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NOTE

A two-variable model for predicting the effects of moisture content and density on compressive strength parallel to the grain for moso bamboo

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Abstract It is well known that mechanical performances of bamboos are significantly affected by moisture content (MC) and specific density. However, until now, no published studies have attempted to combine these two factors into one predictive model. In this paper, a two-variable model for predicting the combined effects of MC and specific density on compressive strength parallel to the grain (CSP) for moso bamboo was established and validated. The results show that the two-variable model is capable of predicting the CSP for bamboos of variable density and MC with significantly higher accuracy than either of the single-variable models. It is envisioned that this model could play an important role in supporting non-destructive evaluations of bamboos mechanical properties, greatly enhancing the potential applications of bamboo-based engineered products in commercial fields.

Keywords Specific density · Moisture content · Compressive strength parallel to gain · Moso bamboo · A two-variable model

Introduction

Bamboo is a typical natural fiber-reinforced composite with fibers as the reinforcement and parenchyma cells as the matrix [1–3]. The radial gradient distribution of fibers further imparts bamboo with the characteristics of a naturally functional gradient material [4]. However, to promote the widespread application of bamboo in construction and other engineering fields, far more knowledge and understanding of its mechanical properties is required. Many investigations have been undertaken to as certain how factors, such as structure, age, location along the culm, and density, as well as external factors, such as moisture content (MC), temperature and biodegradation, affect the mechanical properties of bamboo and many other biomaterials [5–11].

Density is known to be one of the most important factors affecting the mechanical performances of bamboo. Although correlation coefficients are not always very high for some species, generally, the mechanical properties of bamboo can be linearly fitted with specific density as the independent variable. MC is another important factor affecting the mechanical properties of bamboo. Zhou et al. [12] found that all the mechanical properties of bamboo decreased with rising MC until 30–40 % MC was reached.

Compressive strength parallel to the grain (CSP) is a particularly important indicator for evaluating the suitability of bamboo in structural applications. Previous studies have demonstrated that both density and MC significantly affect the CSP of bamboo [5, 6, 8, 13–15]. Jiang et al. found that CSP is most sensitive to MC variation among the several selected mechanical indicators. All of them only focused on one factor, either density or MC.

Given that both factors significantly contribute to the mechanical properties of bamboo, constructing a two-variable prediction model could greatly increase our understanding of CSP, with potential practical applications in generating non-destructive predictive assessment techniques.

In this paper, a two-variable model was proposed to predict the CSP of bamboo with varying density and MC.

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Using the model, the CSP of bamboo with any combination of MC and density could be predicted with improved accuracy, thus demonstrating that this approach may provide a useful tool for guiding the production and design of bamboo-engineering products as well as expanding their use in commercial applications.

Experimental

Sample preparation

Moso bamboo (*Phyllostachys pubescens Mazei* ex H. de Lebaie) of four different ages, 0.5, 1.5, 2.5 and 4.5 years, was collected from a bamboo plantation located in Zhejiang Province, China. All the samples used for mechanical testing were prepared from the 15 to 25th internode of eight culms in accordance with GB/T 15780-1995, a Chinese national standard for performance testing of bamboo. The culms were split into bamboo strips with a width of 30 mm. These strips were then further processed into samples with a final size of length (20 mm) × width (thickness of the bamboo culm wall − 3 mm) × height (20 mm) to test CSP. All the samples were air-dried in environmental conditions (relative humidity 40–60 %) for more than four months before under taking the controlled conditioning.

The measurement of MC, specific density and CSP

The specific density of all of the samples was measured according to the Chinese national standard for bamboo (GB/T 15780-1995). The target MC levels for the compressive tests were 0, 5, 10, 15, 20, 25, 35 % and water saturation, respectively. The MC for the first 5 groups were achieved by placing these samples into desiccators containing different saturated salt solutions or a silica gel [10, 16–18] as listed in Table 1. The relative humidity (RH) was measured with a hygrothermograph (TESTO 608-H1). The samples were conditioned over more than 40 days at a constant temperature of 23 ± 1 °C. The actual equilibrium moisture content (EMC) of each sample was measured by weighing protocol after the conditioning, in accordance with the method used by Jiang et al. [15]. To achieve FSP, the bamboo samples were first soaked in water for a period of time until they had reached a target weight gain of approximately 25 %. The soaked samples were then sealed in plastic bags until they had reached an EMC of about 25 %, which was taken as the FSP for mature moso bamboo [16, 19]. The mechanical experiments were conducted using an electronic universal mechanical testing machine (Instron 5582, USA) in accordance with Chinese national standard GB/T 15780-1995. To minimize the loss of moisture, the specimens were tested immediately after being taken out of the desiccators.

