INFLUENCE OF DRYING TEMPERATURE ON THE PHYSICAL AND MECHANICAL PROPERTIES OF RUBBERWOOD

HS Sik[1,*], KT Choo[1], Z Sarani[2], A Sahrim[2], SS How[1] & MK Mohamad Omar[1]

[1] *Forest Research Institute Malaysia, 52109 Kepong, Selangor Darul Ehsan, Malaysia*
[2] *Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia*

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SIK HS, CHOO KT, SARANI Z, SAHRIM A, HOW SS & MOHAMAD OMAR MK. 2009. Influence of drying temperature on the physical and mechanical properties of rubberwood. Commercial drying of rubberwood at high temperature is still unknown. This study investigated the influence of high temperature on the physical and mechanical properties of rubberwood. Experiments were carried out at 60 °C (conventional temperature) and at high temperatures, namely, 100, 120, 130, 140 and 150 °C. Both quarter and flatsawn showed average thickness shrinkage of less than 7% (< 2 mm) and average width shrinkage of less than 5% (< 5 mm) after drying at conventional and high temperatures. Rubberwood exhibited greater shrinkage in thickness than in width for both radially and tangentially oriented specimens that were dried at temperatures above 100 °C. The incidence of serious collapse and/or honeycombing was not observed at all the high temperatures tested. Improvement of various mechanical properties was observed in all high temperature-dried samples up to 130 °C compared with conventionally dried material. The enhancement of specific strength properties such as hardness, compression parallel to grain and shear strength could be observed up to 150 °C.

Keywords: High temperature, presteaming, drying time, shrinkage allowance

SIK HS, CHOO KT, SARANI Z, SAHRIM A, HOW SS & MOHAMAD OMAR MK. 2009. Kesan suhu pengeringan ke atas ciri-ciri fizikal dan mekanik kayu getah. Kesan suhu pengeringan ke atas ciri-ciri fizikal dan mekanik kayu getah. Pengeringan kayu getah secara komersial pada suhu tinggi masih kurang diketahui. Kajian ini meninjau kesan suhu tinggi terhadap ciri-ciri fizikal dan mekanik kayu getah. Eksperimen dikendalikan pada suhu 60 °C (suhu konvensional) dan pada suhu tinggi iaitu 100 °C, 120 °C, 130 °C, 140 °C dan 150 °C. Kedua-dua kayu potong rentang dan potong tangen menunjukkan purata kecutan ketebalan yang kurang daripada 7% (< 2 mm) dan purata kecutan lebar yang kurang daripada 5% (< 5 mm) selepas pengeringan pada suhu konvensional dan suhu tinggi. Kayu getah menunjukkan kecutan yang lebih pada tebalnya berbanding lebarnya dalam kedua-dua spesimen berpotongan rentang dan tangen yang dikeringkan pada suhu melebihi 100 °C. Kejadian kempisan dan/atau rekah dalam yang teruk tidak dicerap pada kesemua suhu tinggi yang diuji. Pelbagai ciri mekanik diperbaik dalam semua sampel yang dikeringkan pada suhu tinggi sehingga suhu 130 °C berbanding sampel yang dikeringkan pada suhu konvensional. Peningkatan nilai kekuatan tertentu seperti kekerasan, mampatan selari ira dan kekuatan ricih dapat dicerap sehingga suhu 150 °C.

INTRODUCTION

Hevea brasiliensis or rubber tree from the Euphorbiaceae family was introduced into Malaysia more than a century ago. Currently, it is of economic importance to the wood-based furniture sector. The furniture industry has been a major export earner of Malaysia for more than two decades, of which 70% of the furniture exported is derived from rubberwood.

Drying is an important process in the manufacturing of wooden products such as joinery and furniture components whereby minimum warping, low drying stress and uniform moisture distribution are required. A good drying practice will render the material fit for further processing into quality end-products, which give minimum or negligible problem during service. According to Choo and Hashim (1994), rubberwood is a relatively fast drying lumber. It is reported that boards of 25 mm thick take approximately 6–8 days to dry to 8–10% from an initial green moisture content of about 60%. Final dry bulb temperature (DBT) setting for rubberwood drying is approximately 65.5 °C for timber of less than 50 mm thick (Choo & Hashim 1994).

