Effect of Waterproofing Treatment on Mechanical Properties of Bamboo

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Longitudinal tensile, longitudinal compressive, and flexural tests of bamboo from different regions were carried out, and the values of strength and elastic modulus were obtained. The probability distribution models of mechanical properties of bamboo in different regions were studied based on the data. The effects of no waterproofing treatment, tung oil treatment, and wood wax oil treatment on mechanical property degradation of bamboo were studied in response to 7 days of soaking. The main conclusions include: the mechanical properties of bamboo produced in Yunnan Province were the highest, followed by Jiangxi Province, and the lowest in Zhejiang Province. The Weibull distribution model achieved a good fit for all mechanical properties. With the increase of soaking time, the mechanical properties of bamboo were degraded. Degradation in the control group was the highest, followed by the wood wax oil group, and tung oil group was the lowest. On the 7th day, the average mechanical properties of the control group had decreased by 32.0%, the tung oil group by 14.5%, and the wood wax oil group by 25.6%. Through comprehensive comparison, it was evident that tung oil treatment provided the best waterproofing effect for bamboo.

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Keywords: Bamboo; Waterproof; Tung oil; Wood wax oil; Mechanical properties; Degradation

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INTRODUCTION

Bamboo is extensively distributed across the globe, with China serving as the epicenter of the world's bamboo resources. It grows rapidly, attaining considerable heights within a brief period, whereas trees frequently require decades, or even centuries, to achieve comparable utility. This rapid growth makes bamboo an ideal renewable material with a much lower ecological impact than traditional wood (Zhou *et al*. 2012; Chen *et al*. 2018; Lin *et al*. 2019; Gauss *et al*. 2020; Skuratov *et al*. 2021). Bamboo is hard, has good toughness and elasticity, and is often used in construction and manufacturing crafts (Tian *et al*. 2019; Shu *et al*. 2020; Wang *et al*. 2020; Garbaya *et al*. 2021; Guan *et al*. 2021). Bamboo also has a strong regenerative capacity and can quickly recover growth after cutting. Therefore, bamboo is often used in modern green buildings. Bamboo structure has an important influence in Chinese history, since it not only plays a role of bearing load but is also an important cultural symbol. Modern bamboo structure architectural design not only pays attention to traditional craft, but also integrates modern architectural technology. This combination not only preserves local culture, but also helps to improve architectural performance. Bamboo effectively absorbs carbon dioxide and releases oxygen as it grows, taking up twice as much carbon as trees in the same area. This characteristic makes bamboo structure building become one of the important means to reduce global warming (Zachariah *et al*. 2016; Pan *et al*. 2020; Xu *et al*. 2022). The use of bamboo structures can reduce the dependence on oil and building materials, thus reducing greenhouse gas emissions. Furthermore, the construction process of bamboo structures is comparatively straightforward, enabling a significant reduction in both the construction timeline and labor costs. Consequently, bamboo structures emerge as a highly suitable option for numerous countries aiming to enhance their housing standards. The development of bamboo structures can also provide jobs for regional residents and promote the development of the local economy. Bamboo planting, harvesting, processing, and other links can promote the development of a series of related industries.

At present, the research on bamboo building materials and bamboo structures mainly includes the material properties of bamboo, the mechanical properties of bamboo components, and the mechanical properties of bamboo joints. Zhao *et al*. (2021) carried out tensile, bending, and combined tension-bending loading tests of bamboo to study the asymmetric deformation and fracture of bamboo under the above loading conditions. Pineda *et al*. (2023) studied the transverse compressive strength and elastic modulus of bamboo from macroscopic and microscopic perspectives. At the macroscopic level, the relationship between strength and elastic modulus and density was explored. At the microscopic level, the changes of cell structure during stress were observed. Li *et al*. (2017) studied the bearing capacity of bamboo pipe members after they were filled with concrete or cement mortar and made a comparative analysis with that of pure bamboo pipe. Zhou *et al*. (2022) carried out flexural performance tests on single and double bamboo pipe beams to study the bearing capacity and failure mode of bamboo beams. Zhou *et al*. (2023) developed a new type of raw bamboo sleeve grouting joint and analyzed the effects of parameters, such as the number of bolts and bonding depth on the bearing capacity of the joint.