Table 1 Relative humidity (RH) levels in the experiments and the corresponding equilibrium moisture contents (EMC)

No.	RH, Av. (%)	EMC, Av. (%)	Approaches for conditioning
A	2.9	0.26	Silica gel
B	37.1	4.84	Lithium chloride
C	53.9	8.68	Potassium carbonate
D	74.1	14.03	Sodium chloride
E	97.3	21.09	Nitrate of potash
F	–	25.87	Water soaked
G	–	37.36	Water soaked
H	–	110.21	Water soaked

Statistical analysis

A total of 640 samples were randomly selected from a larger batch of samples, which were cut from 100 moso bamboo culms. 63.9 % of the data generated from each group of samples was used to establish predictive models, with remaining specimens used to test the models' predictive validity. A statistical summary of the calibration and prediction sets is given in Table 2.

Origin 8.0, a commercial statistics software package, was used to analyze the data. The standard error of fitting (SEF) (determined from the residuals of the fitting) and the coefficient of determination (R^2) were used to assess the fitting performance. The standard error of prediction (SEP) was employed to evaluate the accuracy of the established model by predicting the parameter of interest for a set of unknown samples that are different from the calibration set. The predicting coefficient of determination (R_P^2) was calculated as the proportion of variation in the independent prediction set.

Results and discussion

CSP prediction model based on MC as a single variable

A total of 409 samples were tested and used to create the model. Figure 1a shows the relationship between CSP and MC for all the tested samples with four ages. In the previous studies, it was demonstrated that the FSP of mature Moso bamboo was approximately 23 % [15, 18]. Therefore, it is clearly observed that CSP decreased significantly with increasing MC levels until MC reaches roughly 23 %. This is followed by minimal variation, when MC rises above FSP. In order to better describe the correlation

Table 2 Statistical summary of the calibration and prediction sets

No.	Calibration set (409) MPa				Prediction set (231) MPa			
	Min.	Max.	Avg.	SD	Min.	Max.	Avg.	SD
A	74.63	137.84	113.15	16.88	108.80	135.82	121.86	8.50
B	60.34	114.99	88.10	14.84	56.07	114.81	88.48	19.00
C	49.92	92.16	72.27	12.16	49.88	91.83	71.89	11.13
D	38.65	79.67	58.66	10.51	43.44	79.67	60.99	11.12
E	24.02	76.23	46.74	11.25	25.88	76.23	49.07	10.99
F	33.43	68.74	54.00	8.73	31.26	65.43	51.09	9.58
G	33.86	64.19	48.81	7.92	25.47	60.28	44.12	9.75
H	24.04	70.31	44.02	10.89	27.21	69.84	46.19	11.38