Drying at high temperature is accomplished at dry-bulb temperatures of 100 °C or higher, usually from 110 to 121 °C (Boone 1984). This

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*E-mail: sik@frim.gov.my

drying regime has been regarded as a time and cost saving processing practice in view of the escalating cost of production in the wood-based manufacturing sector. Reduction in drying time, resulting in lower inventory costs and smaller plant sites (Milota 2000), lower energy consumption and probably fewer deformations (Bekhta & Niemz 2003) are among the many advantages of drying timbers at high temperature. High temperature (HT) drying of softwoods such as plantation-grown radiata pine and other southern pines has long been practised in countries like Australia, New Zealand and United States. However, HT drying of tropical hardwoods is still unknown in Malaysia and other tropical hardwoods producing regions. Dehumidification system and steam-heated, forced-air drying system (conventional kiln) are used in Peninsular Malaysia to dry rubberwood, with the latter being the more preferred system (Anonymous 1982) and accounting for more than 90% of the kiln drying practice in the country.

Generally, temperature has an immediate effect on the strength of wood. The effect depends upon the moisture content, time and manner in which the wood is exposed to the elevated temperature. Koch (1971) reported that high temperatures and large wet-bulb depressions accelerate drying, and that if exposure time is short, strength loss in the wood may be minor at temperatures up to 116 °C. The permanent effect of exposure to high temperatures on mechanical properties varies among wood species, though it is more prominent in hardwoods than in softwoods (Armstrong 1985). Hill (2006) reported that hardwoods generally exhibit higher loss of mass than softwoods when heated under identical conditions. Chang and Keith (1978) also reported that hardwoods are more susceptible to thermal degradation during steam treatment and show greater tendency to shrink and collapse. The shrinkage of wood dried at high temperatures may be either less or more than that of wood dried at conventional temperature (Milota 2000). Excessive or abnormally high shrinkage which leads to deformation and collapse is often observed in HT drying of hardwoods from the green condition (Sharma & Bali 1964).

This paper examines the effects of drying rubberwood at high temperatures on selected properties compared with conventional drying in an experimental kiln.

MATERIALS AND METHODS

The material for the tests was obtained from 20-year-old *H. brasiliensis* of RRIM 600 clone. Equal numbers of quarter and flatsawn samples with dimensions of 30 (T) × 100 (W) × 600 mm (L) were obtained for each drying experiment. The board thickness and width used were based on commercial practice, while the optimum sawn length was produced to the specification of the laboratory experimental kiln. Simpson (1994) reported that two different sawn lengths at eight temperature, relative humidity and air velocity combinations showed little practical difference in the drying times of the boards.

The laboratory drying kiln has a volume capacity of approximately 250 l. It is equipped with vent connection, operated on electronic microprocessor PID-controller with continuous power adaption. It is connected to a PC work station which enables the control of thermostating program and monitoring of air speed and real time monitoring of the temperature in the chamber. It is also retro-fitted with a wet-bulb sensor.

Match sampling was carried out, whereby two test samples obtained from the same 1.5 m long sawn were subjected to both conventional and high temperature drying respectively (Figure 1). All test pieces were dried from the green condition (with average initial moisture content of 63.3%; standard deviation of 1.9%) to approximately 6–8% moisture content (MC).

Predetermined MC values from each board using 25 mm broad strips and weight loss data obtained by periodically weighing the test samples at set intervals during drying were used to monitor the current MC fall of test samples until targeted MC was achieved. Wood blocks of 25 mm^3 were prepared to determine the initial density values for calculation of specific gravity before drying. The specific gravity before drying was calculated based on the green volume and oven-dried weight. At the end of the drying, the respective moisture contents and specific gravities of the samples dried under various temperatures were again determined.