The above research shows that bamboo has excellent performance in both material properties and structural mechanical properties. However, many bamboo structure projects show that bamboo is susceptible to deterioration in the presence of moisture, which has a serious impact on the use of bamboo structures. Therefore, in applications that can involve wetting, it is necessary to waterproof bamboo. When bamboo is soaked in water, it will undergo a series of chemical changes as it absorbs water. Bamboo is rich in natural phenolic substances, which are easy to oxidize with oxygen in the air when in contact with water. For example, melanin is formed, which may lead to deterioration of bamboo materials. At the same time, nutrients such as starch and pectin in bamboo, as well as components such as hemicellulose in the cell wall, will gradually degrade or dissolve during boiling or soaking, thus gradually reducing the mechanical properties of bamboo (Kushwaha and Kumar 2011; Chen *et al*. 2019). Tang *et al*. (2022) heated bamboo treated with tung oil, and the results showed that the treatment of tung oil could enhance the hydrophobicity of bamboo. Piao *et al*. (2022) used wood wax oil to impregnate and heat treat bamboo, and the results showed that the hydrophobicity of bamboo impregnated with wood wax oil was significantly enhanced at high temperatures. The above research shows that tung oil and wood wax oil can enhance the hydrophobicity of bamboo. However, high temperature treatment costs are higher. Therefore, bamboo was treated with tung oil and wood wax oil at room temperature in this paper. The main work included: (1) The longitudinal tensile properties, longitudinal compressive properties and bending properties of bamboo in different regions were tested, and the probability distribution model of each mechanical property is analyzed; (2) Water soaking tests were conducted on bamboo treated with different waterproofing measures, and the changes of mechanical properties of bamboo treated with different waterproofing measures with the time of water soaking are explored.

EXPERIMENTAL

Materials

To investigate the effects of different regions and waterproofing measures on the mechanical properties of bamboo, moso bamboo specimens were selected from Zhejiang, Jiangxi and Yunnan provinces of China, and the sampling time was March. To ensure the scientific results of the test, the moso bamboo was selected to ensure that there were no obvious defects, that is, there was no obvious mildew or cracking of the bamboo. In each province, 150 bamboo stalks were selected. In each case, the bottom 5 m were taken for testing, and after cutting, they were transported to the laboratory for air drying treatment for a week. Then, according to JG/T199 (2007) and ISO 22157 (2004), mechanical properties specimens were made and tested. The mechanical properties tested in this test included longitudinal tensile strength (f_t), longitudinal tensile elastic modulus (E_t), longitudinal compressive strength (f_c), longitudinal compressive elastic modulus (E_c), flexural strength (f_m), and flexural elastic modulus (E_m). The size of the longitudinal tensile specimen was 330 mm × 15 mm × t mm (t is the wall thickness), and the effective section size is 60 mm × 4 mm × t mm. The ratio of height to diameter of the longitudinal compressive specimens was 1 ($H/D = 1$), and the size of the flexural specimens was 220 mm × 15 mm × t mm. The number of longitudinal tensile, longitudinal compressive and flexural specimens produced in each region is 400. Specimens were divided into control group, tung oil group, and wood wax oil group. The tung oil and wood wax oil were provided by Xiamen Laisho Technology Co., Ltd. Tung oil group and wood wax oil group are soaked in tung oil and wood wax oil for 24 h, and then soaked in water for a week to analyze the mechanical properties after soaking. The number of specimens in each group tested per day was 3. The effects of different waterproofing measures on mechanical properties of bamboo can be clarified through the above tests.

Tests

Mechanical performance tests were conducted in accordance with standards JG/T199 (2007) and ISO 22157 (2004). For the longitudinal tensile test, clamps were first installed at both ends of the specimen to ensure no looseness or slippage between the bamboo specimen and the clamps, thus guaranteeing the accuracy of the test results. A universal testing machine was used to apply tensile force along the parallel-to-grain direction of the specimen at a uniform increasing rate of 0.01 mm/s. The maximum load-bearing capacity at the point of specimen failure was recorded, and the longitudinal tensile strength of the bamboo was calculated based on the cross-sectional area of the specimen. The longitudinal tensile modulus of elasticity was determined by selecting appropriate data points from the stress-strain curve during the elastic deformation stage and applying Hooke's law. For the longitudinal compressive test, the specimen was first installed on the testing machine, ensuring close contact between the specimen and the machine's contact surface without any looseness or slippage. The load was then applied at a rate of 0.01 mm/s until failure. The calculation methods for longitudinal compressive strength and modulus of elasticity were consistent with those used in the longitudinal tensile test. The four-point bending method was adopted for the bamboo bending test, with a loading rate of 150 N/mm^2 per minute.

