ORIGINAL ARTICLE

Effect of moisture content on some physical and mechanical properties of juvenile rubberwood (*Hevea brasiliensis* Muell. Arg.)

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Abstract

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Moisture content of rubberwood is an important factor influencing its physical and mechanical behaviours. This research aimed at quantifying effect of moisture content on physical and mechanical properties of juvenile rubberwood core. The specimens at various moisture contents were tested in compression and shear parallel to grain. Information was gathered to determine shrinkage, density and specific gravity of specimens. The equilibrium moisture content determined from desorption experiment, was well described by the Hailwood-Horrobin solution theory. Moisture content of 23±4% best represented the value of apparent fiber saturation point, Mp, determined from physical and mechanical properties data. Above Mp, values of all physical and mechanical properties examined were fairly constant. Maximum volumetric shrinkage from moisture content above Mp to an oven-dry condition was 8.2±1.8%. Specific gravity and density were 0.55±0.03 and 614±30 kg/m^3 at 12% moisture content. Below Mp, ultimate compressive stress (UCS) parallel to grain, ultimate shear stress parallel to grain, modulus of elasticity (MOE) for compression parallel to grain, and shear modulus parallel to grain increased exponentially with decreasing moisture content. Shear strain at fracture and work to fracture of shear parallel to grain were found to increase as

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moisture content decreased below Mp and attained the maximum values at 20% and 12% moisture content, respectively. The values decreased with further lowering of the level of moisture content. Ultimate compressive stress (UCS) parallel to grain was closely correlated with specific gravity and was more sensitive to changes in moisture content at higher specific gravity level.

Key words : juvenile rubberwood, moisture, mechanical, shrinkage

บทคัดย่อ

นิรันดร มาแทน และ บุญนำ เกี่ยวข้อง

ผลของความชื้นต่อสมบัติทางกายภาพและสมบัติทางกลของไม้ยางพาราอายุน้อย
(*Hevea brasiliensis* Muell. Arg.)

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ปริมาณความชื้นในไม้ยางพาราเป็นปัจจัยสำคัญประการหนึ่งที่กำหนดสมบัติทางกายภาพและสมบัติทางกลของไม้ยางพาราการวิจัยนี้มุ่งศึกษาผลของความชื้นต่อสมบัติทางกายภาพและสมบัติทางกลของแก่นไม้ยางพาราอายุน้อย ชิ้นตัวอย่างที่มีค่าความชื้นต่าง ๆถูกทดสอบสมบัติทางกลเพื่อหาความแข็งแรงกดและความแข็งแรงเฉือนในทิศทางขนานเสี้ยน พร้อมทั้งวัดค่าการหดตัว ความหนาแน่น และความถ่วงจำเพาะ ผลการศึกษาพบว่า ค่าความชื้นสมดุลของไม้ยางพาราสามารถอธิบายได้ด้วยสมการ Hailwood-Horrobin ค่าความชื้นปรากฏที่จุดหมาด Mp มีค่าเท่ากับ 23±4% โดยที่ความชื้นสูงกว่า Mp สมบัติทางกายภาพและสมบัติทางกลของไม้ยางพาราจะมีค่าคงที่ การหดตัวเชิงปริมาตรสูงสุดของไม้ยางพาราจากสภาวะที่มีความชื้นสูงกว่า Mp มายังสภาวะที่แห้งมีค่าเท่ากับ 8.2±1.8% ความถ่วงจำเพาะและความหนาแน่นมีค่าเท่ากับ 0.55±0.03 และ 630±30 kg/m^3 ที่ค่าความชื้น 12% ตามลำดับ สมบัติทางกลซึ่งได้แก่ ความเค้นอัดตามเสี้ยนสูงสุด ความเค้นเฉือนตามเสี้ยนสูงสุด มอดุลัสของการอัด และมอดุลัสของการเฉือนจะเพิ่มขึ้นแบบเอกโปแนนเชียลเมื่อความชื้นในเนื้อไม้ลดลงต่ำกว่า Mp ส่วนค่าความเครียดเฉือนที่จุดแตกและงานที่เกิดจากการเฉือนจนถึงจุดแตกจะมีค่าเพิ่มขึ้นเช่นกันเมื่อความชื้นในเนื้อไม้ลดลงต่ำกว่า Mp โดยจะเพิ่มขึ้นจนถึงจุดสูงสุดที่ความชื้น 20% และ 12% ตามลำดับ ค่าดังกล่าวจะลดลงเมื่อความชื้นในเนื้อไม้มีค่าลดลงกว่านี้ นอกจากนี้ยังพบอีกว่าความเค้นอัดตามเสี้ยนสูงสุดนอกจากสัมพันธ์กับความชื้นแล้วยังสัมพันธ์กับค่าความถ่วงจำเพาะด้วย โดยที่ค่าความถ่วงจำเพาะสูง ๆความเค้นอัดตามเสี้ยนสูงสุดจะเปลี่ยนแปลงตามความชื้นมากขึ้น

หน่วยวิจัยวิทยาศาสตร์และวิศวกรรมศาสตร์ไม้ มหาวิทยาลัยวลัยลักษณ์ อำเภอท่าศาลา จังหวัดนครศรีธรรมราช 80160

While a demand for good quality timbers has been increasing worldwide, government regulations and environmental restrictions to preserve the world existing forests have mounted pressures on logging in many developing countries. In Thailand, in particular, commercial logging from natural forests has been prohibited since 1989. Since then, domestic consumption of timbers in Thailand has totally relied on imported timbers from neighboring countries (Royal Forest Department of Thailand, 2000). These factors are major driving forces in the development of alternative structural composite timbers from underutilized wood materials available within the country to supplement domestic uses of imported timbers in the near future. Rubberwood, bamboo, palm wood and coconut wood are examples of wood materials that have been underutilized and overlooked. Rubberwood, in particular, has potential as material for structural composite timbers in Thailand. Rubber trees, widely grown in the South of Thailand for the production of latex, are generally cut down for replanting between 25-30 years of age when the production of latex is uneconomical. An enormous amount of rubberwood biomass of more than 15×10^6 m^3 is obtained each year. However, only 12% of the rubberwood biomass has been processed into finished products. Majority of juvenile rubberwood biomass such as branchwood, pith-associated wood, core wood and crown-formed wood has been underutilized in terms of fuelwood and charcoal or otherwise has been left as waste (Prasertsan and Vanapruk, 1998).

