SENSITIVITY OF SEVERAL SELECTED MECHANICAL PROPERTIES OF MOSO BAMBOO TO MOISTURE CONTENT CHANGE UNDER THE FIBRE SATURATION POINT

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The moisture dependence of different mechanical properties of bamboo has not been fully understood. In this work, the longitudinal tensile modulus, bending modulus, and compressive and shearing strength parallel to the grain were determined for bamboo of ages 0.5, 1.5, 2.5, and 4.5 years under different moisture contents (MC) to elucidate the sensitivity of different mechanical properties of bamboo to MC change. The results showed that the four mechanical properties of bamboo respond differently to MC changes. Compressive and shearing strength parallel to the grain were most sensitive to MC changes, followed by longitudinal tensile modulus, then bending modulus. This can be partially explained by the different responses of the three main components in the plant cell wall to MC change. For tensile modulus and bending modulus, the effect of bamboo age on the sensitivity to MC change was insignificant, while young bamboo (0.5 years old) was more sensitive to MC changes for shear strength and less sensitive for compression strength than older bamboo.

Keywords: Bamboo; Mechanical properties; Moisture dependence; Specific density

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INTRODUCTION

Water exists in plant material during the plant's entire life cycle from growth, to processing, to application. For wood and wood-based products, the relationship between mechanical properties and moisture content (MC) is important for quality control and product applications. For the past decades, considerable research has been performed on water in wood and its relevance to physical and mechanics properties (Green *et al.* 1986; Hernandez 1993; Kretschmann and Green 1996; Wang *et al.* 1999; Kojima and Yamamoto 2004; Liu and Zhao 2004; Esteban *et al*. 2005; Green *et al.* 2007). At a MC from oven-dry to the so-called fiber saturation point (FSP), bound or adsorbed water accumulates in the wood cell wall. Above the FSP, free water accumulates in the cell cavity (Hallwood and Horrobin 1946). It is well known that a decrease in moisture content below the FSP significantly influences the mechanical properties of the wood, whereas above the FSP, variations in moisture content have very little effect. Furthermore, it has been further revealed that different mechanical properties of wood have different sensitivities to a change in MC (Green *et al.* 1999; Ishimaru *et al.* 2001; Sudijono *et al.* 2004). Specifically, data in the *United States Wood Handbook* indicates that the longitudinal tensile strength of wood decreases 16.7% from an air-dried state (MC 12%) to a saturated state; other properties that decrease include bending modulus

(23.7%), shearing strength parallel to the grain (30.0%), and compressive strength parallel to the grain (42.5%).

Bamboo is one of the most important non-wood forest resources in the world, growing faster than almost all other tree species on earth. As a plant material, bamboo is also hygroscopic, meaning that it gains or loses water to equilibrate with its environment (Hui and Yang 1998; Anwar *et al*. 2005; Hamdan *et al*. 2007). Although the effect of MC on the mechanical properties of bamboo might be similar to wood in general (Zhou 1998), the specific relationship might be somewhat different, since significant differences in chemical composition and microstructure exist between bamboo and wood. Knowledge of the bamboo-water relationship is necessary because it influences physical and mechanics properties. These properties decrease as bamboo adsorbs moisture in the hygroscopic range (Janssen 1981). This study is part of a program aimed to better understand the effect of MC on the mechanical properties of bamboo. In this research, the effect of MC (from oven-dry to FSP) on four selected mechanical properties (namely longitudinal tensile modulus, bending modulus of elasticity, shear strength parallel to the grain, and longitudinal compression strength) of bamboo, ages 0.5, 1.5, 2.5, and 4.5 years was investigated in order to reveal the different sensitivities of the various aged bamboo to changes in MC on the selected mechanical properties.