Data Processing

The data analysis in this paper adopted the Origin 2021 software (OriginLab, Northampton, MA, USA. The formulas for calculating the longitudinal tensile properties of bamboo were as follows,

$$f_t = \frac{P_{max}}{A} \tag{1}$$

$$E_t = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{2}$$

where f_t is the longitudinal tensile strength of bamboo (MPa), P_{max} is the ultimate load (N), and A is the force area (mm^2). E_t is the longitudinal tensile elastic modulus of bamboo (GPa), $\Delta\sigma$ is the difference of stress corresponding to the upper and lower limits of load in the elastic phase (MPa), and $\Delta\varepsilon$ is the difference of strain corresponding to the upper and lower limits of load in the elastic phase.

The formulas for calculating the longitudinal compressive properties of bamboo were as follows,

$$f_c = \frac{P_{max}}{A} \tag{3}$$

$$E_c = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{4}$$

where f_c is the longitudinal compressive strength of bamboo (MPa), P_{max} is the ultimate load (N), and A is the cross-sectional area (mm^2) that was subjected to the force. E_c is the compressive elastic modulus of bamboo (GPa), $\Delta\sigma$ is the difference of stress (MPa) corresponding to the upper and lower limits of load, and $\Delta\varepsilon$ is the difference of strain corresponding to the upper and lower limits of load.

The formulas for calculating the bending properties of bamboo were as follows,

$$f_m = \frac{150\mathrm{P}_{max}}{th_b^2} \tag{5}$$

$$E_m = \frac{1920000\Delta P}{8\Delta_m t h_b^3} \tag{6}$$

where f_m is the bending strength of bamboo (MPa), P_{max} is the failure load (N), t is the thickness of the specimen (mm), and h_b is the height of the specimen (mm). E_m is the bending elastic modulus of bamboo (MPa), ΔP is the difference between the upper and lower loads (N), Δl is the difference between the deformation values of the specimen under the upper and lower loads (mm), and Δm is the pure deflection value of the specimen under the action of ΔP (mm).

RESULTS AND DISCUSSION

Probability Distribution Model of Mechanical Property Indexes

The mechanical properties of bamboo were statistically analyzed by region, and the results are presented in Table 1. As shown, bamboo exhibited high mechanical properties in the parallel-to-grain direction. The longitudinal tensile strength of bamboo was slightly higher than its bending strength, and both the longitudinal tensile strength and bending strength were approximately twice the longitudinal compressive strength. A comparison of mechanical property values across different provinces reveals that bamboo from Yunnan Province had the highest mechanical properties, followed by Jiangxi Province, with

Zhejiang Province having the lowest. This is mainly attributed to Zhejiang Province's highest rainfall, higher humidity, and consequently, the highest moisture content in bamboo, resulting in the lowest mechanical properties. Figures 1 to 6 illustrate the probability distribution models for various mechanical properties of bamboo, where Normal distribution, Lognormal distribution, and Weibull distribution were used to fit the data. Table 2 presents the Kolmogorov-Smirnov (K-S) test results for the probability distribution models of bamboo’s mechanical properties.

