Effects of Moisture Content and Fiber Proportion on Stress Wave Velocity in Cathay Poplar (*Populus cathayana*) Wood

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Changes in longitudinal stress wave velocity measured during the drying process of Cathay poplar (*Populus cathayana*) wood at different moisture contents were investigated. The test was performed at five different positions from bark to pith on each part. Five bars, cut successively from bark to pith with different fiber proportions, were also tested. The corrected velocity was calculated by dividing the velocity by the fiber proportion to negate any possible effects of wood structure on the velocity. The results showed that the longitudinal stress wave velocity decreased with increasing moisture content. Such trends were more obvious when the moisture content was lower than the fiber saturation point (FSP). The longitudinal stress wave velocity increased with increasing fiber proportion. A linear relationship between the corrected velocity and the moisture content was observed. This linear relationship was similar to the relationship between the relative velocity and the moisture content.

Keywords: Stress wave velocity; Moisture content; Fiber proportion; Cathay poplar

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INTRODUCTION

Stress waves are an important nondestructive tool for evaluating the quality and elasticity modulus of wood (Garcia *et al*. 2012; Morrow *et al*. 2013). Stress waves have also been used to determine the moisture content of wood for many years. It has been reported that the stress wave velocity decreases with increasing moisture content (Sandoz 1993; Ilic 2001; Wang *et al*. 2002; Gonçalves and da Costa 2008). When the moisture content is lower than the fiber saturation point, the stress wave velocity rapidly decreases with the moisture content. When the moisture content is higher than the fiber saturation point, the stress wave velocity gradually decreases with moisture content (Kabir *et al*. 1998; Kang and Booker 2002; Oliveira *et al*. 2005). Further, a constant increase in the stress wave velocity with the decreasing moisture content from initial to oven-dry was also observed by Simpson and Wang (2001).

In recent years, some researchers have used stress wave measurements to investigate variations in moisture content during the wood drying process. Cruz *et al.* studied the stress wave velocity using two types of *Eucalyptus* (Cruz *et al*. 2009). They found a nonlinear relationship between the stress wave velocity and moisture content. Very recently, Lee *et al.* reported linear dependencies of the stress wave velocity on moisture content when it is lower or higher than the fiber saturation point. They achieved this by evaluating changes in moisture content in Taiwan red cypress with ultrasonic and tap-tone testing (Lee *et al*. 2011).

However, variation of the stress wave velocity at a constant moisture content at the different test positions within the same wood species has received little attention. Previous studies have reported that the stress wave velocity varies widely in such comparisons (Simpson and Wang 2001; Oliveira *et al*. 2005). At a moisture content of 40%, a difference in stress wave velocity of up to 35% was found in specimens of sugar maple. These differences seriously affect the use of the correlation between stress wave velocity and moisture content for kiln control (Simpson and Wang 2001).

In this study, the longitudinal stress wave velocity of Cathay poplar (*Populus cathayana*) at different moisture contents and test positions during the wood drying process was studied. Fiber proportion was calculated and used as a correction factor to prevent non-uniform wood tissue structure from affecting the stress wave velocity. The results from this study give theoretical guidance for the application of wave stress measurements in industry during the wood drying process.

EXPERIMENTAL

Materials

Cathay poplar (*Populus cathayana*) was obtained from Beijing Longshun Wood Sales Department, Beijing, China. Samples were selected that were free of decay and knots and were cut into 3 parts with dimensions of 500 mm × 130 mm × 20 mm (length × width × thickness) and 5 bars with dimensions of 500 mm × 20 mm × 20 mm (length × width × thickness). The test bars were numbered Bar 1 through 5, from bark to pith. The initial moisture content of the samples was 100 to 120% based on dry weight. During the experiments, two sides of each specimen were sealed with epoxy resin and aluminum foil to prevent evaporation.

Stress Wave Velocity Measurement

Five test positions were selected at the center of the transverse surfaces on each of the parts, at intervals of 25 mm as shown in Fig. 1. A pin was fixed onto each test position. The pins were numbered No. 1 through 5, from bark to pith, on each test part.

A commercial stress wave detector (ARBOTOM, Frank Rinn, Germany) was used to measure the stress wave velocity. The sensor pins were fixed on opposite sides of each specimen. The sensors were attached at the pins. After striking the sensors on one side, the transmitted stress wave was detected by the sensors on the other side of each specimen. The measurements were done in fiber direction.

