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Effect of disodium octaborate tetrahydrate on the mechanical properties of *Dendrocalamus asper* bamboo treated by vacuum/pressure method

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Abstract

The chemical treatments applied to some lignocellulosic resources commonly used as building materials can influence their mechanical performance during service, and hence, this effect should be studied for structural safety reasons. In this piece of work, prismatic samples of *Dendrocalamus asper* bamboo were treated in a vacuum/pressure process with disodium octaborate tetrahydrate (DOT) solutions and the corresponding mechanical performance was compared with non-treated and water-treated samples. Full penetration of boron was achieved, with DOT retentions of 14.79 kg m^{-3} and 21.79 kg m^{-3} for 5% and 8% (wt/wt%) solutions, respectively. Dynamic modulus of elasticity (MOE), static MOE, and compressive modulus of elasticity of the material, with values between 23.3–24.0, 15.9–16.2, and 26.2–27.2 GPa, respectively, were statistically equivalent for all the analyzed treatment conditions. However, a significant influence of the treatment could be observed on the specific compressive strength of bamboo, showing an increase of 35.3% for the 5% solution and 30.6% for the 8% solution. Although without statistical difference among the treatments, similar behavior was observed on the specific modulus of rupture (MOR) under flexural loading, with an increase of up to 10.1% in relation to the reference for the treated samples. The results achieved in the present study from nondestructive excitation pulse, three-point bending, and axial compression tests demonstrated that mechanical behavior of bamboo was preserved or even enhanced by the proposed treatments based on disodium octaborate tetrahydrate.

Keywords: Bamboo, Bending, Compression, *Dendrocalamus asper*, Disodium octaborate tetrahydrate, Treatment

Introduction

Developing and using low embodied carbon building materials and services, at the life cycle perspective, is identified as one of the main pivotal opportunities to reduce the carbon emissions of the construction sector [1]. The construction industry requires heavy investment, produces intensive pollutions [2], and accounts for around 36% of worldwide CO_2 emissions [3]. Bio-based construction materials have the advantage of not only being renewable but also having a significant contribution to carbon sequestration during their growth [4, 5], as well as carbon storage during their use phase [6].

Life cycle assessment studies of bamboo-based construction materials clearly showed the potential of bamboo for use in the construction sector [7–10]. In these studies, transportation is an important issue to a product such as bamboo culm which has a high volume per mass. There is a large environmental impact of transferring such raw materials from its origin to site of construction, and this, therefore, makes the use of local materials (local bamboo species) indisputable in the industrial and construction sectors.

The excellent physical and mechanical properties of bamboo have led to its empirical use in construction and have attracted the attention of several researchers to start

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the process of rediscovering bamboo recently [11]. Even for modern buildings, bamboo has been widely employed to fabricate mechanical elements and structures [12, 13] and it is frequently referred as a high-strength alternative material to timber and occasionally as a 'strong-as-steel' reinforcement for concrete [14].

However, bamboo properties are directly related to the species, age, moisture content, soil, harvest season, and culm geometry among other factors [15]. The mechanical strength of *D. asper*, a species which has been used in this research, in compression, tension, and bending is reported to be 53 to 95 MPa, 73 to 326 MPa, and 95 to 258 MPa, respectively, depending on the presence or absence of the node and the position in relation to the culm height [16–20]. These mechanical properties are medium to higher than those of other species of *Dendrocalamus* genera, *Guadua* and *Bambusa* [21, 22].

Along with mechanical strength adequate to the requirements of different applications, a building material should have an acceptable life span. The durability of untreated bamboo varies based on the species, age, and conservation actions taken, and it is strongly related to the bamboo chemical composition [16, 23, 24]. In an open environment, and in the contact with soil, bamboo is estimated to last 1 to 3 years, 4 to 6 years if undercover, and free from soil contact [25, 26]. Only under very favorable use conditions such as internal framing is untreated bamboo estimated to last around 15 years [11] which is not sufficient as a construction material.

The powderpost beetle (*Dinoderus minutus*) which is the main destructive agent of bamboo [27], and other xylophagous organisms, such as decay fungi and termites, can seriously affect its structural integrity and consequently compromise the service life of the resulting structures or constructive systems [26, 28]. Additionally, flammability, the volume variation due to water absorption, and the susceptibility to chemical degradation are other problems that hinder their use in some applications [29, 30]. Therefore, an adequate preservative treatment of bamboo is necessary so that it can be safely used as a structural element. There are several treating methods to improve the durability and preserve bamboo materials, but some methods which use thermal and natural products like vegetable oils (palm, sunflower, or soybean) have been proved to decrease the mechanical properties of bamboo [31–33]. Wahab et al. [34] studied tropical bamboo treated in palm oil at 140, 180, and 220 °C during 30, 60, and 90 min. The results showed that the treatment decreased the mechanical properties (bending, compressive, and shear strengths). When the treatment duration increases, the mechanical strengths could decrease by 15–58% from the initial strength, depending on each treatment procedure and each mechanical property [35]. On the other hand, some treatments lead to color changes [36, 37], which is an undesirable effect [35].