Separate drying runs were carried out at DBT of 60 °C (conventional temperature) and at high temperatures of 100, 120, 130, 140 and 150 °C in the experimental kiln. Specimens were inserted with thermocouples to continuously monitor the effective drying temperature gradient of the wood subjected to various drying temperatures. The temperatures at various depths within the specimens were recorded every 5 min. Constant dry bulb temperatures were applied throughout each drying experiment and the relative humidity (RH) in the chamber was controlled by regulating the damper control. The initial wet bulb depression (WBD) was kept as small as possible, i.e. between 1 and 2 °C at the start of each drying regime to minimize drying and was gradually increased to induce drying at various stages based on the real-time monitoring of the internal wood temperature at the core. The air speed measured in the chamber was approximately 1.5 m s^{-1} for each run.

Figure 2 shows a diagram of typical cross-sections of both quartersawn and flatsawn from different cutting patterns/directions. The shrinkages in width and thickness at the marked cross-section was calculated with reference to green dimensions taken at the same points. The ratios of respective tangential and radial shrinkage of rubberwood dried at various temperatures were also determined.

All dried samples were conditioned at room temperature (25 °C) and RH of approximately 50–60% before being processed into specific dimensions for mechanical testing. The mechanical properties tested were modulus of rupture (MOR), modulus of elasticity (MOE), hardness, compression strength parallel to grain and shearing strength using the Instron Universal Testing Machine in accordance with BS 373 (Anonymous 1957).

RESULTS AND DISCUSSION

Drying schedule and related settings

All high temperature drying runs were set at initial DBT of 100 °C and above at 120, 130, 140 and 150 °C. The initial DBT for conventional drying was 60 °C. The temperature conditions in each run are shown in Table 1.

The initial high temperature (100 °C or above) at the warm-up stage was regarded as presteaming treatment. Presteaming mechanism plasticizes the green timber before any or minimum drying takes place. It helps to reduce distortion during the subsequent drying process when the timber charges are under weight-restraint (Mackay & Rumball 1972). Sumi and McMillen 1979 reported that the equilibrium moisture contents (EMCs) above the boiling point of water were very low. During the high temperature drying runs (100 to 150 °C) in this study, the EMCs were estimated to dip as low as 3 to 5% based on the extrapolated low-temperature EMC data to high temperatures (up to 300 °F) established by Simpson and Rosen (1981).

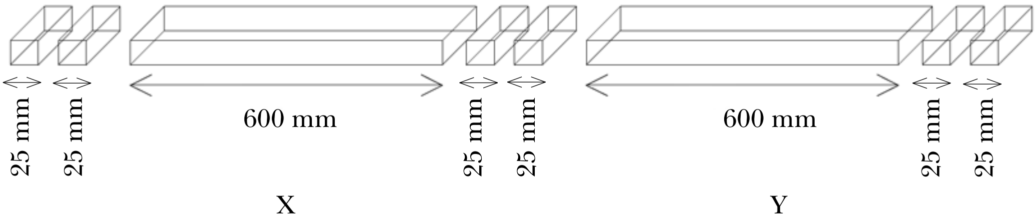

Figure 1 Sampling based on a 1.5 m long sawn to obtain matched samples for drying at conventional (sample X) and high temperatures (sample Y). Sawn strips, 25 mm wide, obtained from adjacent test samples prepared for drying experiment were used for moisture content and density determination.

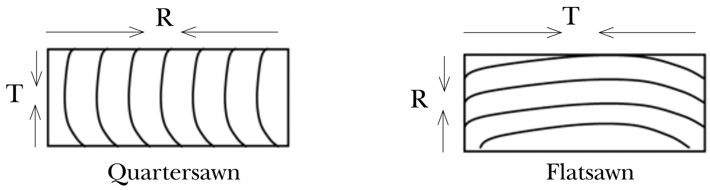

Figure 2 Cross-section of a typical sawn timber; T = tangential shrinkage, R = radial shrinkage