Table 1. Mechanical Properties Statistics of Bamboo

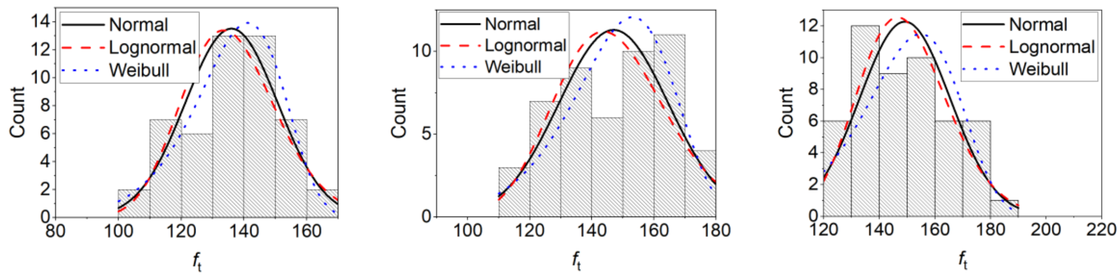
Property Indexes	Number of Specimens	Mean Value			Coefficient of Variation		
		Zhejiang	Jiangxi	Yunnan	Zhejiang	Jiangxi	Yunnan
f_t	50	136.01	146.99	149.19	0.11	0.12	0.11
E_t	50	15.20	16.17	17.52	0.07	0.07	0.07
f_c	50	61.82	65.44	67.74	0.09	0.09	0.08
E_c	50	15.30	15.50	16.78	0.10	0.10	0.09
f_m	50	134.57	135.23	143.84	0.11	0.12	0.12
E_m	50	17.34	18.18	18.97	0.07	0.06	0.06

Table 2. K-S Test Results of Mechanical Properties of Bamboo

Property Indexes	Region	Distribution Model	Statistical Value	*P* value	5% Level Conclusion
f_t	Zhejiang	Normal	0.072	>0.15	Cannot rule out
		Lognormal	0.094	>0.15	
		Weibull	0.065	>0.1	
	Jiangxi	Normal	0.114	0.090	
		Lognormal	0.123	0.059	
		Weibull	0.139	>0.1	
	Yunnan	Normal	0.111	0.125	
		Lognormal	0.109	0.140	
		Weibull	0.102	>0.1	
E_t	Zhejiang	Normal	0.152	<=0.01	Rule out
		Lognormal	0.146	<=0.01	
		Weibull	0.155	>0.1	Cannot rule out
	Jiangxi	Normal	0.121	0.068	
		Lognormal	0.112	0.116	
		Weibull	0.133	>0.1	
	Yunnan	Normal	0.085	>0.15	
		Lognormal	0.088	>0.15	
		Weibull	0.097	>0.1	
f_c	Zhejiang	Normal	0.081	>0.15	
		Lognormal	0.064	>0.15	
		Weibull	0.113	>0.1	
	Jiangxi	Normal	0.124	0.052	
		Lognormal	0.125	0.049	Rule out
		Weibull	0.137	>0.1	Cannot rule out
	Yunnan	Normal	0.143	0.012	Rule out
		Lognormal	0.137	0.028	

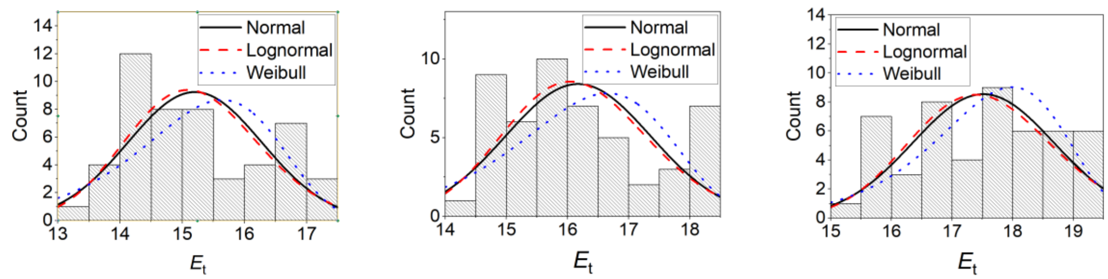
		Weibull	0.146	>0.1	Cannot rule out
E_c	Zhejiang	Normal	0.076	>0.15	
		Lognormal	0.082	>0.15	
		Weibull	0.086	>0.1	
	Jiangxi	Normal	0.146	<=0.01	Rule out
		Lognormal	0.141	0.019	
		Weibull	0.148	>0.1	Cannot rule out
	Yunnan	Normal	0.134	0.034	Rule out
		Lognormal	0.125	0.049	
		Weibull	0.149	>0.1	Cannot rule out
f_m	Zhejiang	Normal	0.091	>0.15	
		Lognormal	0.071	>0.15	
		Weibull	0.119	>0.1	
	Jiangxi	Normal	0.091	>0.15	
		Lognormal	0.100	>0.15	
		Weibull	0.077	>0.1	
	Yunnan	Normal	0.125	0.050	Rule out
		Lognormal	0.114	0.103	Cannot rule out
		Weibull	0.140	>0.1	
E_m	Zhejiang	Normal	0.094	>0.15	
		Lognormal	0.099	>0.15	
		Weibull	0.111	>0.1	
	Jiangxi	Normal	0.094	>0.15	
		Lognormal	0.084	>0.15	
		Weibull	0.146	>0.1	
	Yunnan	Normal	0.085	>0.15	
		Lognormal	0.093	>0.15	
		Weibull	0.063	>0.1	