The work reported here is part of a wider study aimed at developing a novel technology for producing structural composite lumber (SCL) such as laminated veneer lumber (LVL), laminated strand lumber (LSL), oriented strand lumber (OSL) and glued-laminated timber (GLULAM) from such underutilized wood materials. A particular aim is to quantify the effect of moisture content on the fundamental physical and mechanical properties of juvenile rubberwood core. Information obtained will be used in the design of the manufacturing process of structural composite products from rubberwood waste.

Materials and Methods

Rubberwood specimens were prepared from ten juvenile rubberwood cores of diameter 0.1 m and length 1.1 m obtained from local industry in Krabi province, Thailand. These rubberwood cores were obtained from 25-30 years old mature rubber trees felled for replanting. Careful examination of rubberwood growth rings revealed that rubberwood cores obtained were approximately less than 7 years old. Specimens for the compression test of dimensions 60 mm (L) and 20 mm × 20 mm (T) and specimens for the shear test of dimensions 20 mm (L) and 20 mm × 20 mm (T) were cut with care to obtain flat-sawn specimens without pith and noticeable defects. All specimens were first soaked into water to reach saturation point. Saturated specimens were then placed into a conditioning chamber (Termaks KBP 6395 F). Various relative humidity (RH) conditions, namely 95%, 85%, 78%, 67%, 50%, 30% and 12%, at temperature of 35°C were employed to bring the specimens down to required moisture content levels. For some RH conditions, specimens were allowed to equilibrate to obtain the values of equilibrium moisture content (EMC) for the analysis of desorption isotherm. Specimens were divided into 8 groups (A-H) as shown in Table 1 and 2. Approximately 20 specimens for each group attaining required moisture content levels were randomly removed from the conditioning chamber and were immediately put into sealed plastic bags ready for testing. Compression

Table 1. Mean, coefficient of variation (CV), minimum, and maximum data for moisture content (%) and specific gravity based on an oven-dry condition of specimens used in compression test.

Group/ Sample size/ RH (%)	Moisture content (%)				Specific gravity**			
	Mean	CV	Min	Max	Mean	CV	Min	Max
A/58/95	75.7	42.5	23.7	121.1	0.59	5.1	0.54	0.64
B/19/95	22.7*	4.8	21.0	24.6	0.60	6.7	0.54	0.66
C/20/85	17.7*	1.7	17.1	18.3	0.59	6.8	0.51	0.64
D/16/78	14.5*	3.4	13.3	15.0	0.55	7.3	0.50	0.61
E/20/67	12.0*	3.3	11.1	12.6	0.58	5.2	0.53	0.62
F/19/50	9.4*	3.2	8.8	10.0	0.58	6.9	0.52	0.62
G/20/30	6.6*	3.0	6.3	7.0	0.58	5.2	0.53	0.62
H/18/12	4.8	6.3	4.2	5.2	0.56	5.4	0.51	0.63
I/20/oven-dry	0	0	0	0	0.60	5.0	0.53	0.65

*** : Equilibrium Moisture Content (EMC) ; ** : Specific gravity based on an oven-dry condition**

Table 2. Mean, coefficient of variation (CV), minimum, and maximum data for moisture content (%) of specimens used in shear test.

Group/ Sample size/ RH (%)	Moisture content (%)			
	Mean	CV	Min	Max
A/86/95	65.9	51.0	21.0	121.0
B/20/95	21.4*	4.7	20.0	23.0
C/20/85	16.7*	4.8	15.0	18.0
D/-/78	-	-	-	-
E/20/67	12.0*	7.5	10.5	13.5
F/20/50	9.2*	5.4	8.3	10.2
G/20/30	6.2*	4.8	5.7	6.9
H/20/12	5.0	6.0	4.3	5.4
I/20/oven-dry	0	0	0	0

*** : Equilibrium Moisture Content (EMC) ; - : no data**

parallel to grain and shear parallel to grain in radial direction tests were conducted on the Lloyd Universal Testing machine (150 kN) at room temperature of 29°C and RH of 67%. Such testing was compliant with the British Standard No. 373 (British Standard Institute, 1985) and ISO 3346 (International Organization for Standardization, 1975-1976). Stress-strain curves obtained from the tests were used to evaluate values of various mechanical properties. For all tests, information was gathered to determine moisture content at the time of test. For the compression test, additional information to determine specific gravity, density and shrinkage from any given moisture content to oven-dry condition was also collected.

A good separation between moisture content groups was obtained with no overlap in moisture levels (Table 1 and 2). Very good controls of moisture levels (CV~5%) for all groups up to about 22% were obtained. For compression test, the average specific gravity based on an oven-dry condition was 0.58±0.03. All moisture content groups had similar ranges for the specific gravity values. There was a good match among the specific gravity values in the different moisture content groups.