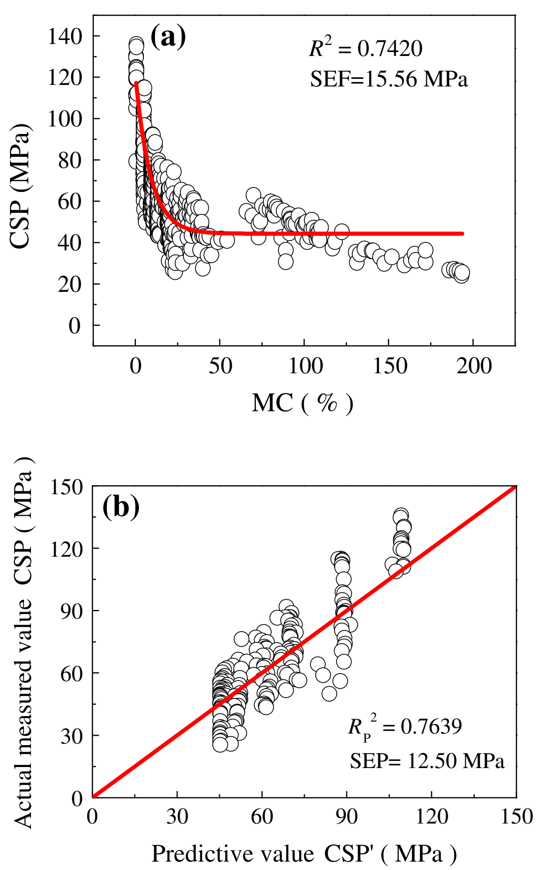

Fig. 1 **a** The relationship between compressive strength parallel to the gain (CSP) and MC. **b** The relationship between predicted compressive strength (CSP′) and experimental compressive strength (CSP) based on MC

between CSP and the whole MC range, a Boltzmann equation was selected to fit the experimental data, with the resultant regression equation presented as follows:

$$\mathrm{CSP} = 45.23 + \frac{180.78 - 45.23}{1 + e^{\left(\frac{\mathrm{MC}+0.1759}{6.7487}\right)}} \quad (1)$$

The correlation coefficient R^2 of the predictive Eq. (1) was calculated to be 0.7420, which indicates that 74.20 % of the variation in CSP could be explained by changes in MC. The SEF of 15.56 MPa indicates that this model not only gave a good relationship, but also had a relatively low calibration error.

CSP of samples used to validate the model was calculated using Eq. (1). The experimental CSP and the predicted one were plotted as shown in Fig. 1b. The predicted value agreed well with the measured one with R_P^2 of 0.7639 and standard error of prediction (SEP) of 12.50 MPa. The big data scatter shown in Fig. 1b may be due to the exclusion of specific density in the model, which is well known to play an important role in CSP for bamboo [14].

CSP prediction model based on specific density as a single variable

The correlation between CSP and specific density for the samples with different MC was plotted and shown in Fig. 2a. A huge variation of CSP could be clearly observed even if the density was the same, which was mainly attributed to the large variation of MC from nearly oven drying to about 110 %. A linear fit was adopted to describe the correlation between CSP and density, producing the following equation:

$$\mathrm{CSP} = 151.23 \cdot \rho - 33.37 \quad (2)$$

The correlation coefficient R^2 was found to be only 0.4323, while the SEF was 19.08 MPa. These values were significantly lower and higher, respectively, than the corresponding values given by Eq. (1). Similarly, the correlation between the predicted value based on Eq. (2), and the actual measured one was plotted and linearly fitted as shown in Fig. 2b. The resultant correlation coefficient R_P^2 of 0.4109 and the SEP of 20.08 MPa indicated the accuracy of the prediction model with specific density as the only independent variable was lower than that of the model with MC as the only independent variable. This can be explained by the significant effect of MC levels have on CSP for bamboo as shown in Fig. 1a.