MATERIALS AND METHODS

Sample Preparation

Moso bamboo plants (*Phyllostachys pubescens* Mazei ex H. de Lebaie) of ages 0.5, 1.5, 2.5, and 4.5 years were collected from a bamboo plantation located in Zhejiang Province, China. Thirty two bamboo culms were cut down in total with eight culms for each age. All the samples for mechanical testing were cut from 15 to 25 internodes and prepared according to a Chinese national standard for bamboo (GB/T 15780-1995). The specific dimensions of the samples were as follows: 20 (L)×20 (T)×t (thickness of bamboo culm wall) for compression strength parallel to the grain; 160 (L)×10 (T)×t (thickness of culm wall) for three point bending modulus. The specific shape and size of the samples for longitudinal tensile modulus and shear strength parallel to the grain are shown in Fig. 1. All the samples were air-dried in the lab environment for more than six months before moisture conditioning.

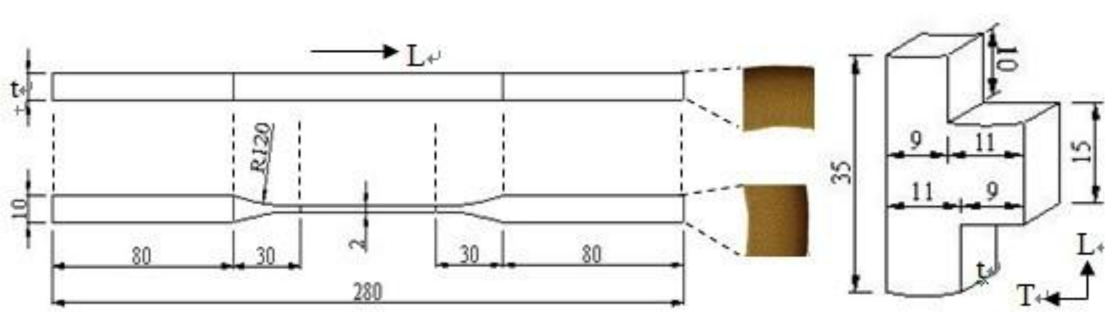


Fig. 1. The specific shape and size of the two kinds of samples: Longitudinal tensile (Left) and shear strength parallel to grain (Right)

Moisture Conditioning

All the air-dried mechanical samples were randomly divided into nine groups for moisture conditioning. Each of the four groups (one group for each age group) contained 20 samples for compressive strength, 16 samples for longitudinal tensile modulus, 16 samples for bending modulus, and 12 samples for shear strength. The samples with a MC less than the FSP were conditioned in desiccators containing the different aqueous saturated sale solutions listed in Table 1.

Table 1. Relative Humidity (RH) Levels in the Experiments and the Corresponding Equilibrium Moisture Contents (EMC)

NO.	RH, Average (%)	EMC, Average (%)	Chemicals for Conditioning
A	2.9	0.5	Silica Gel
B	12.5	4.7	LiCl
C	37.1	5.5	$MgCl_2$
D	53.9	7.1	K_2CO_3
E	68.7	11.8	NaBr
F	74.1	12.5	NaCl
G	88.9	16.3	KCl
H	100	30.5	Watersoaking
I	100	50.9	Watersoaking

The desiccators were put in the lab with a constant temperature of 20 ^{o}C for at least one month. Relative humidity (RH) in the desiccators was measured with a hygrothermograph (TESTO 608-H1) placed in the containers. The actual EMC of each sample was measured by weighing after conditioning. The EMC above FSP were achieved by water soaking.

Measurement of Mechanical Properties

Mechanical testing was conducted according to a Chinese National Standard for bamboo (GB/T 15780-1995). A universal mechanical tester (5582, Instron Co. USA) was used for both three point bending and tensile testing. The span for the bending test was 120 mm, and the loading speed was 4 mm/min. A noncontact video extensometer was used for measuring tensile strain during tensile testing. The tensile speed was set at 1.5 mm/min. Compressive strength parallel to the grain and shear strength parallel to the grain were tested by another mechanical tester (WDW-E100D, JINANSHIJIN Co. China) because the 5582 mechanical tester was not equipped with the needed standard grips.