Results and Discussion

Moisture desorption isotherm

Equilibrium moisture content values of juvenile rubberwood core are plotted against corresponding relative humidities in Figure 1 (filled

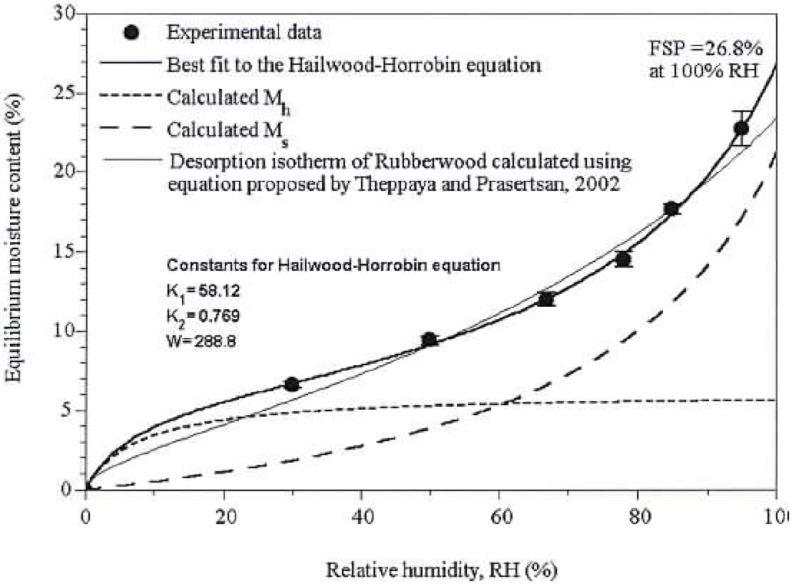

Figure 1. Desorption isotherm of juvenile rubberwood core at 35 °C.

circle). The Hailwood-Horrobin solution theory (Skaar, 1972) was employed to analyze the desorption data in Figure 1. This theory assumes that the bound water in wood exists in two basic forms e.g. chemi-sorbed water and dissolved water. Total equilibrium moisture content, EMC (%), at any given relative humidity, RH (%), is represented by

$$\mathrm{EMC} = M_h + M_s = \frac{1800K_1K_2(\mathrm{RH})}{W(100 + K_1K_2(\mathrm{RH}))} + \frac{1800K_2(\mathrm{RH})}{W(100 - K_2(\mathrm{RH}))} \qquad (1)$$

where K_1 is the equilibrium constant, when a hydrate is formed from dissolved water and dry wood, K_2 is the equilibrium constant between dissolved water and external vapour pressure and W is the molecular weight of the substance required to associate one gram mole of water (Skaar, 1972). The first term of the equation (M_h) describes the water of hydration of wood which is characteristic of chemi-sorption where a monolayer is formed. The second term describes the dissolved water (M_s) in wood corresponding to formation of multi-layer sorption (Skaar, 1972 and Chauhan *et al.*, 2001). Equation (1) was found to fit the desorption data reasonably well. The values of constants obtained from curve fitting are shown in Figure 1. Fiber saturation point (FSP), the moisture content level at which free water has been totally removed from cell cavities but the woody cell walls are still saturated with bound water, could be estimated by summing M_h and M_s at 100% RH. The values of M_h and M_s at 100% RH were 5.6% and 21.2%, respectively, which gave FSP of 26.8% at 35°C. Desorption isotherm for rubberwood at 35°C calculated using equation proposed by Theppaya and Pasertsan (2002) was also plotted in Figure 1 for comparison. General agreement between two curves can be seen.

Determination of apparent fiber saturation point

It is practically useful to assume that wood properties are not affected by the existence of free water in wood cavities above fiber saturation point. Below fiber saturation point, wood properties do change as bound water within woody material changes (Green and Kretschmann, 1994). As a result, determination of fiber saturation point could then be carried out using a graphical method presented in Figure 2. By employing segmented regression, two curves representing wood properties above and below fiber saturation point are drawn. Fiber saturation point is the moisture content at which those two curves intercept. It is unfortunate, however, that different wood properties seem to give different values of "apparent" fiber saturation point, denoted as Mp. Fiber saturation point derived using such method is therefore only a useful modeling tool for wood properties and is different from an actual fiber saturation point (Green and Kretschmann, 1994). For each property, data of groups A-H were plotted against moisture content. Suitable equation was used to fit data of group B-H. An intercept between a horizontal line drawn through the average data of group A and the curve fit to the B-H data sets was then calculated. The average Mp value of 23±4% moisture content, derived from all physical and mechanical properties considered in this work, best represented an overall Mp value for juvenile rubberwood core.

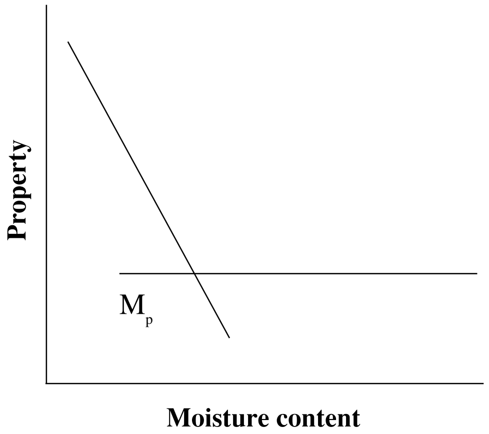

Figure 2. Method for determining the apparent fiber saturation point, Mp, value.