Since ancient times, chemical methods have been used for wood and bamboo preservation and while non-chemical methods have also been used, the chemical methods are considered as more appropriate for bamboo preservation in large-scale building projects [11]. There are a lot of chemical materials that have been used to preserve wood and bamboo against water, insect, and fungal attack and as a fire retardant. However, the use of some chemical preservatives is ambivalent. For example, conventional wood treatment solutions used in Brazil have good performance but are normally based on heavy metals and other toxic elements, such as chromated copper arsenate (CCA) and pentachlorophenol, which have an impact on animals and plants.

Among the various substances and their mixtures that have been suggested, investigated, and commercialized, the use of low-cost soluble salts, such as boron-based salts specifically disodium octaborate tetrahydrate (DOT), boric acid, and borax, is interesting alternatives for the treatment of bamboo and wood [24, 28, 38, 39]. Boron compounds are some of the most effective and versatile preservatives solutions used nowadays since they combine the broad-spectrum efficacy, low mammalian toxicity, odorless, colorless, and fire-retardant properties [40–43]. The preservation method with boron compounds can be even a way to improve the quality of bamboo, increasing the tensile strength in comparison with bamboo without preservatives [44, 45].

Bamboo requires essential preservation treatment before its utilization as a structural material to ensure the durability of a building. Although chemical treatment is considered a commonly used treatment procedure in the construction industry, it might damage the material mechanically. Therefore, the influence of chemical treatments in the mechanical properties of those building materials must be known. It is worth mentioning that most part of the structural projects using bamboo in Latin America and Asia use boron compounds (boric acid, borax or DOT) as the main preservative and therefore studies of treatability, mechanical performance, and durability are necessary. In spite of the high use of DOT, which is an active component in Bora-Care® and is an available popular commercial preservative, to the best of our knowledge, there has been no prior comprehensive study on the effect of this type of treatment on bamboo with regard to the mechanical performance.

The objectives of this work were to determine the retention of DOT for treated bamboo and evaluate the effects of DOT treatment on mechanical properties assessed by nondestructive test by excitation pulse, three-point static bending, and axial compression tests.

Materials and methods

Materials and sample preparation

The *D. asper* bamboo species has been used for this study due to its availability and easy access in several tropical regions. Bamboo culms were harvested at the experimental field in the University of São Paulo Campus at Pirassununga, Brazil (21°58′53.5″S 47°26′03.3″W). The referred collection area is located at an altitude of 630 m above the sea level, with an annual average rainfall of 1363 mm and tropical climate with well-defined seasons (rainy summer and dry winter).

Mature culms (more than 3 years old) were collected and conditioned in a protected environment for drying until reaching constant moisture content. Tangentially oriented strips, approximately 250 mm long and 20 mm wide, were then cut from the inner region between nodes, also called internodes. Since the samples have been taken from the same or adjacent internodes, a possible influence of the variation of the mechanical properties along the culm in the effect of each treatment was minimized. Then, the samples were sanded to obtain dimensional uniformity in width and thickness.

The physical properties of the samples, moisture content (MC) and apparent density (ρ), before treating with DOT are listed in Table 1. Internodes (Int) of two different culms have been used for this study. Int A in the table stands for the samples taken from the middle part of a bamboo culm with the external diameter of approximately 11 cm and Int B, taken from the bottom part of a bamboo culm with approximately 16 cm external diameter.

Treatment procedures

A combination of boric acid and disodium borate decahydrate was used in the ratio of 1:1.54 by mass for the formation of DOT, ($Na_2B_8O_{13}{\cdot}4H_2O$) according to the stoichiometric reaction:

$$\mathrm{Na_2B_4O_7 \cdot 10H_2O} + \mathrm{4H_3BO_3} \rightarrow \mathrm{Na_2B_8O_{13} \cdot 4H_2O} + \mathrm{12H_2O}$$

Table 1 Apparent density (ρ) and moisture content (MC) of the bamboo samples used for treatment (COV in parentheses)

	ρ (g cm^{-3})	MC (%)
Int A	0.69 (0.043)	8.3 (0.012)
Int B	0.77 (0.026)	8.7 (0.023)

Boric acid and disodium borate decahydrate of analytical grade were used. Then, aqueous solutions of the preservatives with concentrations of 5% and 8% (wt/wt%) were prepared using distilled water for the impregnation procedure. These concentrations were selected based on recommendations of bamboo treatment manuals of the International Network of Bamboo and Rattan (INBAR) (with concentrations between 5 and 10%), Indian Standard of preservation of bamboo for structural purposes (concentration of 4 and 5%), and other related papers [24, 46, 47]. Additionally, those are concentrations normally used in bamboo treatment plants around Colombia and Brazil.

The obtained solutions were applied through a vacuum/pressure steel chamber with a diameter of 150 mm and 270 mm height. This method was adopted to guarantee the penetration of the boron compounds in the samples. Prior to treatment, the samples were oven-dried at 60 ± 5 °C until constant weight.