RESULTS AND DISCUSSION

Mechanical Properties of Bamboo under Different MC

To a large extent, the general relationship between MC and mechanical properties of bamboo is similar to that of wood, but some specific differences still exist due to the different structures and chemical compositions between them. Tensile modulus, bending modulus, shear strength parallel to the grain, and compression strength parallel to the grain of bamboo plotted against MC are respectively shown in Figs. 2A to 2D. Figure 2A shows the effect of MC on the longitudinal tensile modulus of bamboo of different ages (0.5, 1.5, 2.5, and 4.5 years). A general decreasing trend with an increasing MC can be easily observed; however, there seems to be a plateau from a MC of 10% to 15%, followed by a continuing decrease with rising MC until the FSP. For the bending modulus, a general decreasing trend with rising MC from nearly zero to the water saturation was also observed (Fig. 2B). The bending modulus of 0.5- and 1.5-year-old bamboos at a MC of 5% and 6%, however, was abnormally higher than the value measured at a nearly zero MC, which might be attributed to the inherent sample variation between groups since the bamboo that was 2.5 and 4.5 years old did not show similar behavior. The relationship between MC and shear strength parallel to the grain of the four ages of bamboo are shown in Fig. 2C. An initial reduction in the early stage of moisture increasing can be observed, followed by a rise to the maximum value at a MC of 8% and 9%. The shear strength then decreased again with increasing MC to FSP. For compressive strength parallel to grain (Fig. 2D), a stable and more linear decreasing trend was obtained with MC increasing to 20% for the 1.5-, 2.5-, and 4.5-year-old bamboos, and 25% for the bamboo of 0.5 years old; however, an unexpected, small but stable increase when MC was about 25% or more was repeatedly observed for the bamboo of all ages, which has not been previously reported and no explanations can be presently proposed.

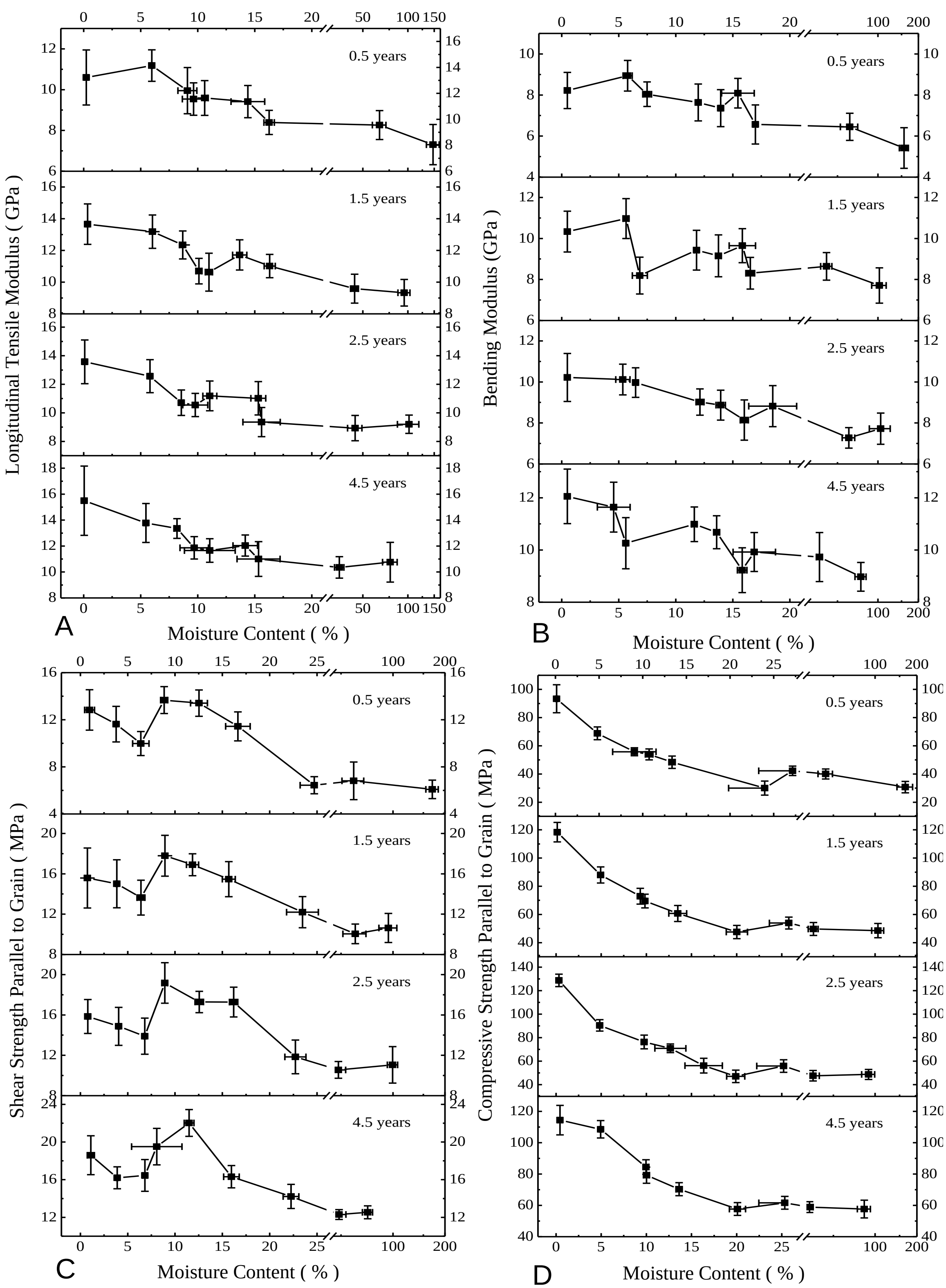
Sensitivity to MC Change of Different Mechanical Properties of Bamboo