According to Table 2, all three typical distribution models showed good fitting results for the longitudinal tensile strength of bamboo from all regions, the longitudinal tensile elastic modulus of bamboo from Jiangxi and Yunnan, the longitudinal compressive strength and elastic modulus of bamboo from Zhejiang, the bending strength of bamboo from Zhejiang and Jiangxi, and the bending elastic modulus of bamboo from all regions. For the longitudinal compressive strength of bamboo from Jiangxi and the bending strength of bamboo from Yunnan, there were two distribution models with good fitting results. For the longitudinal tensile elastic modulus of bamboo from Zhejiang, the longitudinal compressive strength of bamboo from Yunnan, and the longitudinal compressive elastic modulus of bamboo from Jiangxi and Yunnan, there was one distribution model with a good fitting result. Among all mechanical properties, the Weibull model achieved good fitting for all indicators.



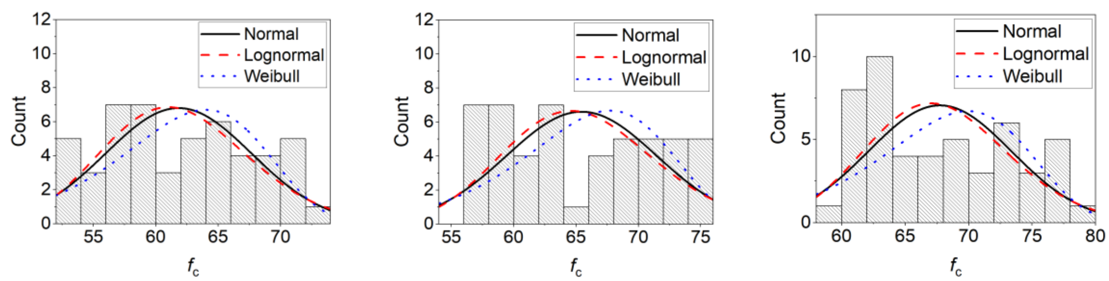
(a) Zhejiang (b) Jiangxi (c) Yunnan

Fig. 1. Distribution of f_t



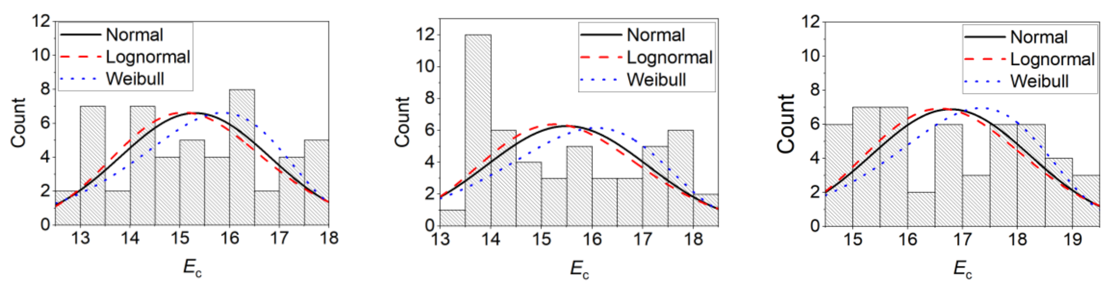
(a) Zhejiang (b) Jiangxi (c) Yunnan

Fig. 2. Distribution of E_t



(a) Zhejiang (b) Jiangxi (c) Yunnan

Fig. 3. Distribution of f_c



(a) Zhejiang (b) Jiangxi (c) Yunnan

Fig. 4. Distribution of E_c

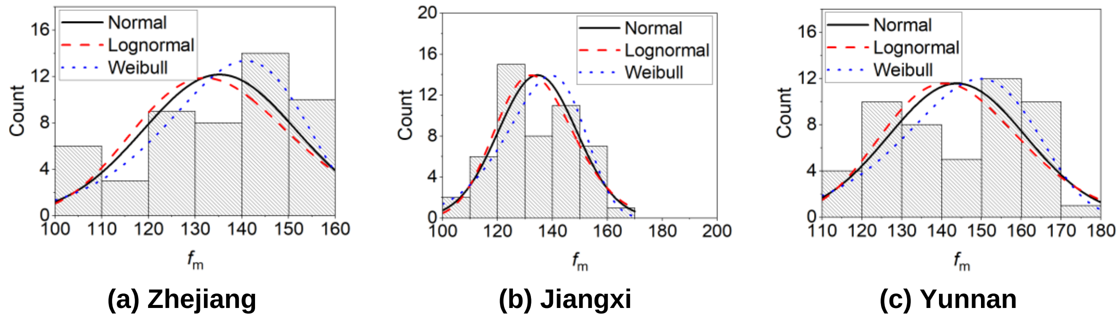


Fig. 5. Distribution of f_m

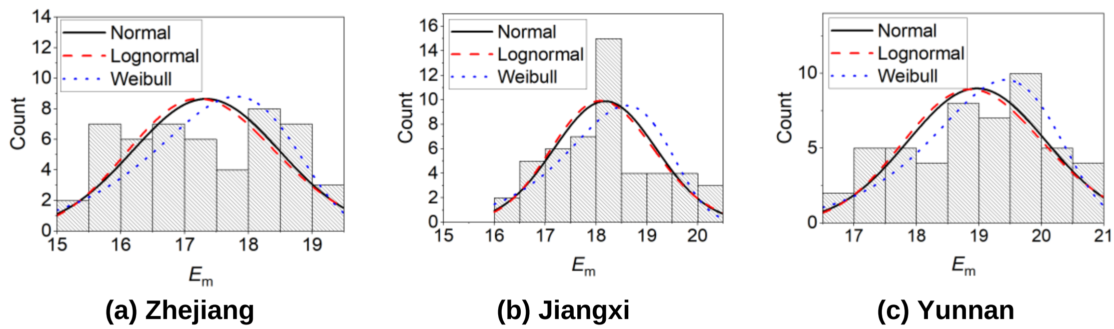


Fig. 6. Distribution of E_m

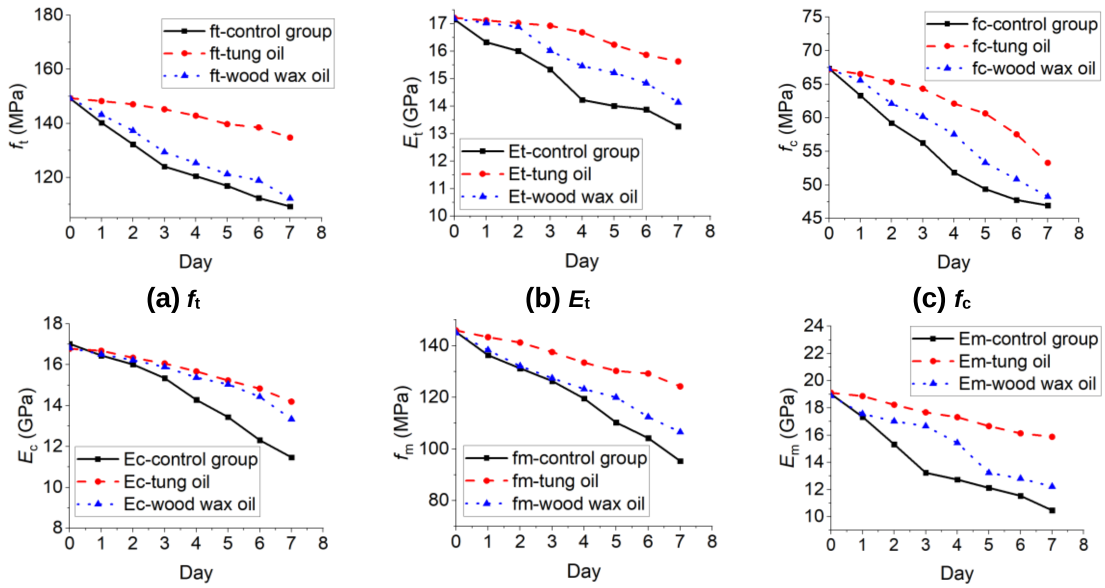
In summary, the mechanical properties of bamboo exhibited significant anisotropy, with large differences between different mechanical properties. There were variations in the mechanical properties of bamboo produced in different regions. The Weibull distribution model provided good fitting for different mechanical properties of bamboo from various regions.