The stress wave velocity was calculated based on the distance between the two sensor pins on the sides of the specimen using the equation,

$$V = \frac{L}{T} \tag{1}$$

where V is the longitudinal stress wave velocity (m/s), L is the distance between the two sensor pins on the opposite sides (m), and T is the time a pulse takes to travel through the specimen (s).

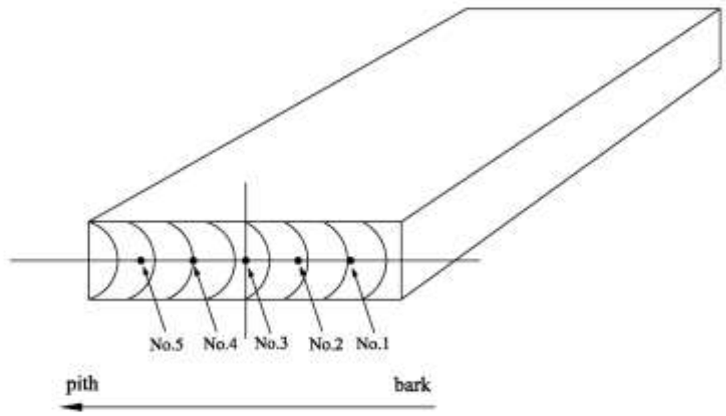

Fig. 1. Illustration of the configuration of test positions on each test part

A 420-mm-long guide rail (V shape) was attached to the test part and tilted by 30 degrees. A steel ball with a diameter of 17.5 mm was released from the top of the guide rail. It rolled down the guide rail and struck the sensors. The equipment for stress wave testing is shown in Fig. 2. Each measurement was replicated 16 times. All measurements were conducted at room temperature. The drying schedules are described in Table 1.

Fig. 2. Experimental set-up for stress wave velocity measurements

Table 1. Kiln Schedules during Drying

Moisture content (%)	Dry-bulb temperature (°C)	Wet-bulb temperature (°C)
＞30	50	46
25 to 30	56	47
20 to 25	60	48
15 to 20	66	48
＜15	74	50

Moisture Content Measurement

During the experiments, the nominal moisture contents of the samples were estimated using the original measurements taken by the moisture meter. Only at the end of the experiments, after the samples were oven-dried at 103 °C, could their true moisture contents at any moment in the experiment be determined (Chan *et al*. 2011).

The true moisture content was calculated according to the following equation,

$$MC = \frac{m_2 - m_1}{m_1} \times 100 \tag{2}$$

where MC is the true moisture content of the sample (%), m_2 is the actual weight of the sample at a certain stage of the experiment (g), and m_1 is the oven dry weight of the sample (g).

Tissue Proportion Measurement

A small block with dimensions of 20 mm × 10 mm × 10 mm was cut from each oven-dried testing bar. The blocks were softened for sectioning. A slice with a thickness of 10 μm was cut off using a sliding microtome (860, American) and immersed in 1% safranine of alcohol solution for 2 h for staining. Next, the slices were successively dehydrated with alcohol solutions of 50%, 70%, 85%, 95%, and 100%. The samples were dipped into xylene and cemented with neutral gum. The tissue proportions of these samples were tested using an Olympus BH-2 optical microscope. The proportions of vessel elements, wood fibers, wood rays, and parenchyma were measured using a microscopic image analysis system according to conventional quantitative anatomy testing methods for wood (Xi and Zhao 2011). The tissue proportions were measured 20 times for each test bar.

The wood fiber proportion was calculated according to the following equation,

$$FP = 100 - VP - RP - PP \tag{3}$$

where FP is the wood fiber proportion of the sample (%), VP is the vessel proportion of the sample (%), RP is the wood ray proportion of the sample (%), and PP is the parenchyma proportion of the sample (%).

RESULTS AND DISCUSSION

Variations in Stress Wave Velocity with Different Measurement Positions and Moisture Contents

The changes in stress wave velocity as functions of the moisture contents of the tested parts, measured at different positions, are plotted in Figs. 3, 4, and 5.