First, the specimens were placed in the empty chamber under an initial vacuum (− 650 mmHg) for 15 min with the intention of withdrawing air from the chamber and from the bamboo structure. Thereafter, the solution was injected into the chamber (about 8 L was required for total immersion of the samples) and the same vacuum was maintained for an additional 1 h. Then, a pressure of approximately 3103 mmHg (60 psi) was applied into the chamber and held constant for 1 h. After this step, the solution was drained and the samples were taken out from the chamber and left in room temperature for 48 h and then dried at (100 ± 2) °C for 48 h. After the drying process, the samples were conditioned in a climatic chamber at 25 °C and 70% RH prior to mechanical testing.

Retention and boron penetration

Retention is usually expressed as weight of chemical per unit volume of wood (pounds per cubic foot or kilograms per cubic meter) or on weight of chemical to weight of wood basis (wt/wt%). The weights of the specimens were measured before and shortly after the treatment to determine the absorption of the treatment solution, and then, the theoretical retention was calculated using Eq. 1, as per AWPA E10:2016 Standard [48].

$$R\left(\mathrm{kg\,m^{-3}}\right) = \frac{Ab \times C_{\mathrm{w}}}{V} \times 10 \quad (1)$$

where R is the DOT retention (kg m^{-3}); Ab mass of absorbed solution after treatment (g); C_{w} concentration of the preservative solution (wt/wt) (%); and V sample volume (cm^3).

The penetration analysis was also performed on samples treated with the boron compounds according to Brazilian Standard ABNT NBR 6232:2013 (Penetration and retention of preservatives in pressure treated wood) and Indian Standard IS 1902:2006 (Preservation of bamboo and cane for non-structural purposes) to observe the presence of boron [46, 49]. A cross-sectional area of $(10 \times 20)\ \text{mm}^2$ from samples extracted from the central region of the treated prismatic specimens was reacted with two different etching solutions. Solution 1 is composed of curcumin (earth turmeric) and ethyl alcohol (10% wt/vol alcohol) and solution 2 composed of a saturated salicylic acid alcoholic solution (13 g to 100 mL solution) and 20 mL of concentrated hydrochloric acid. First, solution 1 is applied, and when dried, solution 2 is used. The observation of red color indicates the presence of boron. Except for turmeric, all reagents used are analytical grade.

Mechanical tests

Samples originated from Int A and Int B were used for the mechanical characterization, with a total of eight specimens per treatment condition: reference, water treated, DOT 5% solution, DOT 8% solution). Each sample was subjected to the three tests performed in this work (excitation pulse, three-point bending, and axial compression tests).

Excitation pulse nondestructive test

The dynamic elastic modulus was determined for each sample which was subsequently tested via static bending and in compression. The tests were performed in an excitation pulse testing machine Sonelastic®, as per recommendations of the ASTM E1876-15 Standard [50]. The dynamic modulus of elasticity was determined in the longitudinal and flexural mode. Samples with nominal dimensions of 250 mm × 20 mm × thickness were used with a gap between the inferior supports of 0.552 × L.

Three-point bending test

After the determination of the dynamic elastic modulus by the impulse excitation technique, the same samples were subjected to a static three-point bending test using a universal testing machine EMIC model DL30000. The supported distance for each specimen was $L = 160$ mm, and single point load F was applied at $L/2$. These dimensions are established in order to maintain a minimum length-to-depth ratio of 15 (according to the ASTM D1037-12 Standard) [51]. The specimens were loaded continuously until failure at a loading rate of 5 mm min^{-1}, and a deflectometer was used to record the deflection in the center of the specimen. The modulus of rupture (MOR) and the modulus of elasticity (MOE) were then calculated according to Eqs. 2 and 3.

$$\text{MOR(MPa)} = \frac{3 \times F_\text{r} \times D}{2 \times w \times \left(t^2\right)} \tag{2}$$

$$\text{MOE(MPa)} = \frac{F_\text{LP} \times \left(D^3\right)}{4 \times d \times w \times \left(t^3\right)} \tag{3}$$

where F_r is the load at failure (N); D distance between the supports (mm); w width of the sample (mm); t thickness of the sample (mm); F_LP maximum load in the elastic region (N); d deflection related to F_LP (mm).

Axial compression tests

Compression tests parallel to fibers were conducted in a servohydraulic test system, MTS Landmark, with a 15 kN load cell. Before the official axial compression tests, several tests were carried out to evaluate the applied methodology. First, the deformation difference between the inner and outer faces of the bamboo was evaluated. In samples extracted from the same specimens that were used in the bending tests, an extensometer was placed on the outer and the inner layers. It was found that due to the dimensions of the specimen, there was no significant difference between the different positions.

After the static bending test, two samples of approximate dimensions of 40 mm × width × thickness (width = thickness) per test piece were cut. The test was performed at a rate of 10 MPa min^{-1}, according to the recommendations of the Brazilian ABNT NBR 7190:1997 Standard (Wood Structures Project) and within the recommended testing time of ASTM D4761-13 [52, 53]. First, a test specimen was used to determine the compressive strength, without the use of extensometer, calculated using the maximum load at failure. Then, a second specimen (of the same sample used in bending) was used to determine the compressive modulus of elasticity. In this step, two loading cycles were performed between 20 and 50% of the compressive strength (determined previously), as shown in Fig. 1. The elastic modulus was then calculated through linearization of the second loading step. After the double loading, the extensometer was withdrawn, and the test continued until failure of the specimen.