In order to get a quantitative relationship between the four mechanical properties of bamboo and MC for practical application, a linear fit was performed on the data involving the four ages (Fig. 3). The values of mechanical properties at the FSP are actually the average of the two values measured at water saturation presented in Fig. 2. Here oven-dry has not been selected as the start point of low MC only because such low MC is seldom encountered in practical applications; therefore, the ranges of variation of MC of longitudinal tensile modulus, bending modulus, shear strength parallel to the grain, and compressive strength parallel to the grain were approximately 5.5%, 5.5%, 8%, and 5% at the FSP, respectively. FSP was obtained by extrapolation from the adsorption isotherm (Stamm 1964; Martins 1992; Hamdan *et al*. 2007). A previous study found that the FSP of Moso bamboo is related to its age (Wang *et al.* 2010).

For the 0.5-year-old bamboo, the FSP was about 28%, while the bamboo of ages 1.5, 2.5, and 4.5 years had nearly the same FSP at 23%. From the obtained four linear equations, it can be inferred that a 1% MC change would result in an increase or decrease of 0.17 GPa for tensile modulus, 0.15 GPa for bending modulus, 0.52 MPa for shear strength, and 2.50 MPa for compression strength.

In order to further compare the sensitivities of the four properties to MC change, a reference value must be obtained in advance. Here, the properties at MC 12% were selected as the reference value, which can be calculated according to the above four equations. The moisture sensitivity K, namely the change rate of the properties per 1% MC change, can then be defined by the ratio between the slope of the linear equations and the properties at 12% MC (P_{12}) according to Eqn. (1). The calculation result is shown in Fig. 4.

$$\mathrm{K} = 100\% \times \frac{Slope}{P_{12}} \tag{1}$$



Figs. 2A - D. Longitudinal tensile modulus (2A), bending modulus (2B), shear strength parallel to grain (2C), and compressive strength parallel to grain (2D) of four aged bamboos measured under different RH and in water