During the drying process, the velocity of the stress wave increased with decreasing moisture content, a result consistent with those previously reported (Kang and Booker 2002; Oliveira *et al*. 2005; Gonçalves and da Costa 2008). In the case of part 3 (Fig. 5), the stress wave velocity was approximately 3500 m/s at test position No. 5 at the initial moisture content. It increased to around 6200 m/s after the part was oven-dried, which is 1.7 times more than that at the initial moisture content. The stress wave velocity decreased rapidly with increasing moisture content when the moisture content of the part was less than 30%. In contrast, the stress wave velocity decreased gradually with increasing moisture content when the moisture content of the part was greater than 30%. This phenomenon occurred because the properties of wood change when the moisture content is lower than the fiber saturation point (He *et al*. 2013).

It can be seen from Figs. 3, 4, and 5 that the stress wave velocity varied at constant moisture content when tested at different positions on a part. In the case of part 1 (Fig. 3), the stress wave velocity was approximately 4000 m/s at test position No. 1 at a moisture content of 20%, while it was around 5000 m/s at test position 5. This was a difference of about 20%, based on the larger of the two velocities. The stress wave velocity was larger near the pith than it was close to the bark.

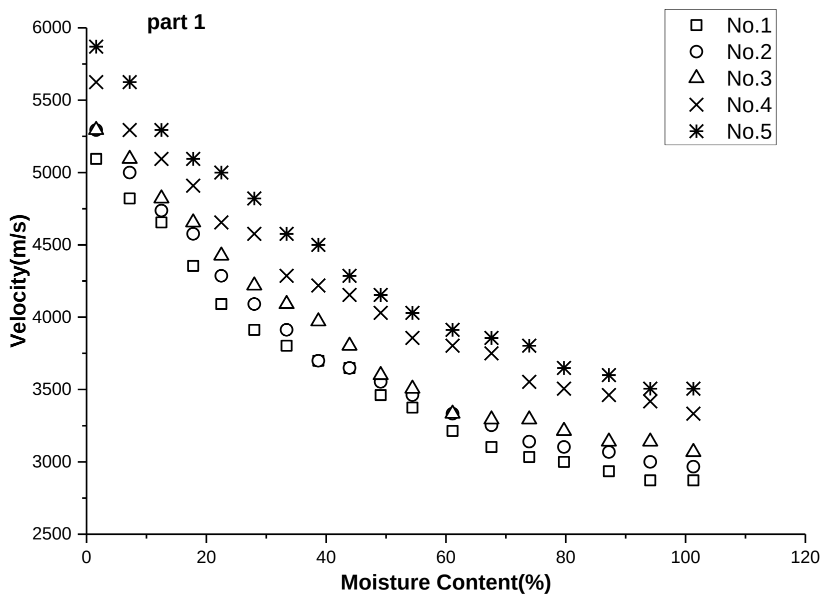

Fig. 3. Longitudinal velocities at different test positions of part 1 at different moisture contents

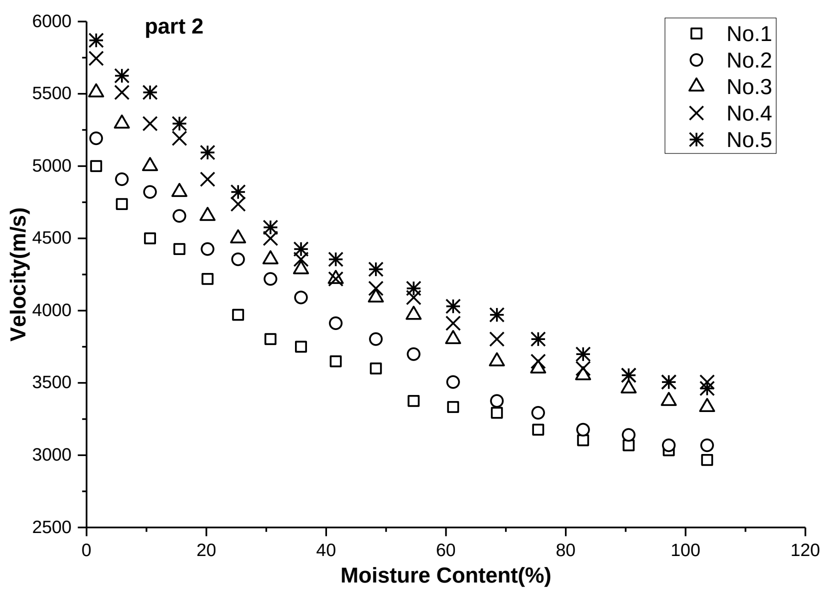

Fig. 4. Longitudinal velocities at different test positions of part 2 at different moisture contents