Statistical analysis

The averages of the results from each test are presented with the corresponding coefficient of variation (COV presented in parentheses). The differences between the treatment conditions on the mechanical properties were checked by a Tukey's test and analysis of variance (ANOVA) ($p < 0.05$) in case of a significant difference. For

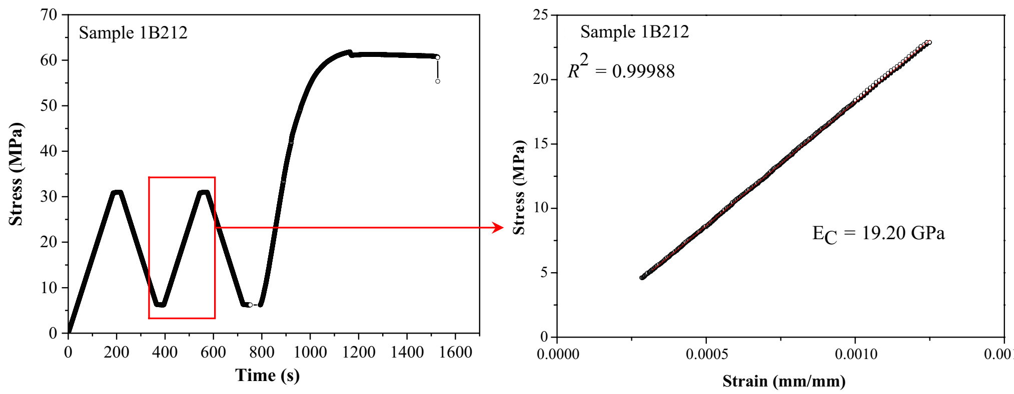

Fig. 1 Loading cycles used for determination of modulus of elasticity in the axial compression tests

Table 2 Absorption of solution after the treatment process in the vacuum/pressure vessel

Absorption after impregnation, weight increase (%)			
Treatment	**Int A**	**Int B**	**Overall**
Water	67.6 (0.20)	57.9 (0.17)	61.6 (0.19)
5% DOT	73.1 (0.031)	61.3 (0.059)	65.7 (0.10)
8% DOT	65.7 (0.11)	55.4 (0.052)	58.8 (0.11)

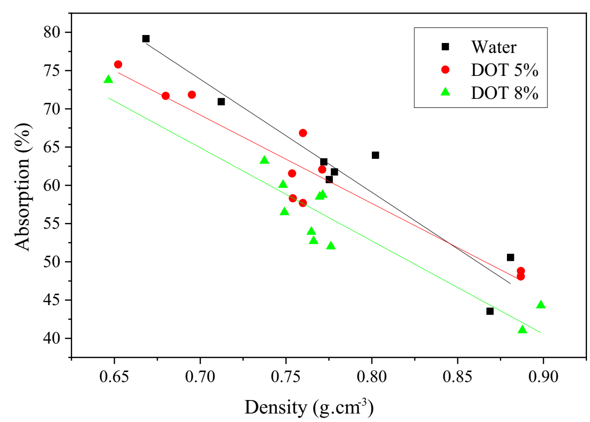

Fig. 2 Relationship between solution absorption and the apparent density of bamboo samples

the statistical analysis, normalized mechanical properties in relation to density (also called specific property) were used in order to better observe the effect of each treatment. All analyses were performed by the software MINITAB® Release 14 Statistical Software.

Results and discussion

Retention and boron penetration

Table 2 shows the analyzed solution absorption values of each condition. Apparently, despite increasing the viscosity of the solution, the concentration of DOT did not significantly affect the absorption of the solution compared to water. However, it is noticed that the absorption is correlated with the density, as shown in Fig. 2. This relationship is related to the number of pores since the solution uptake is strongly dependent on wood/bamboo permeability [54].

In general, the treatment involves placing an adequate amount of chemical to a depth that will achieve the desired degree of protection. Thus, most treatment standards address penetration or the depth to which the chemical penetrates and the retention, or the amount of chemicals deposited in a specific area of the wood [55]. The retention values calculated according to Eq. 1 are presented in Table 3. It is worth mentioning that these theoretical values have been calculated considering the absorption of the treatment solution. The retention is presented as the equivalent of dried DOT per unit volume of bamboo. According to the stoichiometric reaction shown previously, for solutions based on boric acid and borax in the proportion of 1:1.54 (wt:wt), the resulting mass of DOT is 65.6% from the total mass of boric acid and borax. For the 5% solution, for example, the mass of absorbed solution is multiplied by 0.328 to have the corresponding amount of formed DOT. The results given in Table 3 can also be represented as the retention of B_2O_3 per unit volume of bamboo. In the case of DOT, B_2O_3 represents 79.91% of its molecular weight, resulting in retention of 11.82 kg m^{-3} and 17.41 kg m^{-3} for the 5% and 8% solutions, respectively. These both results satisfy the desired B_2O_3 retention as recommended by American Wood Preservers' Association (2.7 kg m^{-3}) [38] and the Indian Standard IS401:2001 (5 kg m^{-3}) for indoor use application of wood [56]. Although acceptable retention levels were obtained, compared to sapwood, the