Table 1 Temperature settings and kiln conditions in high temperature and conventional drying runs

Temperature (°C)	Warm-up period (Presteaming)		EMC (%)	After 3 hours of presteaming		EMC (%)	Current MC at approximately 30%		EMC (%)	Current MC at approximately 10% (Conditioning)		EMC (%)	[a]Drying time (hours)
	DBT (°C)	WBT (°C)		DBT (°C)	WBT (°C)		DBT (°C)	WBT (°C)		DBT (°C)	WBT (°C)		
60	60	58	> 20	60	45	7	60	40	5	60	40	5	132
100	100	98	3–5	100	90	3–5	100	90	3–5	80	59	3–5	29
120	120	118	3–5	120	100	3–5	120	90	3–5	80	59	3–5	15
130	130	128	3–5	130	100	3–5	130	90	3–5	80	59	3–5	11
140	140	138	3–5	140	100	3–5	140	90	3–5	80	59	3–5	8
150	150	148	3–5	150	100	3–5	150	90	3–5	80	59	3–5	7

DBT = dry bulb temperature, WBT = wet bulb temperature, EMC = equilibrium moisture content, MC = moisture content
[a]Drying time from green to approximately 6 to 8% moisture content

After the warm-up stage, all drying schedules were adjusted based on the real-time recording of the internal temperature of the sample boards in each individual charges, as well as the current MC of the specimens calculated from predetermined MC of green sawn timber. The drying times of all high temperature drying runs were reduced significantly (> 75%) compared with conventional drying time.

Shrinkage properties

The influence of drying temperatures on the anisotropy (transverse and longitudinal) shrinkages of rubberwood is shown in Table 2. As wood dries below the fibre saturation point (fsp), it starts to shrink in an anisotropic manner in the tangential, radial and longitudinal directions, in order to achieve dimensional stability. Overall, the average tangential and radial shrinkages in both sawn types at the respective drying temperatures remained less than 7% (< 2 mm) in thickness and less than 5% (< 5 mm) in width (Table 2). Hence, there is no necessity to increase the existing shrinkage allowances for green sawn size as normally practised by sawmillers if drying of rubberwood at high temperatures up to 150 °C is carried out.

In general, longitudinal shrinkage in normal wood is about 0.1–0.3%. Due to its smaller magnitude compared with juvenile or reaction wood, the measurement of shrinkage in the longitudinal direction is often neglected (Siau 1995). However, abnormally high longitudinal shrinkages of up to 0.67% was observed in this study (Table 2). The detection of slight distortion on dried sawn rubberwood dimensionally sawn was possibly due to the presence of tension wood or coupled with the effect of elevated drying temperatures. Anonymous (1972) found that abnormally high longitudinal shrinkage due to tension wood may cause distortion in the form of bow and spring or even twist. Lim *et al.* (1999) also reported that tension wood could contribute to drying defect such as bowing. He concluded that the percentage of tension wood had little effect on the degree of bow when restraint weights were applied on the stacks of wood, as physical weights facilitate to minimize the amount of bow in the drying process.

The anatomical structure of wood causes sawn timber to shrink greater in the tangential direction (T) as compared with the radial direction (R). This is termed differential shrinkage (Kirby 2008). The ratio of tangential to radial shrinkage, T/R, is approximately 2:1, although it varies considerably with species (Siau 1971). Generally, the higher the T/R ratio, the more distorted is the sawn, hence lower the rate of recovery. Table 2 also summarizes the ratio of rubberwood shrinkage in the tangential direction to radial direction at different drying temperatures. The T/R shrinkage ratio obtained from conventional drying temperature at 60 °C was used to gauge the effect of temperature on the differential shrinkage of rubberwood dried at high temperatures.