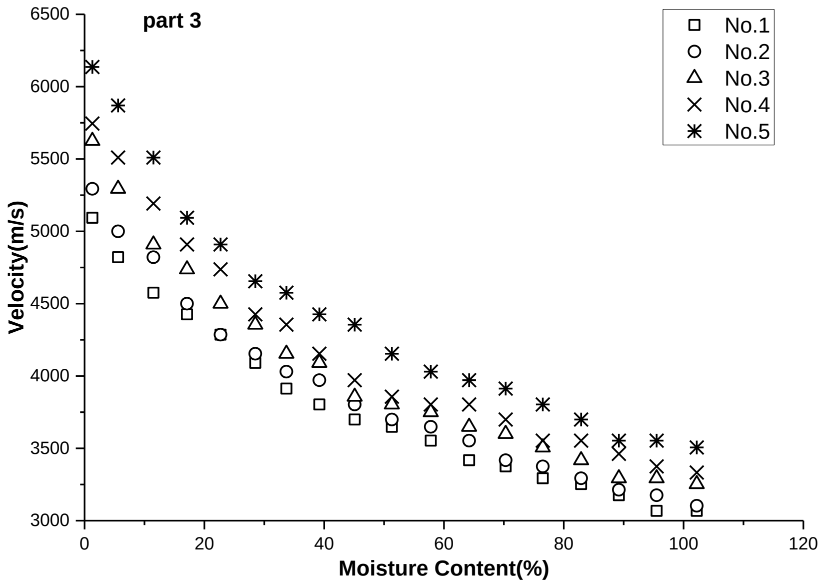

Fig. 5. Longitudinal velocities at different test positions of part 3 at different moisture contents

Effects of Moisture Contents on Stress Wave Velocity

Figure 6 shows the stress wave velocity as a function of moisture content measured on test bars made from different parts of the wood.

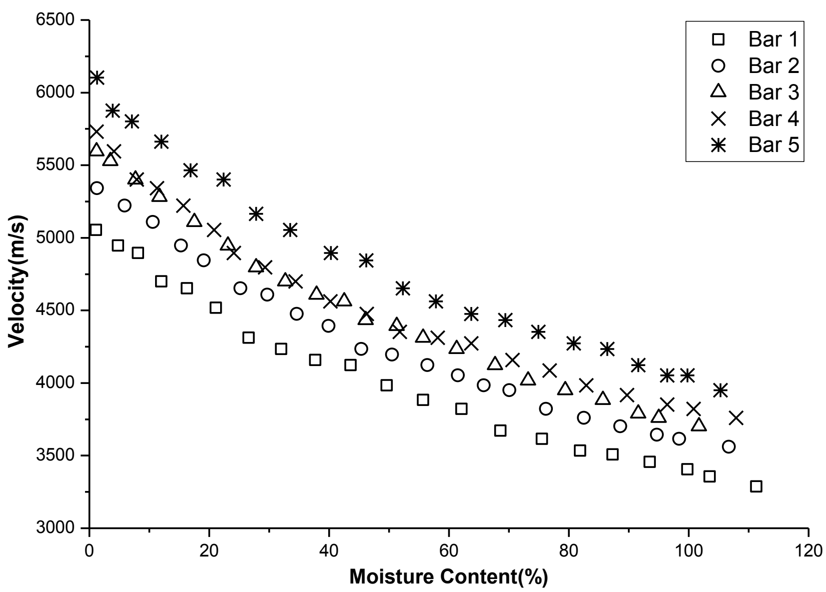

Fig. 6. Longitudinal stress wave velocity in different test bars at different moisture contents

Similar to previous results, the stress wave velocity decreased with increasing moisture content. It can be seen that the stress wave velocity varied across different bars under the same moisture content. This is consistent with previous findings (Simpson and Wang 2001; Oliveira *et al*. 2005).

When the moisture content was 20%, the stress wave velocity in bar 1 was approximately 4500 m/s, while it was 5500 m/s in bar 5. This is a difference of about 20%, based on the larger of the two velocities.

To gain a better understanding of the results, the actual velocity was transformed to relative velocity (Oliveira *et al*. 2005). The relative velocity was calculated according to the equation,

$$RV = \frac{V}{V_0} \times 100 \quad (4)$$

where *RV* is the relative velocity (%), *V* is the velocity at any moisture content (m/s), and V_0 is the oven dry velocity (m/s). Figure 7 illustrates the relative velocity as a function of the moisture content, measured in different test bars.