Table 3 Retention values of DOT calculated according to Eq. 1

Retention of DOT (kg m^{-3})			
Treatment	Int A	Int B	Overall
5% DOT	15.28 (0.012)	14.35 (0.061)	14.79 (0.056)
8% DOT	22.93 (0.030)	20.65 (0.047)	21.79 (0.063)

retention levels of bamboo are smaller mainly because of its anatomical structure. The bamboo used in this work has higher density than Scots pine (0.4–0.5 g cm^{-3}), for example, which limits the maximum amount of solution that can be absorbed by the material. In sapwood treatment, more than 100% of its weight can be absorbed. In bamboo, the outer layer part of the culm wall is protected by an epidermis as a waterproof seal. Additionally, there are no radial penetration pathways in bamboo, like the rays in wood. Especially in dry bamboo, the main path for penetration is the metaxylem vessels of the vascular bundles and the access to the parenchyma is difficult [24, 47, 57].

In Fig. 3, photographs obtained through a stereoscope show the total penetration of boron over the thickness of the treated samples (Fig. 3b). In Fig. 3a, an image of a sample without treatment subjected to the test is presented for comparison. Both samples treated with 5% and 8% DOT solutions showed similar staining and total penetration.

Mechanical characterization

Dynamic modulus of elasticity

Nondestructive testing (NDT) was used to evaluate the dynamic modulus of elasticity of treated and untreated bamboo samples. Since bamboo is a natural composite composed of aligned fiber bundles in the growth direction in a parenchyma matrix, it is expected an anisotropic behavior. Therefore, the measurements were taken in flexural and longitudinal mode.

Figure 4 shows the relationship between the dynamic MOE and density of each sample. There is an almost linear correlation between the dynamic MOE and density of bamboo. This observation is correlated with the fact that higher density in bamboo means higher volume fraction of fibers within its structure. Dixon et al. [58] found the same relationship between the MOE (obtained by static flexure tests) and the density of the bamboo species Moso, Tre Gai, and Guadua, with MOE varying between 10 and 40 GPa.

A summary of the achieved results for each treatment condition is given in Table 4. Since there is a correlation of the dynamic MOE with density (Fig. 4) and in order to better compare the effect of each treatment condition, the specific MOE was calculated for each specimen and an average for the eight samples was obtained. It can be observed that even with high retention, there was no significant change in the dynamic MOE among the investigated conditions and the preservatives have no negative

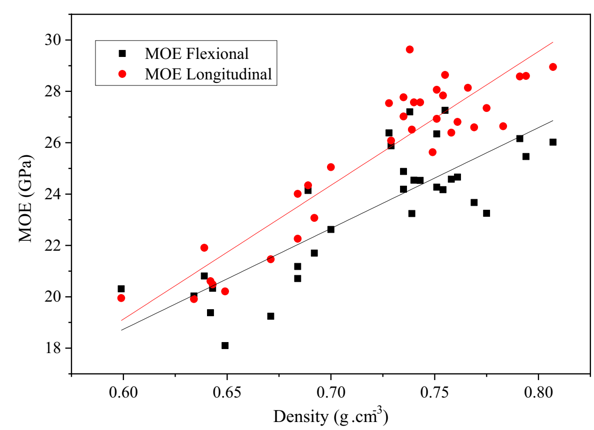

Fig. 4 Correlation between dynamic MOE (flexural and longitudinal modes) and apparent density

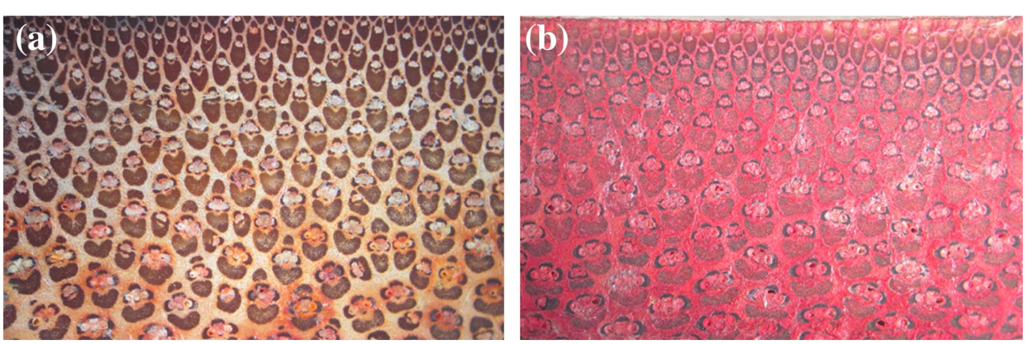

Fig. 3 Analysis of penetration with solution of curcumin and salicylic acid. **a** The solution was used in an untreated sample and **b** the treated sample

Table 4 Summary of NDT excitation pulse measurements for determination of the dynamic MOE