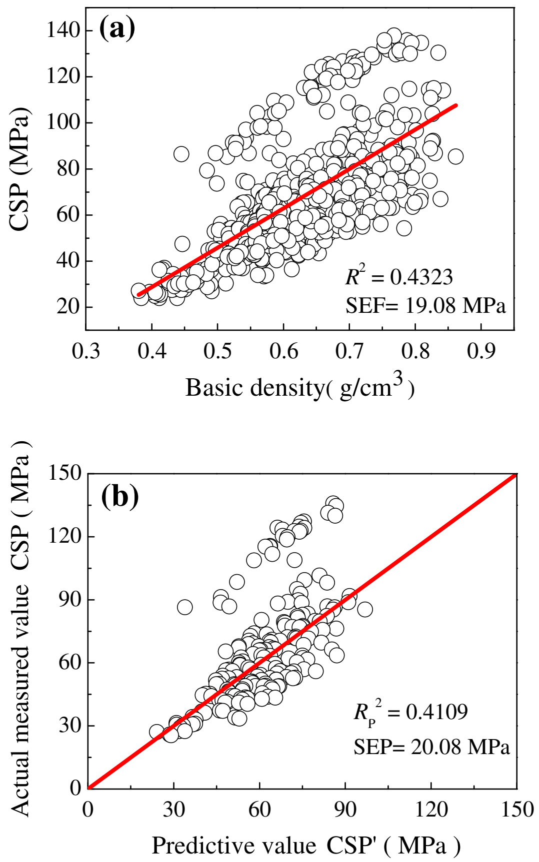

Fig. 2 **a** The correction of compressive strength parallel to the gain (CSP) and density (ρ) for all bamboo samples. **b** The relationship between predicted compressive strength (CSP′) and experimental compressive strength (CSP) based on density (ρ)

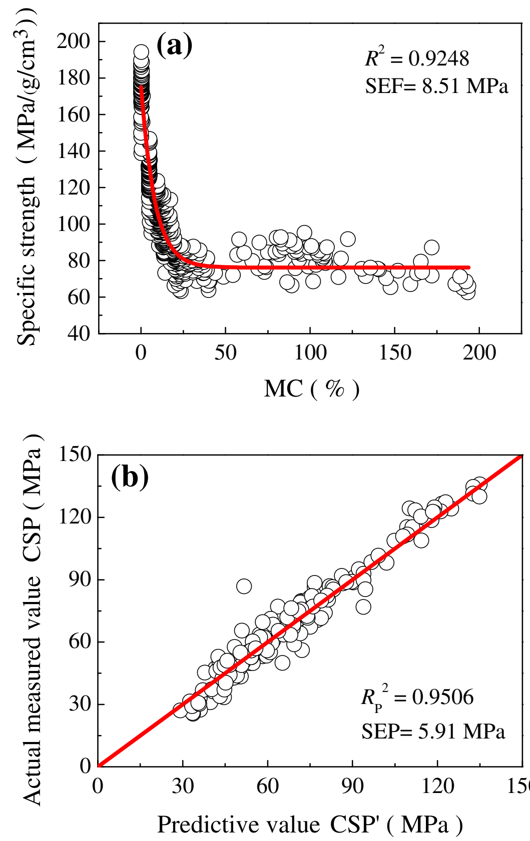

Fig. 3 **a** The relationship between specific strength and MC. **b** The relationship between predicted compressive strength (CSP′) and experimental compressive strength (CSP) based on MC and density (ρ)

CSP prediction model based on both MC and specific density as independent variables

The previous analysis showed the prediction models with single variable, either MC or specific density, will not be always satisfying under complex conditions. Therefore, investigation on the combined influence of these two factors is necessary. Since the CSP of bamboo linearly increased with rising density, the specific CSP (the ratio between CSP and specific density, i.e., CSP/ρ) was proposed as a dependent variable while MC was incorporated as an independent variable (Fig. 3a). The Boltzmann function is selected to fit the data, and the regression model is shown in Eq. (3).

$$\frac{\mathrm{CSP}}{\rho} = 76.62 + \frac{738.90 - 76.62}{1 + e^{\left(\frac{\mathrm{MC}+13.46}{7.6296}\right)}} \quad (3)$$

The correlation coefficient R^2 of the improved prediction model reached as high as 0.9248, which is much higher than those of the regression Eqs. (1) and (2). Furthermore, the SEF is only 8.51 MPa. Figure 3b shows the correlation between the experimental CSP and the calculated CSP based on the Eq. (3). Excellent agreement between the predicated CSP and the experimental value demonstrates the accuracy of the improved predictive model. Finally, the SEP is only 5.91 MPa, much lower than those produced by the single-variable prediction models. The results demonstrate that to a large extent, specific density and moisture content together determine the CSP of bamboo.

Conclusion

In this study, three experimental models for predicting the CSP of bamboo with variable MC and specific density were established and compared. A two-variable model containing both MC and specific density as independent variables was developed, which was capable of accurately predicting longitudinal CSP of Moso bamboo with any combination of specific density and MC, delivering much higher predictive accuracy than that of corresponding single-variable models. The route and method presented in the present study could be extended to the non-destructive prediction of other mechanical properties of bamboo, greatly enhancing potential applications of bamboo-based engineered products in commercial fields.

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