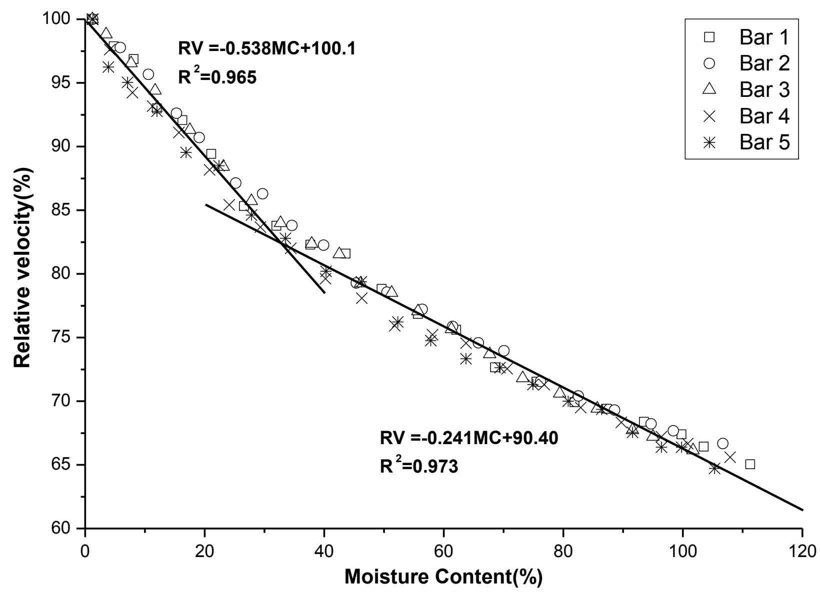

Fig. 7. Relative velocity at different moisture contents

Interestingly, all data collapsed onto one curve regardless of the test bar. Two regression lines were generated and drawn in Fig. 7. When the moisture content was lower than the FSP, the regression line is described by the following equation,

$$RV = -0.538MC + 100.1 \; (R^2 = 0.965) \quad (5)$$

where RV is the relative velocity (%) and MC is the moisture content (%). When the moisture content was higher than the FSP, the regression line is described by,

$$RV = -0.241MC + 90.40 \; (R^2 = 0.973) \quad (6)$$

Effects of Fiber Proportion on Stress Wave Velocity

The fiber proportion was used to negate the impact of wood structure on the experimental results. It has been reported that the proportion of fiber is positively correlated with air-dry density (Chowdhury *et al.* 2012). The microstructure of a cross section of test bar 1 is shown in Fig. 8.

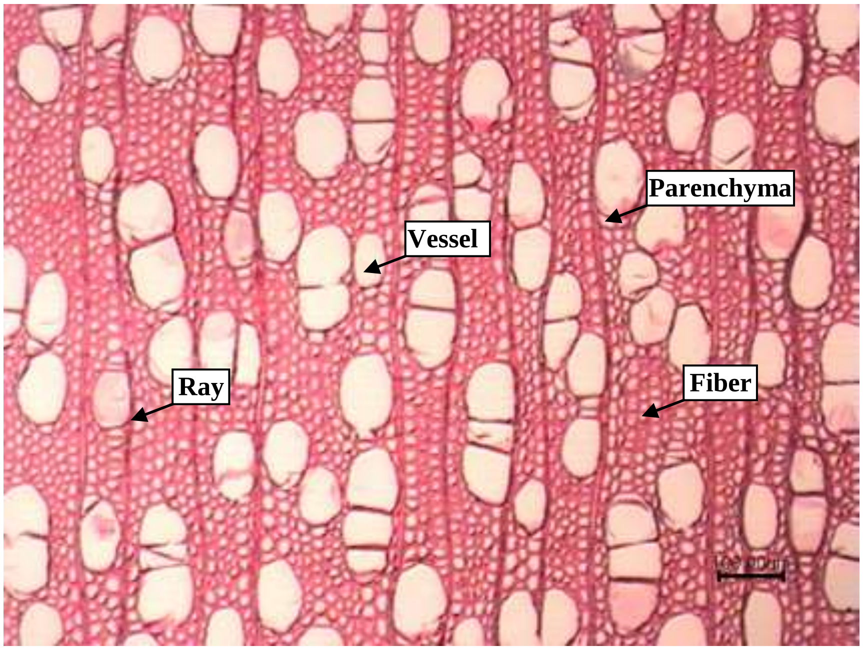

Fig. 8. The microstructure of a cross section of test bar 1

Wood fibers, wood rays, vessels, and parenchyma can be clearly seen in Fig. 8. The proportion of these components was calculated and is shown in Table 2. The proportion of vessels decreased from bar 1 to bar 5, while the fiber proportion increased. There was no significant difference in the proportions of rays and parenchyma between the different bars.