Table 2 Anisotropy shrinkage (%) of quartersawn and flatsawn rubberwood at different drying temperatures

Temperature (°C)	Quartersawn				Flatsawn			
	Thickness	Width	T/R	Longitudinal	Thickness	Width	T/R	Longitudinal
60	3.65	2.22	1.64	0.45	2.80	4.12	1.47	0.33
	(0.33)	(0.38)		(0.10)	(0.09)	(0.51)		(0.17)
100	2.75	1.58	1.74	0.22	3.29	3.79	1.15	0.07
	(0.26)	(0.34)		(0.00)	(0.38)	(0.40)		(0.13)
120	6.53	3.21	2.03	0.28	5.52	3.81	0.69	0.44
	(0.87)	(0.24)		(0.19)	(0.69)	(0.51)		(0.25)
130	6.24	4.07	1.53	0.44	5.27	3.75	0.71	0.50
	(0.74)	(0.59)		(0.10)	(0.50)	(0.32)		(0.17)
140	4.19	3.56	1.18	0.22	4.89	3.96	0.80	0.67
	(0.13)	(0.46)		(0.10)	(0.49)	(0.18)		(0.00)
150	4.00	3.25	1.23	0.33	4.55	3.45	0.76	0.33
	(0.40)	(0.41)		(0.00)	(0.49)	(0.48)		(0.17)

Figures in parentheses are standard deviations.
T/R = ratio of shrinkage, T = tangential direction, R = radial direction

The T/R shrinkage ratios for both quartersawn (1.18 to 2.03) and flatsawn (0.69 to 1.15) dried at high temperatures indicated that the differential shrinkages of HT-dried rubberwood were comparable with conventional-temperature dried material with respective T/R shrinkage ratio of 1.64 for quartersawn and 1.47 for flatsawn. The T/R shrinkage ratios of flatsawn were found to be generally less than those of quartersawn at the respective drying temperatures (Table 2). In flatsawn, T/R ratios for all drying temperatures ranged from 0.69 to 1.47, which were close to the norm and within a typical differential shrinkage (T/R = 2:1). According to Kirby (2008), T/R shrinkage ratio of 2 means a typical block of wood shrinks twice as much tangentially as it does radially, while T/R shrinkage ratio of 1 indicates no differential shrinkage and, thus, no cross-sectional distortion of boards is expected as the boards would merely dry and shrink uniformly into smaller dimension.

T/R shrinkage ratio of less than one was detected in flatsawn samples dried at 120, 130, 140 and 150 °C (Table 2). T/R shrinkage ratio < 1 shows that the tangential samples have shrunk more in thickness (radially) than in width (tangentially) when dried at temperatures above 100 °C, which is similar to the shrinkage pattern observed in quartersawn (Figures 3 and 4). This phenomenon agrees with Hann (1964) on the drying of yellow-poplar at temperatures above 100 °C. He found that shrinkage in thickness is consistently greater than shrinkage in width for both radially and tangentially oriented specimens that were dried at high temperatures. He deduced that specimen geometry is more important than grain orientation in controlling shrinkage patterns during high temperature drying of yellow-poplar.

The flatsawn specimens utilized in this study were from logs of smaller diameter, which were positioned much closer to the centre of the log (near pith) compared with normal-sized logs. Hence, a 'semi' flatsawn will shrink irregularly across the transverse face that often results in cupping incidence (Figure 5). However, subsequent planing of at least 3–4 mm of both the surfaces of the rubberwood as practised by the industry will render the timber suitable for manufacturing of furniture components and other wooden products.

Post-drying assessment and occurrence of residual drying stress

All dried samples obtained from various drying temperatures were visually examined for occurrence of drying defects. The incidence of collapse was undetected in all samples. A typical collapsed lumber often shows grooves on its surface (McMillen 1958). Collapse is caused by abnormal shrinkage accompanied by distortion of the cell wall structure, which is common when