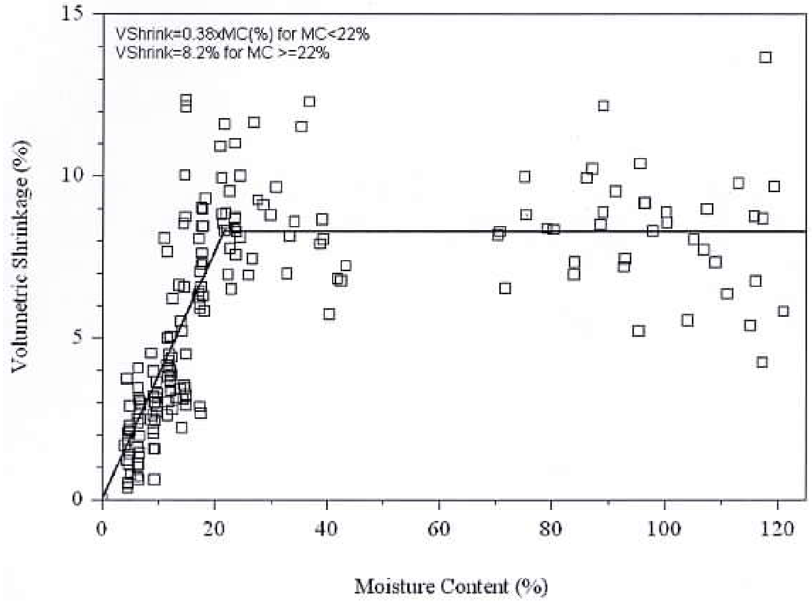

Figure 3. Volumetric shrinkage (%) of rubberwood dried from various levels of moisture content to oven-dry condition plotted against initial moisture content.

Effect of moisture content on shrinkage

Volumetric shrinkage of rubberwood dried from various levels of moisture content to an oven-dry condition is plotted against moisture content in Figure 3. A linear equation was used to fit the B-H data sets. Value of Mp for volumetric shrinkage was equal to 22% moisture content (Figure 3). Wood dimension is not affected by removing free water in the cell cavity above Mp (Haygreen and Bowyer, 1989 and USDA 1999). As a result, volumetric shrinkage of rubberwood dried from moisture content above Mp to the oven-dry moisture content was fairly constant at 8.2±1.8%. Losing bound water, water from the cell wall, however makes the cell wall and wood to shrink. As bound water molecules are removed from between long-chain cellulose and hemicellulose molecules, the chain molecules will then move closer together (Haygreen and Bowyer, 1989 and USDA 1999). The amount of volumetric shrinkage below Mp was therefore proportional to the amount of water removed from the cell wall (Figure 3).

Effect of moisture content on density and specific gravity

Density and specific gravity are correlated very closely with most mechanical properties of wood (Haygreen and Bowyer, 1989). Using the graphical method described in section 3.2, Mp was determined to be 20% from the density-moisture content plot (Figure 4). Average value of density of juvenile rubberwood core at 12% moisture content was 614±30 kg/m^3. Figure 5 shows specific gravity of juvenile rubberwood core at various moisture levels plotted against moisture content. Average specific gravity was relatively constant at 0.54±0.03 above Mp of 18%. Average value of specific gravity based on 12% moisture content was 0.55±0.03. Below Mp, the value of specific gravity gradually increased to 0.58±0.03 at an oven-dry condition. Large variability of specific gravity of juvenile rubberwood (CV~6%) is within a range (CV~10%), which is considered suitable for describing the variability of specific gravity within species (USDA 1999).

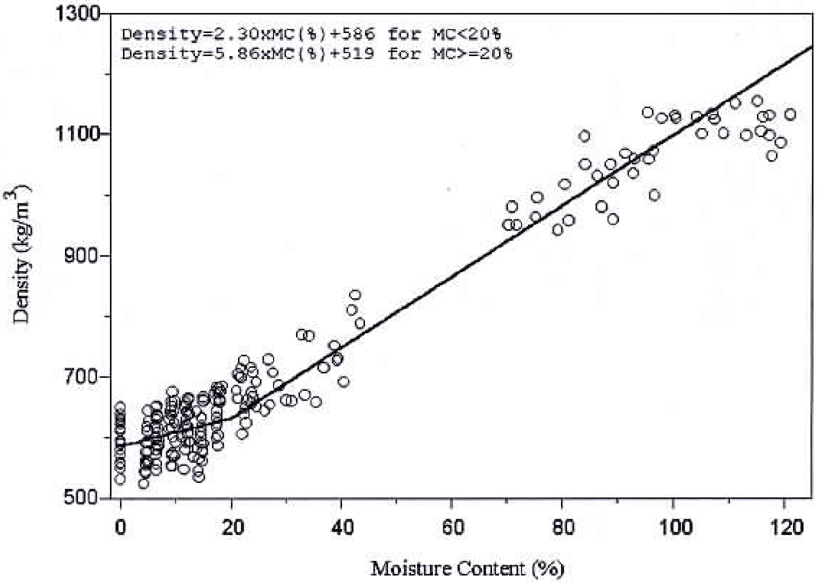

Figure 4. Density of juvenile rubberwood core plotted against moisture content.

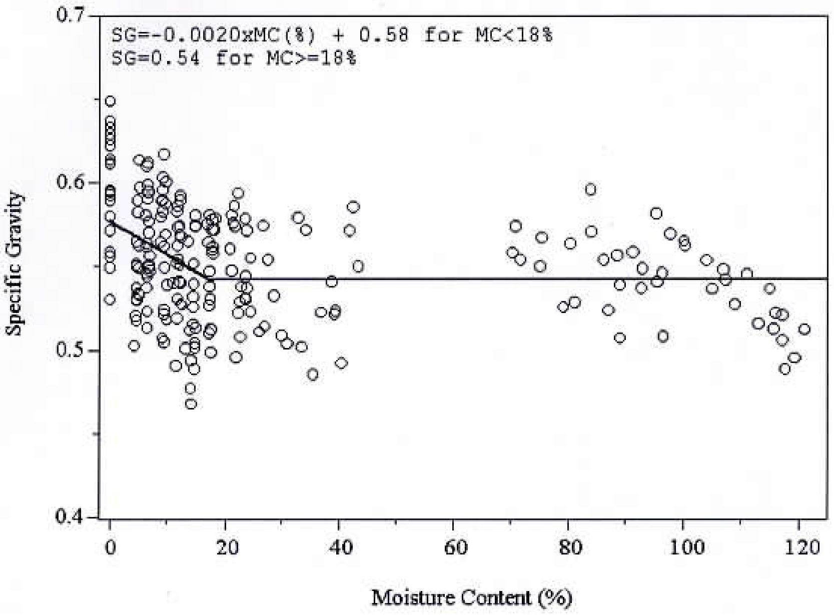

Figure 5. Specific gravity of juvenile rubberwood core plotted against moisture content.