Table 2. Mean, Range, and Standard Deviation (SD) of Tissue Proportions

		Bar 1	Bar 2	Bar 3	Bar 4	Bar 5
Vessel (%)	Min.	36.2	33.6	30.4	30.3	26.4
	Mean(S.D.)	39.2(1.5)	36.0(2.0)	32.9(1.2)	32.7(1.2)	29.8(1.8)
	Max.	41.4	39.3	34.8	34.3	32.0
Ray (%)	Min.	7.1	8.2	9.0	8.3	8.4
	Mean(S.D.)	8.9(1.3)	9.8(0.9)	11.0(0.9)	10.7(1.4)	10.3(1.2)
	Max.	11.2	11.4	12.2	12.7	12.0
Parenchyma (%)	Min.	0.8	0.7	0.6	0.8	0.6
	Mean(S.D.)	1.3(0.6)	1.3(0.6)	1.2(0.5)	1.3(0.5)	1.1(0.4)
	Max.	2.7	2.6	2.2	2.4	2.0
Fiber (%)	Min.	47.9	49.5	52.2	53.4	56.3
	Mean(S.D.)	50.6(1.5)	52.9(2.6)	54.9(1.4)	55.3(1.4)	58.8(2.2)
	Max.	52.7	56.5	57.0	58.5	62.0

In order to examine the effect of fiber proportion, the stress wave velocities at the same moisture content for these five bars were obtained by interpolation. The relationship and significance analysis at five conditions with moisture content of 20, 40, 60, 80, and 100%, respectively, are presented in both Fig. 9 and Table 3. It was found that at the same moisture content, the longitudinal stress wave velocity was raised with increasing the fiber proportion for all cases. In a further step, significance analysis indicated that there was a statistically significant difference ($p<0.01$ in all the five cases) in the stress wave velocity for the bars with different proportions of fibers. In addition, stress wave velocity turned out to be highly linear with respect to the fiber proportion of the studied materials with high coefficients of determination (all R^2>0.98) by regression analysis, as shown in Table 3. In general, based on the abovementioned analysis, it is believed that, as increasing the fiber proportion, the longitudinal stress wave velocity of the Cathay poplar increased linearly at constant moisture content.

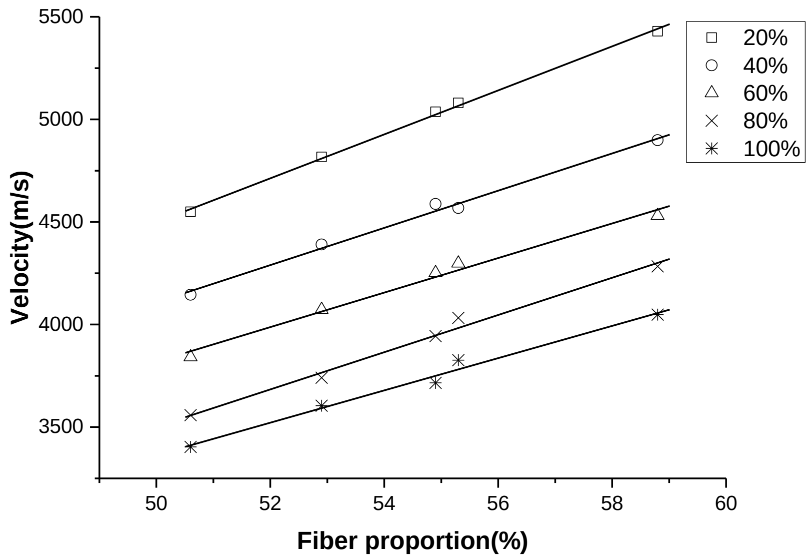

Fig. 9. Longitudinal stress wave velocity at different fiber proportion of test bars with same moisture contents