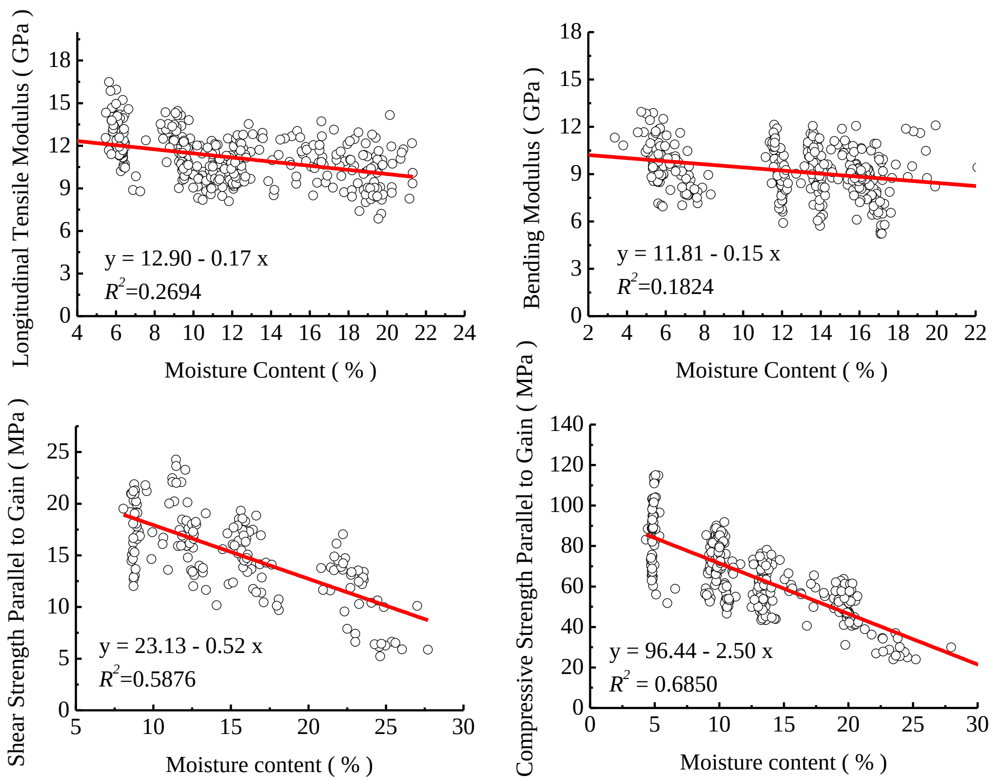


Fig. 3. The relation model of moisture content and mechanical properties

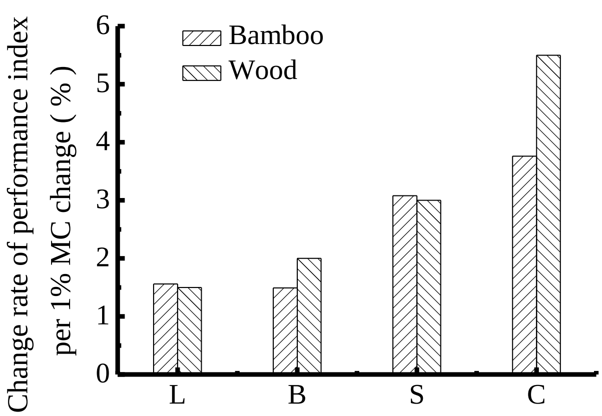


Fig. 4. The change rate of mechanical properties per 1% MC change; L: Longitudinal tensile modulus; B: Bending modulus; S: Shear strength parallel to the grain; C: Compression strength parallel to the grain
The data of performance index for wood comes from the book "Science and technology of wood" (Tsoumis 1991)

Figure 4 indicates that the bending modulus exhibits the smallest sensitivity to MC change by having a *K* value of 1.49%, followed by longitudinal tensile modulus with 1.56%, shear strength parallel to the grain with 3.08%, and compression strength parallel to the grain with 3.76%. The bending modulus and tensile modulus showed much less sensitivity to MC change than shear strength and compression strength, which can be partially explained by the different responses to MC change of the three main components (cellulose, hemicelluloses, and lignin) in the plant cell wall. The mechanical properties of the lignin/hemicelluloses matrix have been experimentally (Cousins 1976, 1978) and theoretically (Sakurada *et al.* 1962; Koponen *et al.* 1989) proven to be much more sensitive to MC changes than cellulose. In the process of shear and compression testing, the hemicellulose/lignin matrix gives considerable contribution to the final failure, while for the stiffness measurement both in the tensile and bending modes, cellulose undoubtedly dominates the whole process.

Although bamboo belongs to the class of lignocellulosic materials, its mechanical responses to MC change show some differences from wood. The sensitivity of bending modulus to MC change in bamboo is slightly less than that of tensile modulus, while the former is higher than the latter for wood; meanwhile the sensitivity of shear strength to MC change in bamboo is nearly wood; however compression strength is significantly less than that of wood. Such differences seem to be incapable of being explained by the chemical differences between the two types of material, and is more likely attributable to the two-phase composite structure of bamboo with much softer parenchymal cells embedded in much stiffer fiber bundles.