Effect of moisture content on mechanical property

Stress-strain curves

Typical stress-strain curves of specimens tested in compression and shear parallel to grain at various moisture contents are shown in Figures 6 and 7, respectively. For compression test, stress-strain curves obtained were used to evaluate the values of ultimate compressive stress (UCS) and modulus of elasticity (MOE). Ultimate compressive

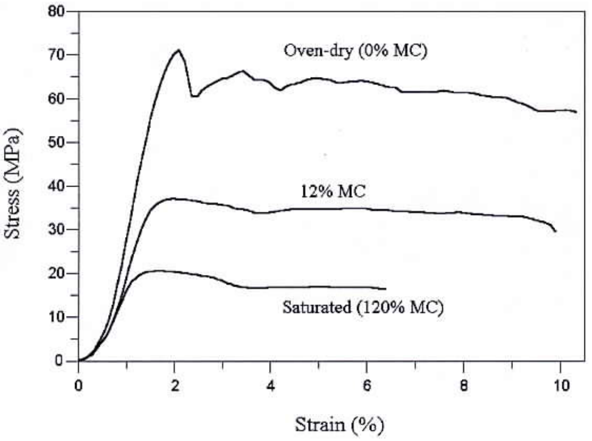

Figure 6. Typical strain-strain curves of specimens tested in compression parallel to grain at various moisture contents.

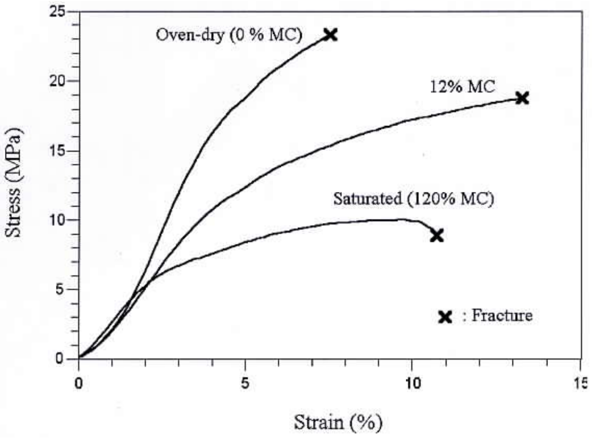

Figure 7. Typical strain-strain curves of specimens tested in shear parallel to grain in the radial direction at various moisture contents.

stress is the maximum stress attained and modulus of elasticity is the slope of the stress-strain curve in the linear regime. Both ultimate compressive stress and modulus of elasticity tended to increase at lower moisture content. The degree of brittleness reflected in characteristic of the curves in the failure region (Figure 6) (Bodig and Jayne, 1982), also increased at lower levels of moisture. For shear test, ultimate shear stress and shear modulus increased at lower moisture content. From the shear stress-strain curves, it was also possible to determine values of shear strain at fracture and work to fracture. Work to fracture is determined by area under the curve. Both shear strain at fracture and work to fracture increased as the moisture decreased to reach maximum values at particular moisture contents and then declined at lower levels of moisture (Figure 7). Average data for various mechanical properties derived from stress-strain curves for compression and shear tests are summarized in Table 3.

Ultimate stress

Ultimate stress of specimens tested in compression and shear parallel to grain are plotted against moisture contents in Figures 8 and 9, respectively. As one would expect from wood, ultimate stress data are clearly divided into two groups which are dependent and independent of moisture level. Declined exponential function was used to fit the group of data in the moisture dependent regime (Bodig and Jayne, 1982). Mp was calculated to be 22% and 27% for ultimate compressive and shear stress, respectively. Average ultimate compressive and shear stress of the moisture independent data were 26.6±13.2 MPa and 10.2±1.6 MPa, respectively. Average values of ultimate compressive stress of juvenile, 10 years old, and mature, 22 years old, rubberwood at 12% moisture content reported elsewhere (Mohamad, 1998) are also plotted in Figures 8 and 9 for comparison. Ultimate compressive stress of juvenile rubberwood core is comparable to that of juvenile 10 years old rubberwood and is lower than that of mature 22 years old rubberwood. This implies a similarity in structure of rubberwood core in mature rubberwood and that of juvenile rubberwood.

Modulus

Modulus is an intrinsic property of material reflecting strength of bonding at the atomic level. It can be derived from the slope of the linear regime in the stress-strain curve. Modulus of elasticity, MOE, derived from compressive stress-strain curves and shear modulus derived from

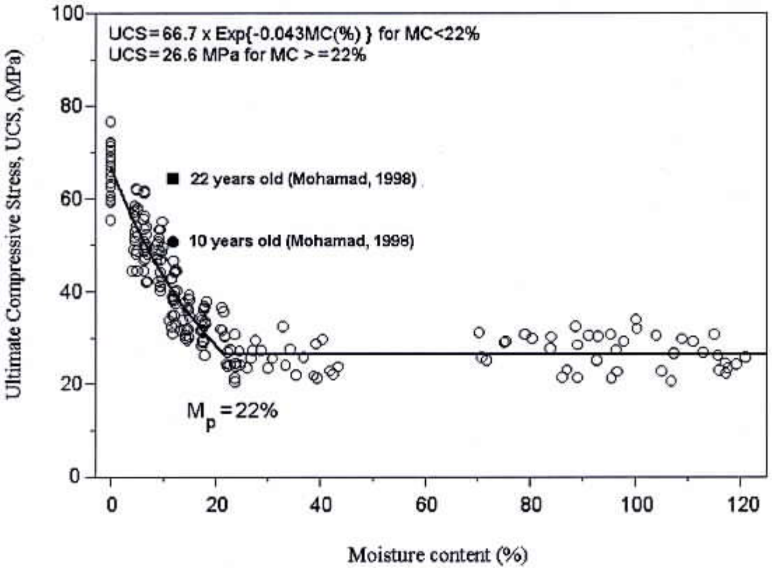

Figure 8. Ultimate compressive stress (UCS) plotted against moisture content of specimens tested in compression parallel to grain. Below Mp, UCS increases exponentially with decreasing moisture content.