Table 3. Relationship and Significance Analysis of Fiber Proportion and Stress Wave Velocity

Moisture content	p-value	Regression model	Regression coefficient
20%	P=6.53E(-10)<0.01	V= 107.26FP - 863.34	0.998
40%	P=3.90E(-10)<0.01	V= 90.76 FP - 428.66	0.992
60%	P=3.96E(-10)<0.01	V= 84.25 FP- 392.17	0.988
80%	P=1.25E(-10)<0.01	V= 90.72 FP- 1032.40	0.989
100%	P=6.16E(-10)<0.01	V= 78.65 FP- 566.90	0.985
Note: V, the stress wave velocity of test bars; FP, the fiber proportion of test bars.			

To evaluate the influence of the fiber proportion on stress wave transformation, a new parameter, the corrected velocity, was calculated according to Eq. 7,

$$CV = \frac{V}{FP} \tag{7}$$

where *CV* is the corrected velocity (m/s), *V* is the velocity at any moisture content (m/s), and *FP* is the wood fiber proportion of the sample (%).

Figure 10 shows the corrected velocity of the stress waves through the test bars at different moisture contents.

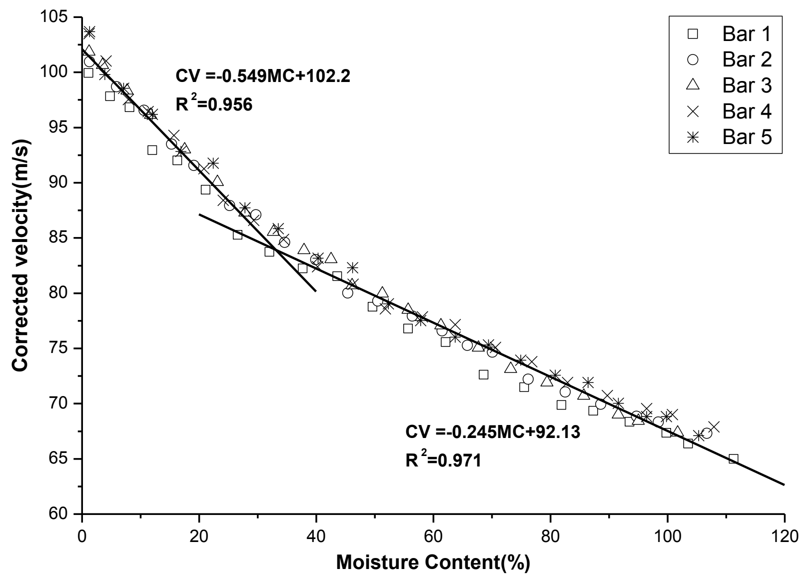

Fig. 10. Corrected velocity at different moisture contents

Two regression lines were generated and drawn in Fig. 10. The regression line when the moisture content was lower than the FSP was according to the equation,

$$CV = -0.549MC + 102.2 \qquad (R^2 = 0.956) \qquad (8)$$

where CV is corrected velocity (m/s) and MC is moisture content (%). When the moisture content was higher than the FSP, the regression line was according to the equation,

$$CV = -0.245MC + 92.13 \qquad (R^2 = 0.971) \qquad (9)$$

The changes of the corrected velocity with changing moisture content were similar to those of the relative velocity with changing moisture content. At moisture contents of 10%, 20%, 40%, and 50%, the differences between the CV and the RV, normalized by RV, were 2.10, 2.10, 1.94, and 1.95, respectively.

CONCLUSIONS

1. At the same test position, the stress wave velocity decreased with increasing moisture content. The stress wave velocity decreased rapidly with moisture content when the moisture content was lower than the FSP. The decrease in stress wave velocity was more gradual when the moisture content was higher than the FSP.
2. At constant moisture content, the longitudinal stress wave velocity increased with increasing fiber proportion. An increase in stress wave velocity was observed from bark to pith.
3. Moisture content can be estimated using the corrected velocity by dividing the velocity by the fiber proportion. The linear regression model of the corrected velocity *versus* moisture content showed a similar trend to that of the relative velocity *versus* moisture content.

ACKNOWLEDGMENTS

We are thankful for financial support for our research from the National Natural Science Foundation of China (51172028).

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Article submitted: December 24, 2013; Peer review completed: February 6, 2014; Revised version received and accepted: February 28, 2014; Published: March 3, 2014.