Treatment conditions	MC (%)	Flexural MOE (GPa)	Longitudinal MOE (GPa)
Reference			
Int A	10.72	20.91 (0.033)	21.94 (0.060)
Int B		24.57 (0.091)	27.99 (0.031)
Overall Avr		23.35 (0.067)	25.97 (0.12)
Specific[1]		31.26 (0.044)[a]	34.67 (0.051)[a]
Water			
Int A	9.37	21.44 (0.11)	22.29 (0.085)
Int B		24.34 (0.19)	26.36 (0.044)
Overall Avr		23.25 (0.17)	24.83 (0.10)
Specific[1]		32.53 (0.14)[a]	34.73 (0.039)[a]
5% DOT			
Int A	10.24	19.22 (0.057)	20.54 (0.039)
Int B		25.79 (0.067)	28.02 (0.042)
Overall Avr		23.26 (0.15)	24.90 (0.16)
Specific[1]		33.34 (0.10)[a]	35.61 (0.091)[a]
8% DOT			
Int A	10.23	22.36 (0.14)	23.33 (0.13)
Int B		24.76 (0.032)	27.33 (0.017)
Overall Avr		23.96 (0.086)	26.00 (0.099)
Specific[1]		32.99 (0.044)[a]	35.76 (0.051)[a]

[1] MOE (GPa)/ρ (g cm^{-3}). Specific averages with the same letter (a–d) are statically equivalent. Three replicates were tested for Int A and five for Int B, with a total of eight replicates per treatment condition

effect on bamboo samples in terms of MOE in both flexural and longitudinal directions. Although a slight increase was observed, 6.65% and 5.53% on the flexural MOE and 2.7% and 3.14% on the longitudinal MOE for the 5% and 8% DOT-treated samples, respectively, these results are statistically equivalent to the reference samples.

Three-point bending

According to the previous discussion, there is a correlation between the dynamic MOE and apparent density. Similar behavior could be observed with the modulus of rupture obtained by static bending, corroborating with the observations of other authors [58]. Therefore, specific values of MOR and MOE were also calculated for all the samples.

The stress–strain curves of several samples from all the conditions (reference, water, 5% and 8% DOT) are shown in Fig. 5, and the results of MOR and MOE are given in Table 5. It is possible to observe that all the curves, independently of the applied treatment, showed similar behavior upon straining. The obtained average values of MOR, between 150.4 and 167.2 MPa, are similar to those observed by other authors in the same bamboo species, in which values between 140 and 258 MPa were reported using comparable testing procedure [17, 20].

According to the results given in Table 5, although a slight increase in the average specific MOR of the samples treated with DOT was observed (8.5% and 10.1% for the 5% and 8% treatments, respectively), this difference is not statistically relevant using the ANOVA. The same behavior was noticed for the results of MOE, in which case there was no considerable effect of the treatments with DOT. Comparing the results of MOE obtained by static bending and by excitation pulse test, it was observed that the dynamic data were approximately 55% higher than the static MOE. In fact, this difference is normally found in NDT tests for the determination of dynamic MOE, with a difference between 40 and 50% [59, 60].

It is worth mentioning that since the same specimens were used for NDT and static bending tests, a correlation between the obtained data through both techniques can be made. Figure 6 shows the relationship between the longitudinal dynamic MOE and static MOR. Interestingly, although they describe different mechanical properties, there is an almost linear correlation between them ($R^2 = 0.8629$). This observation can be very useful for quality control of bamboo products since a nondestructive test could be used to estimate other properties normally obtained only by destructive and time-consuming tests.

Compression parallel to the fibers

The compressive modulus of elasticity (E_C) was determined by following the stress–time pattern shown in Fig. 1. Very good linearization ($R^2 = 0.9998$) of the stress–strain plot was obtained using the second loading step, assuring good quality of the extracted E_c.

A summary of the compressive strength (C_S) and E_C results obtained for the DOT-treated, water-treated, and reference samples is presented in Table 6. From the results, the influence of preservative treatment also did not have any significant effect on the compressive modulus of elasticity, corroborating with the elastic properties obtained by static bending and excitation pulse tests. However, on compressive strength, a positive and statistically different effect of the treatment can be observed. The samples treated with 5% and 8% DOT solutions presented a specific C_S increase of 35.3% and 30.6%, respectively, in comparison with the reference samples. The water-treated samples also had a slight increase in the compression strength (17.1%). Similar behavior was observed in the MOR obtained by static bending, although statistical analysis showed no valid difference.