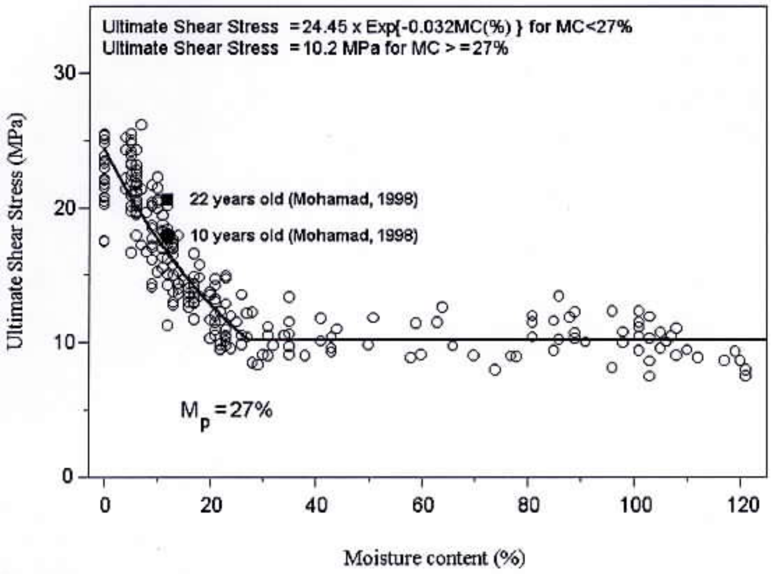

Figure 9. Ultimate shear stress plotted against moisture content of specimens tested in shear parallel to the grain in the radial direction. Below Mp, shear strength increases exponentially with decreasing moisture content.

shear stress-strain curves plotted against moisture content are shown in Figures 10 and 11, respectively. Mp was calculated to be 20% and 19% for compression and shear tests, respectively. Above Mp, average values of modulus of elasticity and shear modulus were 3491±827 MPa and

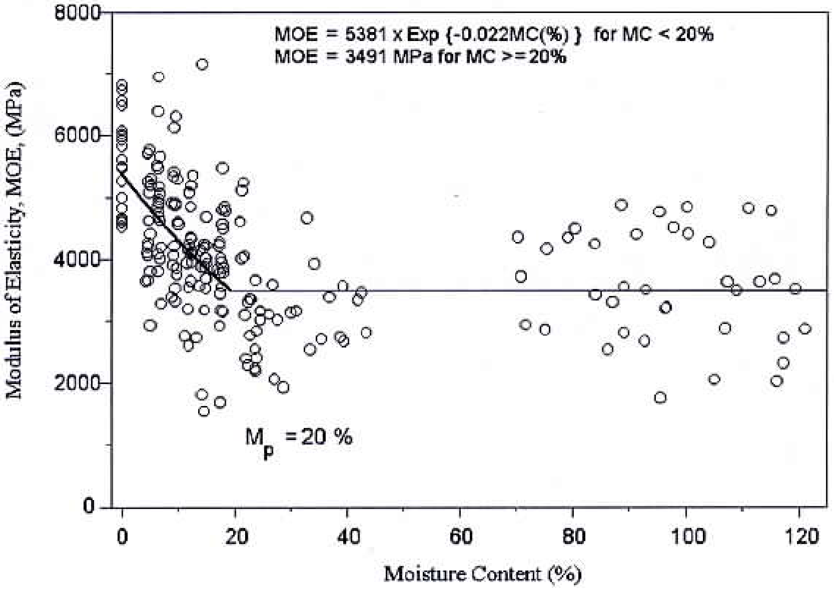

Figure 10. Modulus of elasticity (MOE) plotted against moisture content of specimens tested in compression parallel to grain.

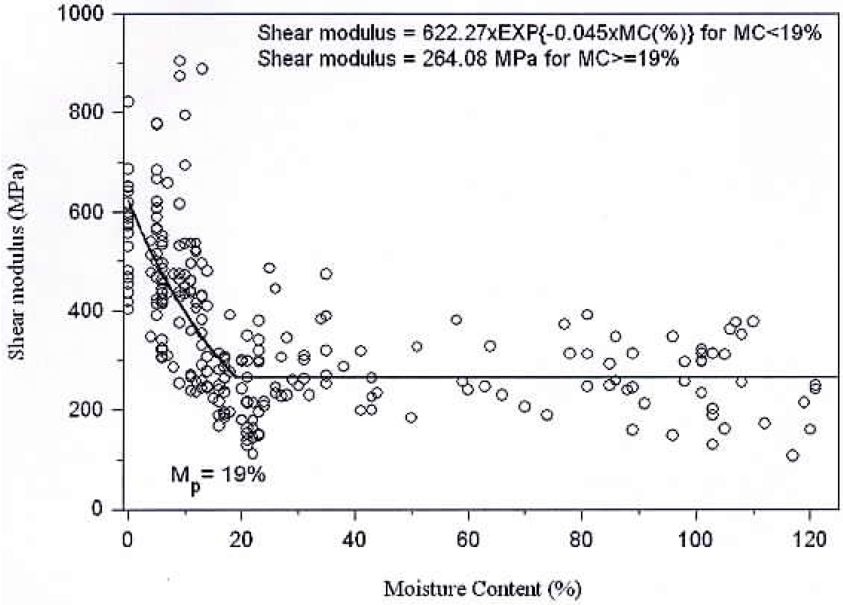

Figure 11. Shear modulus parallel to grain plotted against moisture content of specimens tested in shear.