Changes of Mechanical Properties with Time

The specimens were divided into control group, tung oil group, and wood wax oil group to explore the effects of different waterproofing treatments on the mechanical properties of bamboo. This test was conducted for bamboo produced in Yunnan province. The specimens were soaked in water and the mechanical properties were tested once a day, with a test period of 7 days.

Figure 7 shows the change of mechanical properties over time. As the soaking time increased, all mechanical properties exhibited a decline, indicating a deterioration in the mechanical characteristics of bamboo due to an elevation in its water content. Comparing the change law of different groups of specimens, the performance degradation degree of the control group was the highest, followed by the wood wax oil group, and the tung oil group was the lowest.

Through the above analysis, without any treatment of bamboo, the mechanical properties of bamboo will be degraded greatly over the course of time after immersion. The treatment of bamboo with tung oil and wood wax oil can play a certain role in slowing down the decline of mechanical properties, especially the waterproof effect of using tung oil treatment is the most obvious.



(a) f_t (b) E_t (c) f_c

(d) E_c (e) f_m (f) E_m

Fig. 7. Changes of mechanical properties with time after immersion

Parameter Analysis

The results shown in Fig. 8 were obtained by comparing the initial mechanical properties of bamboo with those on the 7th day. As can be seen from Fig. 8, compared with the initial state, the mechanical properties of bamboo after soaking in water all decreased to a great extent. The mechanical properties of the control group decreased the most, and those of the tung oil group the least. Taking the longitudinal tensile strength as an example, after 7 days of soaking, the strength value of control group decreased 26.8%, the strength value of tung oil group decreased 9.8%, and the strength value of wood wax oil group decreased 24.8%. The above results showed that the mechanical properties of bamboo without waterproofing treatment will decrease greatly, which is unfavorable for engineering applications. Using tung oil or wood wax oil to treat bamboo can slow down the decrease of mechanical properties to a certain extent. The waterproofing effect of bamboo treated with tung oil was obvious. Based on a comprehensive analysis, the average mechanical properties of bamboo in the control group decreased 32.0%, while those in the tung oil group decreased 14.5%, and the wood wax oil group decreased 25.6%. In conclusion, this paper recommends using tung oil for waterproofing treatment of bamboo. This measure is of great significance for the engineering application of bamboo products and bamboo structures.

Tung oil mainly contains the unsaturated fatty acid α-eleostearic acid (accounting for 77% to 82%). The highly unsaturated conjugated system is expected to facilitate rapid oxidative polymerization of tung oil, forming a dense protective film. This film exhibits excellent dynamic mechanical properties and thermal stability at room temperature, effectively blocking moisture intrusion (He *et al*. 2022). When tung oil is applied to the surface of bamboo, it penetrates the bamboo material, fills the intercellular spaces, and rapidly oxidizes and polymerizes in the presence of oxygen. During this process, tung oil not only interacts with components, such as lignin, on the bamboo surface but it also forms a stable oil film within the bamboo material, thereby enhancing its waterproof performance. The waterproof mechanism of tung oil on bamboo is primarily achieved through the waterproof characteristics of its components, penetration, and curing effects, as well as the improvement of bamboo's microstructure. These effects collectively enhance the waterproof performance of bamboo, enabling it to maintain stability and durability in humid environments.