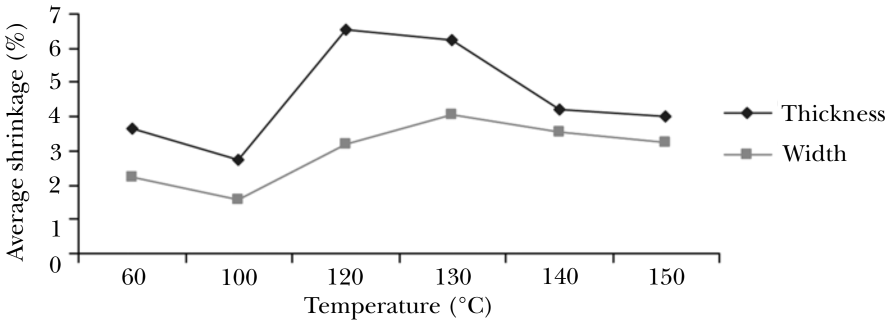

Figure 3 Average thickness and width shrinkages in quartersawn rubberwood

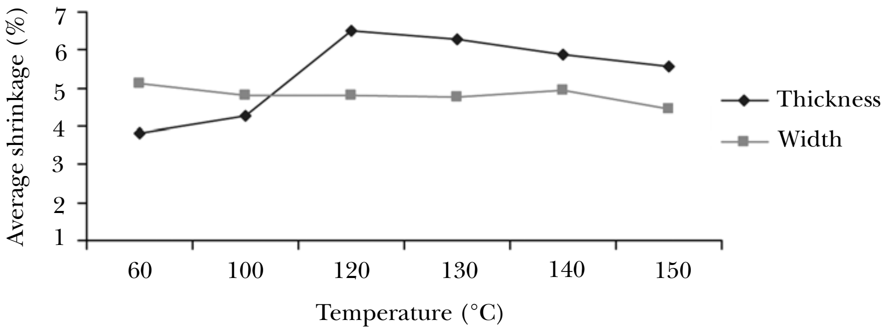

Figure 4 Average thickness and width shrinkages in flatsawn rubberwood

Figure 5 Cupping of an unevenly-shrunk sawn rubberwood

high temperatures are used. The cross-sections of all test samples showed no occurrence of honeycombing. Honeycombing is internal checking in wood often observed during fast drying at elevated temperatures (Boone 1984), when internal tensile stress perpendicular to grain exceeds the maximum strength of wood (McMillen 1958).

Prong test for detection of stress was carried out to investigate the residual drying stress, measured by the magnitude of pinched-in of slotted prong samples from test samples. The pinched-in of all test pieces at all temperatures were in the permissible range of 1 to ≤ 3mm (Anonymous 1997) after conditioning for 24 hours at room temperature (25 °C) and RH of approximately 50–60%.

Specific gravity

Figure 6 shows the increment in specific gravity (SG) of test samples determined at green condition (MC 63.3 ± 1.9%) and after drying (MC 6–8%) at different temperatures. A significant improvement in SG of rubberwood was observed in all HT-dried wood. This could be attributed to densification of wood with decreased pore size and void volume after heat treatment as reviewed by Rowell (2004). Regression analysis showed high correlation, $r^2 = 0.81$ (Figure 6). Analysis of variance (ANOVA) results showed significant differences ($p < 0.05$) between the mean increments of SG obtained at each drying temperature (results not shown).

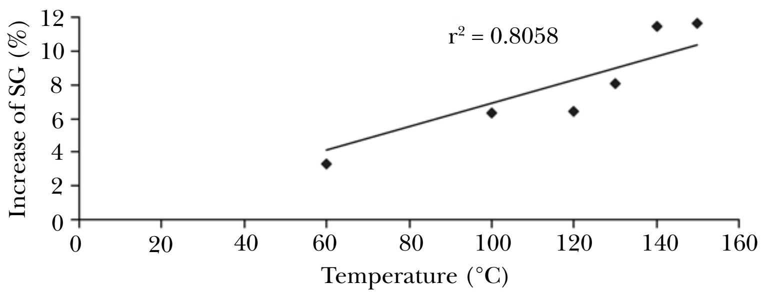

Figure 6 Increase (%) of specific gravity (SG) of rubberwood after drying at various temperatures

According to Winandy (1994), the properties of wood increases with increasing SG, which is an index of mechanical property of wood free from defects.