It is assumed that the increase of MC tended to weaken the interfacial bonding between parenchymal cells and fibers, resulting in extra internal slipping and reduced stiffness. Compared with wood, bamboo was less sensitive to MC changes when considering bending modulus and compression strength. However it was comparable or slightly more sensitive when considering tensile modulus and shear strength. This suggests that some mechanical properties of bamboo are better than wood in resisting a change in environmental humidity.

The Effect of Age on the Sensitivity to MC Change of Different Mechanical Properties of Bamboo

In order to further investigate the effect of age on the moisture dependence of different mechanical properties of bamboo, a linear fitting was performed for the MC range of 5.5% (or 8% for shear strength) to the FSP (Fig. 5). From the obtained linear equations, it could be inferred that the mechanical properties of 0.5-year-old bamboo normally had smaller changes in absolute value than older bamboo per 1% MC change. No significant difference was found, however, among bamboo of ages 1.5, 2.5, and 4.5 years in general. Similarly, for further comparison of the different sensitivities that various aged bamboo has to MC change, the K values of bamboos were calculated according to the approach adopted in the previous section. The results were plotted in Fig. 6.

It seemed that the age of the bamboo had little effect on the K value of the tensile modulus and the bending modulus. The K value of the shear strength of 0.5 year-old bamboo, however, was a little higher than that of mature bamboo of 1.5 to 4.5 years old, which means young bamboo may be more sensitive to MC change in shear strength. For compression strength, the K value of bamboo of 0.5 years old was significantly lower than that of bamboo 1.5 to 4.5 years old, which indicates young bamboo may be less sensitive to MC change in compression strength. The reason as to why different mechanical properties of bamboo of different ages respond differently to MC change needs to be further explored from the standpoint of both its microstructure and chemical composition.