264±73 MPa, respectively. Increase in modulus as the moisture content decreased below Mp was explained in terms of an increase in the effective number of hydrogen bonds available to maintain the saturated integrity of the cell wall (Kretschmann and Green, 1996a,b). According to the above assumption, the relationship between modulus and moisture content, MC, in this regime was

Table 3. Average data for various mechanical properties for compression and shear tests.

Compression parallel to grain			**Shear parallel to grain**				
Group/ MC (%)	**UCS (MPa)**	**MOE (GPa)**	**Group/ MC (%)**	**Ultimate shear stress (MPa)**	**Shear modulus (GPa)**	**Strain at fracture (%)**	**Work to fracture (J)**
A/75.7	26.6 [13]	3.5 [23]	A/65.9	10.2 [16]	0.26 [31]	11.8 [17]	6.8 [28]
B/22.7	27.1 [17]	3.3 [27]	B/21.4	11.3 [13]	0.20 [35]	14.9 [18]	9.0 [23]
C/17.7	32.6 [10]	3.9 [20]	C/16.7	13.8 [9]	0.25 [24]	14.5 [15]	11.0 [22]
D/14.5	34.5 [10]	3.6 [25]	D/-	-	-	-	-
E/12.0	39.0 [12]	4.1 [17]	E/12.0	17.6 [6]	0.37 [30]	13.5 [19]	12.2 [19]
F/9.4	47.3 [10]	4.5 [20]	F/9.2	18.6 [13]	0.56 [38]	11.2 [24]	11.6 [32]
G/6.6	50.6 [10]	4.9 [18]	G/6.2	21.3 [10]	0.43 [23]	11.0 [16]	11.5 [26]
H/4.8	53.5 [10]	4.6 [17]	H/5.0	22.6 [10]	0.55 [22]	10.9 [22]	11.7 [32]
I/0	66.9 [8]	5.6 [12]	I/0	24.3 [10]	0.58 [22]	9.7 [25]	10.8 [35]

- : no data ; Coefficient of variation (CV) is given in brackets.

expressed by

$$\frac{d(\ln(Modulus))}{d(MC)} = -K \qquad (2)$$

where K is constant. The values of K were equal to 2.2×10^{-4} and 4.5×10^{-4} for compression and shear tests, respectively (Figure 10 and 11).

Shear strain at fracture and work to - fracture

Shear strain at fracture plotted against moisture content is shown in Figure 12. Mp was calculated to be 31%. Above Mp, average value of shear strain at fracture was 11.8±2.0%. Below Mp, shear strain at fracture increases as moisture content decreases, reaching a maximum value at 20% moisture content and then declines at lower levels of moisture. The shear strain at fracture and moisture content relationship was described by a quadratic equation. The constants used in the equation with their values obtained from curve fitting are also shown in Figure 12. Work to fracture, determined by area under the stress-strain curve, is plotted against moisture content in Figure 13. Below Mp of 25%, work to fracture reaches a maximum at 12% moisture content. Average value of work to fracture above Mp is 7.2±1.9 J. The results obtained from this work are consistent of those of Southern pine reported elsewhere. Kretschmann and Green (1996) reported that K_{IIcTL} (Mode II stress intensity factor) of Southern pine, which characterizes resistance to the formation of cracks as a result of shearing stress parallel to grain, reached a maximum value at 12% moisture content. It was also suggested that failure is likely to initiate in the S_1 layer or

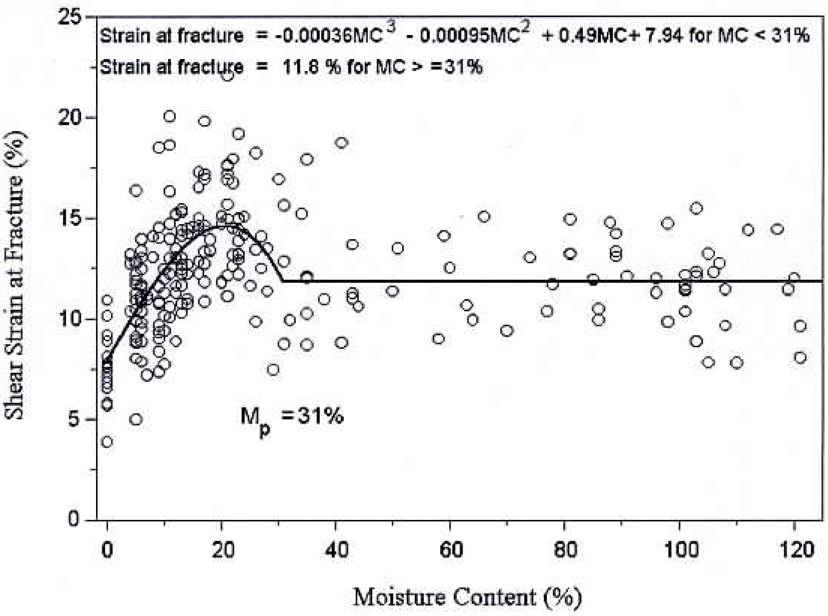

Figure 12. Strain at fracture plotted against moisture content of specimens tested in shear parallel to grain.