Comparative strength properties

Modulus of rupture and modulus of elasticity

ANOVA showed that the MOR and MOE of rubberwood were affected by drying temperatures (Table 3). The overall experimental effect was highly significant ($p < 0.001$) in the MOR values obtained at all drying temperatures. This is followed by post hoc test (PHT) which consists of pair wise comparisons that are designed to compare all different combinations of the treatment groups (Field 2000). PHT showed that MOR for samples dried at 60, 100, 120 130 and 140 °C had no significant differences between respective groups (Table 3). The lowest MOR value was recorded in 150 °C. It showed no difference when compared with MOR values obtained at 60, 130 and 140 °C. However, approximately 15–16% reduction of MOR values obtained at 150 °C compared with 100 and 120 °C were found to be significant at 95% confidence level.

ANOVA showed no significant effect at 95% confidence interval for MOE values. Armstrong (1985) also mentioned that MOE, a measure of stiffness, is least affected when dry wood is exposed to high temperatures. This finding is further affirmed by PHT which verified that even the reduction of MOE value at 150 °C showed no significant difference ($p > 0.05$) when compared with 120 °C dried sample which had the highest MOE value.

Hardness, compression strength parallel to grain and shear strength

All HT-dried sawn samples showed increases in hardness, compression strength parallel to grain and shear strength when compared with conventional dried samples (Table 3). ANOVA showed that the increases in hardness and compression strength parallel to grain were significant at 95% confidence level for all high temperatures against the conventional temperature. However, the mean for shear strength was insignificant.

PHT showed that the differences in the mechanical properties (hardness, compression strength and shear strength) of HT-dried samples between 100 and 150 °C were insignificant. Hence, the slight reductions in hardness and shear values for 150 °C dried samples and reductions in compression strength values for 120–150 °C dried samples were acceptable for HT-dried rubberwood up to 150 °C.

Salamon (1969) found that some species did not lose strength when dried at high temperatures, while other lost 7 to 20% compared with conventionally dried samples. Kollmann and Cote (1984) reported that one of the advantages of HT drying and its effects on wood properties are the slight increase of MOE, maximum crushing strength and MOR. According to Armstrong (1985), strength properties of wood are affected differently by exposure to high temperatures. In the case of rubberwood, improvement in all strength properties up to 130 °C were observed in all HT-dried rubberwood samples (compared with conventional) and increase of specific strength properties such as compression parallel to grain, hardness and shear strength could be observed up to 150 °C. This improvement could

Table 3 Mechanical strength values of rubberwood dried at different temperatures

Temperature (°C)	MOR (MPa)	MOE (MPa)	Compression strength (MPa)	Hardness (KN)	Shear strength (MPa)
60	117.01 ab (10.15)	12187 a (1064)	44.47 a (5.25)	4.1552 a (0.497)	15.06 a (3.01)
100	127.97 a (15.67)	12377 a (993.7)	59.74 b (3.92)	4.9258 b (0.617)	17.47 a (3.12)
120	126.44 a (9.03)	12731 a (1235)	57.24 b (4.60)	5.1357 b (0.375)	17.95 a (3.60)
130	120.27 ab (14.72)	12333 a (1078)	57.80 b (3.83)	5.1525 b (0.419)	17.55 a (3.23)
140	115.88 ab (17.41)	12385 a (1272)	57.12 b (5.48)	5.2282 b (0.454)	19.66 a (3.48)
150	107.05 b (9.88)	11909 a (1190)	57.44 b (3.29)	5.1735 b (0.560)	18.77 a (3.29)

Means followed by the same letter in the same column are not significantly different at $p \leq 0.05$.
Values in parentheses are standard deviations.

be attributed to the increase in specific gravity (Figure 6) and occurrence of some very minor collapse of the cell walls, as detected in the cross-section of 150 °C dried rubberwood (Figure 7) compared with 60 °C dried rubberwood (Figure 8). The overall wood structure was undamaged under high temperature drying conditions. This is reflected by the absence of incidences such as collapse of the vessels and radial cracks in the vicinity of the rays.