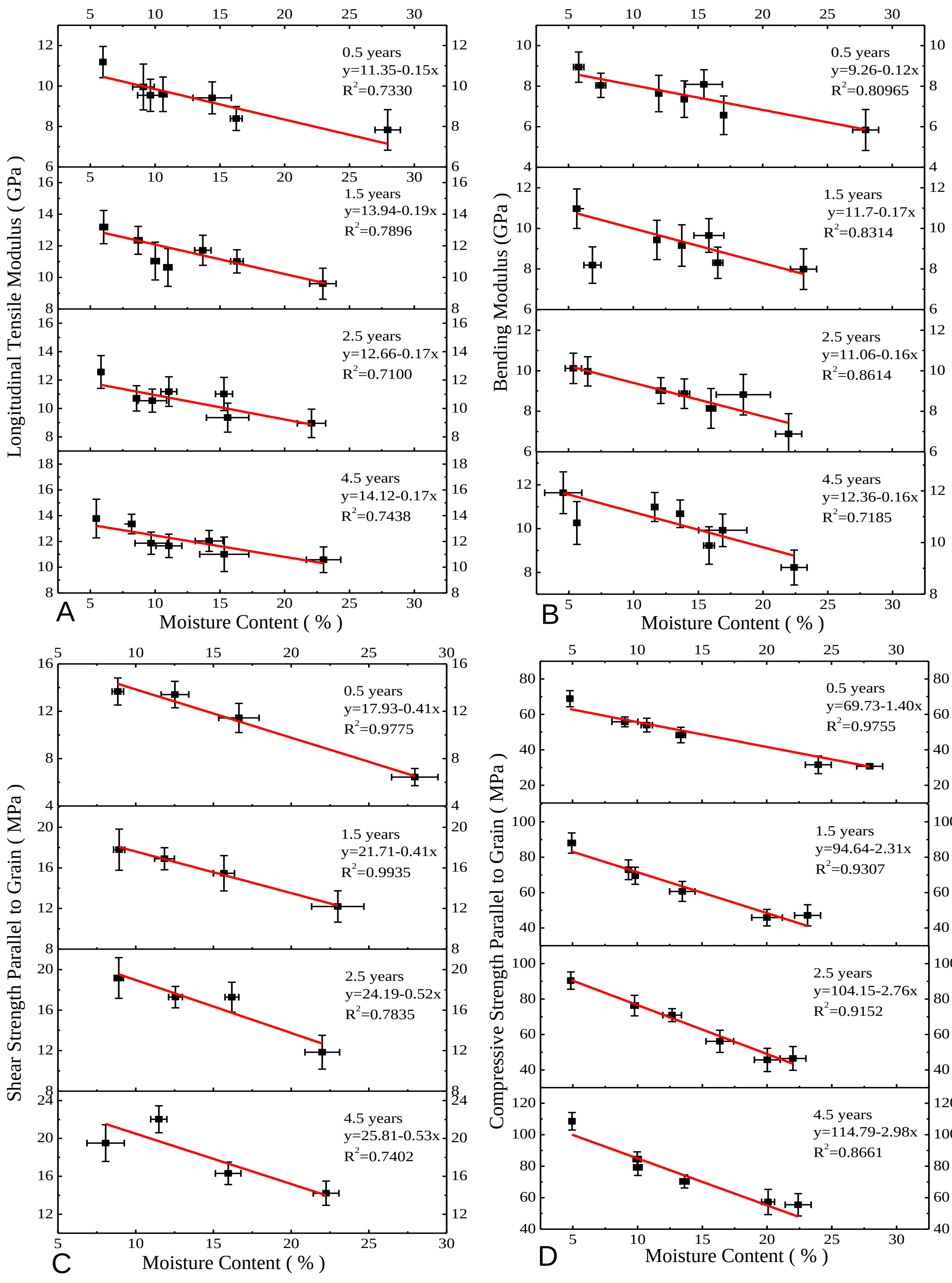


Fig. 5. Correlation between the four mechanical properties and moisture content. A: longitudinal tensile modulus; B: bending modulus; C:shear strength; D:compressive strength

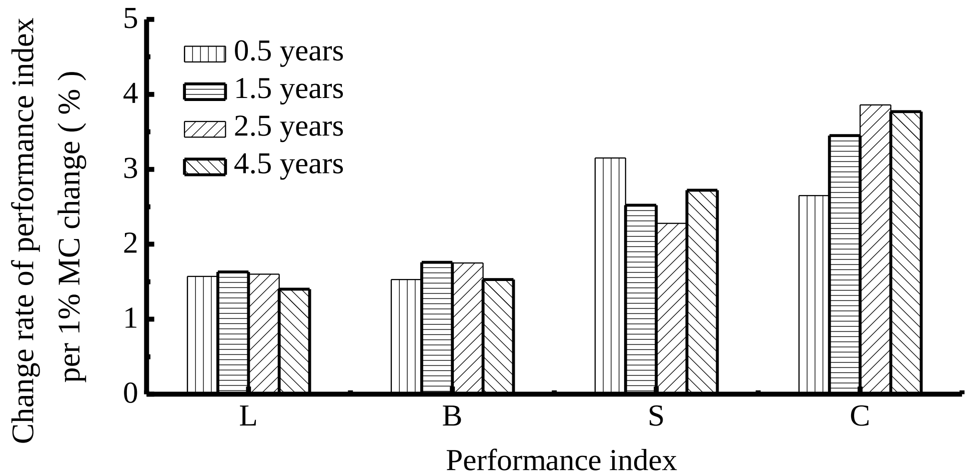


Fig. 6. The change rate of different mechanical properties per 1% MC change under different ages of bamboo; L: Longitudinal tensile modulus; B: Bending modulus; S: Shear strength parallel to the grain; C: Compression strength parallel to the grain

CONCLUSIONS

The results of combined investigation of four mechanical properties of bamboo under different moisture content (MC) permit the following conclusions:

Four mechanical properties of bamboo exhibited different sensitivities to MC change. Compressive and shearing strength parallel to the grain were most significantly affected by MC, followed by longitudinal tensile modulus and then bending modulus. Age has little effect on the sensitivity of the tensile modulus and bending modulus to MC change, while young bamboo was more sensitive to MC change for shear strength and less sensitive for compression strength.

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