According to the results of the mechanical tests, the solutions used for treatment did not cause any

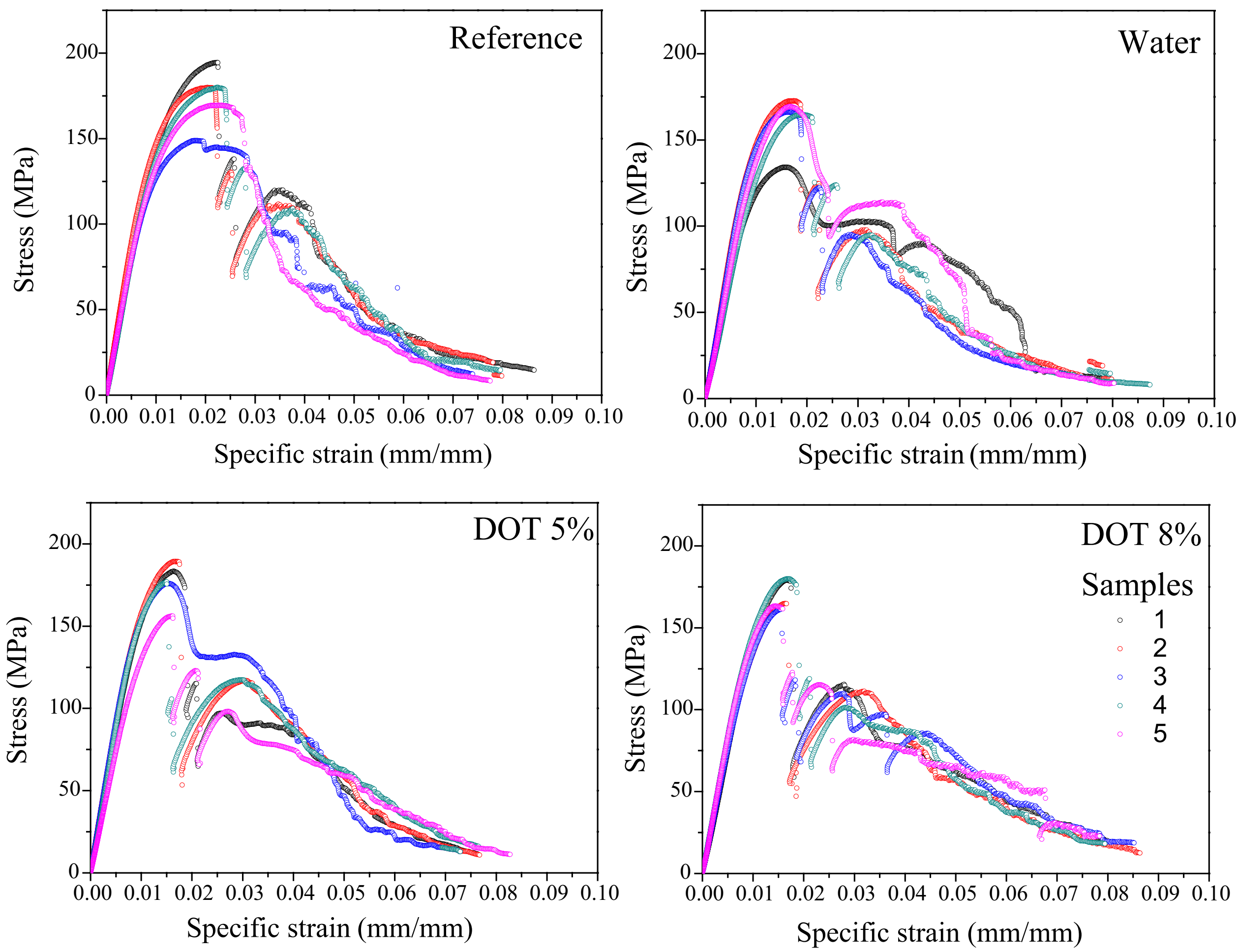

Fig. 5 Stress vs specific strain curves obtained by static bending of samples treated with DOT, water, and untreated

detrimental effect on the structure of bamboo even with high retention levels. Furthermore, it is possible to infer that the increase in the compressive strength can be correlated with the formed DOT salt crystals within the bamboo microstructure, which could help to accommodate the applied forces during loading. Since the pH of 5% and 8% solutions is close to neutral pH (between 7.9 and 7.7), which is one of the advantages over the use of only boric acid and borax as sources of boron, chemical reactions are not expected during treatment. In fact, preservatives with pH above 4.1 are not expected to cause considerable detrimental effects on wood properties [61]. Therefore, the increase in the mechanical properties found in this study is hypothesized to be attributed partially by the accommodations of forces by DOT crystals inside the bamboo porous structure or other mechanisms not yet known.

Conclusions

The effectiveness of an available commercial preservative—DOT—treatment on the mechanical properties of *D. asper* bamboo was investigated. In general, it was possible to conclude that there is no negative effect of DOT treatment on the investigated mechanical tests, even considering high DOT retention levels. The main conclusions are as follows:

- *D. asper* bamboo strips can be successfully vacuum/pressure treated using boron compounds, achieving acceptable retention and penetration of DOT using 5% and 8% (wt/wt%) solutions.
- For the dynamic MOE determined from the excitation pulse tests, there was no statistically significant change among the investigated conditions.