Based on its composition, tung oil contains natural anti-degradative components. When applied on the surface of an object, it can form a waterproof film, which can effectively prevent water penetration, so it is particularly suitable for outdoor bamboo building waterproof treatment. Wood wax oil is a natural plant extracted wiping agent, mainly composed of refined linseed oil, palm wax, and other natural vegetable oils and plant wax. Although it can also penetrate the inside of the bamboo, forming a protective film to waterproof, the waterproofing effect of painting wood wax oil on bamboo was less effective than that of painting with tung oil.

Through this study, it can be found that the use of tung oil and wood wax oil can play a role in the waterproofing of bamboo, and the waterproofing effect of tung oil was particularly significant. In future research, it is still necessary to explore more reasonable treatment methods of tung oil in order to achieve the purpose of low cost and waterproof performance.

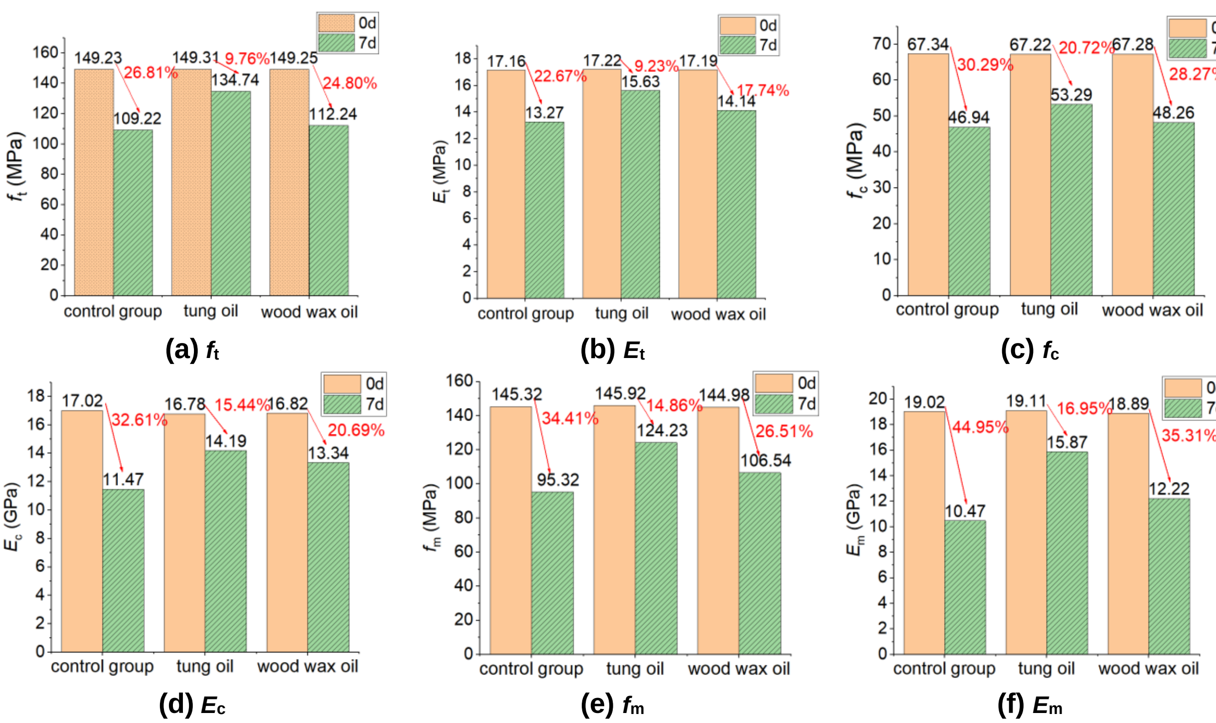


Fig. 8. Comparison of mechanical properties

CONCLUSIONS

1. Comparing the mechanical properties of bamboo in different provinces, it was found that the mechanical properties of bamboo in Yunnan Province were the strongest, followed by Jiangxi Province and Zhejiang province.
2. After being soaked in water for 7 days, the mechanical properties of bamboo treated by different methods all decreased. The control group experienced the greatest decline, followed by the wood wax oil group, with the tung oil group showing the smallest

decline. The average decrease in mechanical properties for the control group was 32.0%, for the tung oil group it was 14.5%, and for the wood wax oil group it was 25.6%. Therefore, it is recommended to use tung oil for the waterproof treatment of bamboo.

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