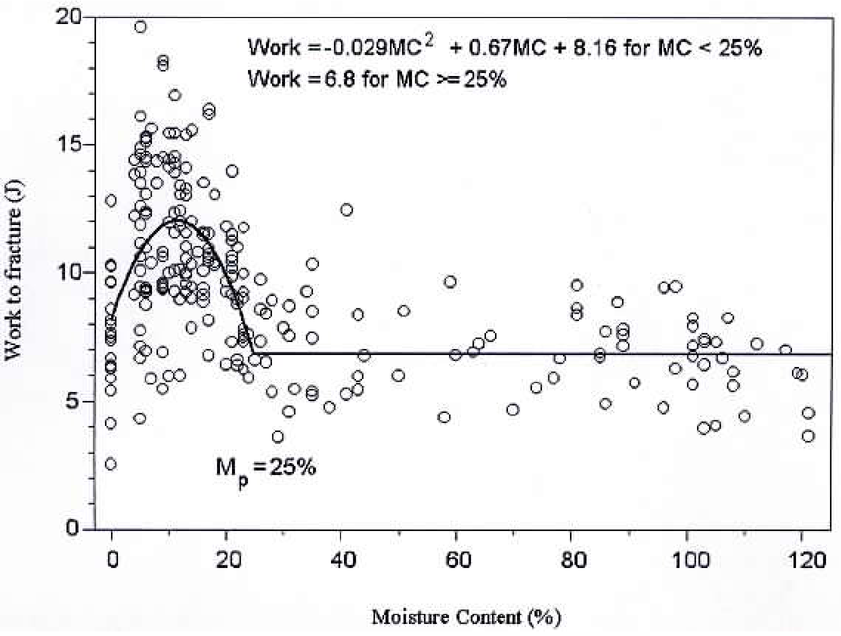

Figure 13. Work to fracture plotted against moisture content of specimens tested in shear parallel to grain.

at the S_1/S_2 interface with final failure in the S_2 layer in the cell wall (Green and Kretschmann, 1994 and Kretschmann and Green, 1996a,b).

Moisture content - density interactions

Variability in many properties of wood is partly explained by the interactions between specific gravity and changes in moisture content (Green and Kretschmann, 1994 and Kretschmann and Green, 1996a,b). Empirical model proposed by Kretschmann and Green (1996) was used to describe the ultimate compressive stress (UCS) data as a function of moisture content and specific gravity. The equation is

$$UCS = Int + a(M) + b(M^2) + c(SG)^2 + d(SG)^2 + e(M)(SG) \qquad (3)$$

where *Int* is the intercept, M is moisture content(%), SG is specific gravity at oven-dry condition, and *a, b, c, d, e* are constants. Fitted response surface for the UCS is shown in Figure 14. Filled circles represent individual UCS data points at each specific gravity and moisture content location. Shape of response surface of the UCS obtained from this work is consistent with that of Southern pine reported elsewhere (Kretschmann and Green, 1996a,b). The UCS surface indicates that samples with low specific gravity values were less sensitive to changes in moisture content than samples with high specific gravity values. At particular moisture content, higher values of UCS corresponded to samples with higher specific gravity.

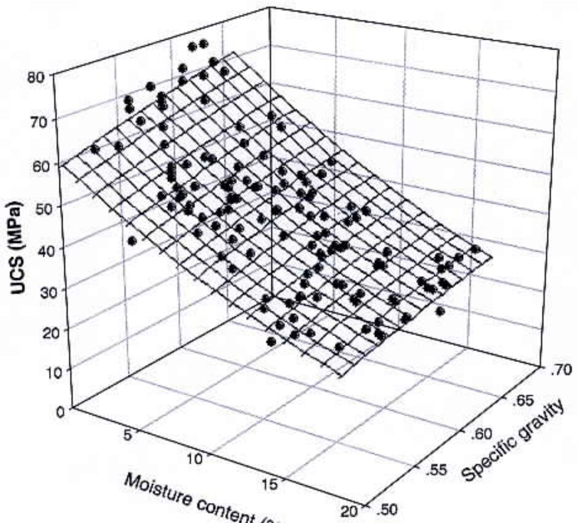

Figure 14. Surface plot of ultimate compressive stress, UCS (MPa), against moisture content, MC(%), and specific gravity (SG). Filled circles represent test data used in the fitting. Values of constants in equation 3 obtained from curve fitting are *Int* = 31.92, *a* = -1.16, *b* = 0.03, *c* = 39.93, *d* = 31.99 and *e* = -2.29.

Conclusions

The following conclusions on the effect of moisture content on some properties of juvenile rubberwood core can be drawn from this work:

1. The equilibrium moisture content determined from desorption experiment, was well described by the Hailwood-Horrobin solution theory.

2. Moisture content of 23±4% best represented the value of apparent fiber saturation point, Mp, determined from physical and mechanical properties data. Above Mp, values of all physical and mechanical properties examined were fairly constant.

3. Maximum volumetric shrinkage from moisture content above Mp to an oven-dry condition was 8.2±1.8%. Specific gravity and density were 0.55±0.03 and 614±30 kg/m^3 at 12% moisture content.

4. Ultimate compressive stress (UCS) parallel to grain, ultimate shear stress parallel to grain, modulus of elasticity (MOE) compression parallel to grain, and shear modulus parallel to grain increased exponentially as moisture content decreases below Mp.

5. Shear strain at fracture and work to fracture of shear parallel to grain increased as moisture content decreased below Mp and attained maximum values at 20% and 12% moisture content, respectively. The values decreased with lower level of moisture content.

6. Ultimate compressive stress (UCS) parallel to grain was closely correlated with specific gravity and was more sensitive to changes in moisture content at higher specific gravity level.

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Nomenclature

a, b, c, d, e, Int	: Constants in equation 3
CV	: Coefficient of variation
EMC	: Equilibrium moisture content
FSP	: Fiber saturation point
K	: Constant in equation 2
K1, K2	: Equilibrium constants in Hailwood-Horrobin equation
Mh	: Water of hydration of wood
Mp	: Apparent fiber saturation point
Ms	: Dissolved water in wood
MC	: Moisture content
MOE	: Modulus of Elasticity
RH	: Relative humidity
SG	: Specific gravity
UCS	: Ultimate compressive stress
W	: Molecular weight in Hailwood-Horrobin equation