Table 5 Summary of obtained results from three-point bending test

Treatment conditions	MC (%)	MOR (MPa)	MOE (GPa)
Reference			
Int A	10.92	125.8 (0.072)	16.16 (0.010)
Int B		174.5 (0.097)	16.20 (0.065)
Overall Avr		156.2 (0.18)	16.18 (0.050)
Specific[1]		209.4 (0.12)[a]	21.97 (0.10)[a]
Water			
Int A	10.00	132.1 (0.10)	16.80 (0.073)
Int B		161.4 (0.097)	15.13 (0.097)
Overall Avr		150.4 (0.14)	15.76 (0.098)
Specific[1]		209.9 (0.068)[a]	23.24 (0.14)[a]
5% DOT			
Int A	10.70	134.8 (0.087)	15.69 (0.055)
Int B		176.4 (0.071)	17.12 (0.089)
Overall Avr		158.6 (0.15)	16.65 (0.086)
Specific[1]		227.3 (0.091)[a]	23.70 (0.089)[a]
8% DOT			
Int A	10.77	163.1 (0.22)	16.47 (0.074)
Int B		169.7 (0.053)	15.57 (0.058)
Overall Avr		167.2 (0.13)	15.91 (0.066)
Specific[1]		230.6 (0.10)[a]	22.03 (0.087)[a]

[1] MOE (GPa)/ρ (g cm^{-3}) and MOR (MPa)/ρ (g cm^{-3}). Specific averages with the same letter (a–d) are statically equivalent. Three replicates were tested for Int A and five for Int B, with a total of eight replicates per treatment condition

Table 6 Summary obtained results from compression tests parallel to fiber

Treatment conditions	MC (%)	C_S (MPa)	E_C (GPa)
Reference			
Int A	9.74	50.3 (0.064)	17.64 (0.032)
Int B		65.4 (0.050)	32.00 (0.12)
Overall Avr		59.9 (0.14)	27.21 (0.29)
Specific[1]		81.8 (0.073)[a]	36.21 (0.22)[a]
Water			
Int A	9.10	60.3 (0.056)	18.04 (0.13)
Int B		74.3 (0.067)	25.49 (0.14)
Overall Avr		67.3 (0.12)	22.30 (0.22)
Specific[1]		95.80 (0.081)[b]	32.10 (0.17)[a]
5% DOT			
Int A	9.61	68.0 (0.059)	17.07 (0.18)
Int B		82.5 (0.042)	29.65 (0.10)
Overall Avr		75.8 (0.11)	23.73 (0.31)
Specific[1]		110.7 (0.056)[c]	34.59 (0.20)[a]
8% DOT			
Int A	8.95	73.4 (0.11)	20.35 (0.13)
Int B		78.0 (0.045)	30.57 (0.14)
Overall Avr		75.7 (0.086)	26.19 (0.25)
Specific[1]		106.8 (0.056)[c]	36.84 (0.18)[a]

E_C: Compressive modulus of elasticity; C_S: compressive strength [1]E_c (GPa)/ρ (g cm^{-3}) and C_S (MPa)/ρ (g cm^{-3}). Specific averages with the same letter (a–d) are statically equivalent. Six replicates were tested for Int A and eight for Int B, with a total of 14 replicates per treatment condition

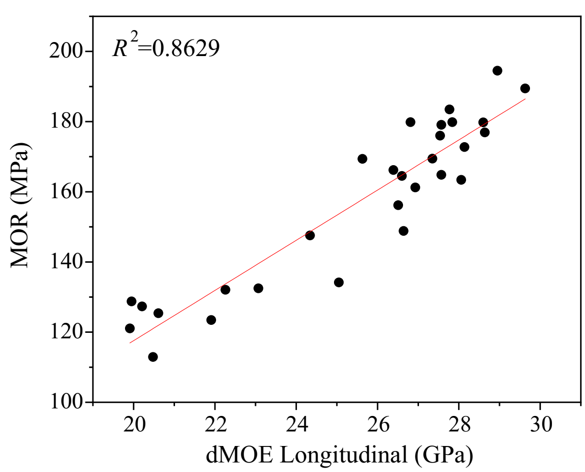

Fig. 6 Correlation between dynamic longitudinal MOE and the MOR obtained by static bending

- Although DOT treatment using both 5% and 8% concentration solutions positively affected specific MOR, the difference is not statistically valid.
- There is a linear correlation between dynamic MOE (NDT) and MOR obtained by static bending.
- Bamboo treated with 5% and 8% DOT solutions increased the compressive strength by 35.3% and 30.6%, respectively, but no significant difference was observed in the modulus of elasticity in compression.

Additional degradation tests with decay fungi (white rot and brown rot) are currently being performed for the achievement of information regarding the effectiveness of DOT on the protection of bamboo against fungi before and after severe leaching cycles.

Abbreviations

DOT: disodium octaborate tetrahydrate; Int: internode; MC: moisture content; MOE: modulus of elasticity; MOR: modulus of rupture; NDT: nondestructive testing; E_C: compressive modulus of elasticity; C_S: compressive strength; ρ: apparent density.

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Authors' contributions

CG made the experimental work, including the treatments and mechanical/physical characterization. CG also analyzed and interpreted the obtained data and was involved in organizing and writing the results presented in this manuscript. MK helped in the interpretation of the results and was an important contributor in writing the manuscript. HSJ was involved in drafting and revising the contents of this work. All 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.

Competing interests

The authors declare that they have no competing interests.

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