw holding strength; THS: thickness swelling coefficient; V_u: ultrasonic-wave velocity; WA%: water absorption rate.

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Authors' contributions

SYW designed the concept of the study. MJC performed the experiments and analyzed the data. SYW wrote the initial version of the paper, and SYW edited it through to the final version. Both authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

Not applicable for this study.

Competing interests

The authors declare that they have no competing interests.

Author details

[1] Experimental Forest, National Taiwan University, No. 12, Section 1 Chien-Shan Road, Chu-Shan, Nantou Hsien 55750, Taiwan. [2] Department of Forestry, National Chung-Hsing University, No. 145, Xingda Road, Taichung 402, Taiwan. [3] Agricultural Biotechnology Research Center, Academia Sinica, Taipei 128, Taiwan.

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