In addition, improvements in compression, hardness and shear strength during drying at HT are possibly a result of hardening or heat-tempering effect. At the same time, the accompanied minor embrittlement after exposure to high temperatures could have caused slight reduction in the MOR and MOE of HT-dried rubberwood. Sehlstedt-Persson (1995), in her study on HT-dried Scots pine, concluded that no significant influence of drying method was found on surface hardness despite a general impression of hard and brittle HT-dried wood. This inference, however, is in contrast to her earlier findings on HT-dried timber of the same species, which she had specifically described the presence of hard and brittle feature, as observed in HT-dried rubberwood.

CONCLUSIONS

The potential of commercial high temperature drying of rubberwood is very encouraging. High-temperature-dried rubberwood showed insignificant shrinkage difference compared with conventionally-dried material in terms of industrial practicality. There is no necessity in

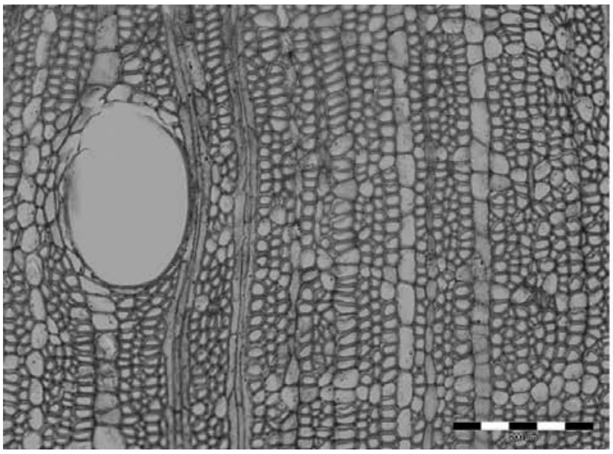

Figure 7 Micrograph cross-section of 150 °C dried rubberwood

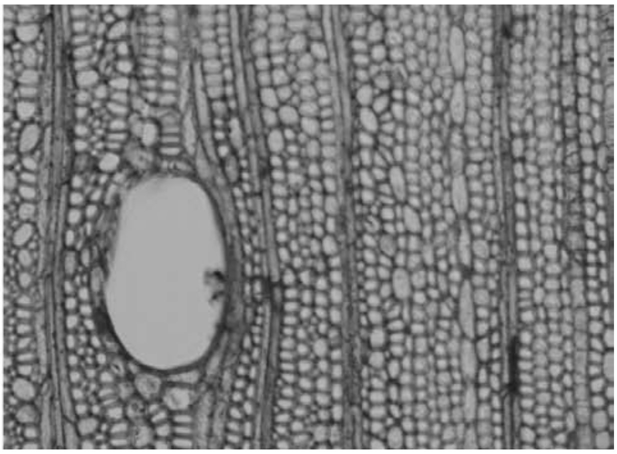

Figure 8 Micrograph cross-section of 60 °C dried rubberwood

increasing the existing shrinkage allowances for green sawn size as normally practised by sawmillers if drying of rubberwood at high temperatures up to 150 °C is carried out. Rubberwood exhibited greater shrinkage in thickness than in width for both radially and tangentially oriented specimens, dried at high temperatures (above 100 °C). Hence, specimen geometry is more important than grain orientation in controlling shrinkage patterns in HT drying of rubberwood. Overall, drying at high temperature has enhanced various mechanical properties of rubberwood, and more essentially, the drying defects such as excessive shrinkage which often leads to serious collapse and honeycombing were undetected in HT drying up to 150 °C. This shows that rubberwood is able to withstand drying stresses at high temperatures and is tolerant of drying up to at least the set high temperatures employed in this study. Several mechanical properties of rubberwood sawn dried at set high temperatures up to 130 °C had improved markedly compared with conventionally-dried sawn. The increase of specific strength properties such as compression strength parallel to grain, hardness and shear strength could be observed up to 150 °C.

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