ORIGINAL ARTICLE

Effects of superheated steam on the drying of rubberwood

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Abstract

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Rubberwood drying is the most time and energy consuming step in the processing of wood product. This research studied the effect of superheated steam drying on the drying time required and the physical and mechanical properties of rubberwood after drying. In this study, a cylindrical drying chamber with a length of 1.2 m and a diameter of 0.5 m was constructed and injected with superheated steam. The dimensions of the wood lumber were 1 m × 7.62 cm × 2.54 cm. The wood samples were impinged with alternating cycles of superheated steam and hot air at ratios of 6:1, 4:1 and 1:6 hours until the moisture content was less than 15% dry basis. The conditions inside the chamber were 110ºC and ambient pressure. Continuous superheated steam and continuous hot air were also used for comparisons. The drying rate and the temperature profile for each process were determined.

Initial acceptability of the dried wood was conducted using the prong test and visual inspection. Results showed that if the drying rate was too fast, the dried wood did not pass the prong test due to stress buildup. Therefore, an optimum drying condition was developed based on minimizing defects and reducing the drying time. For the optimum condition, the following schedule was carried out: (1) saturated steam at 100ºC was used during the first 4 hours of drying to prevent the wood surface from drying too quickly which

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would minimize the moisture gradient between the center and wood surface, (2) superheated steam at 105ºC and 110ºC was used in alternating cycle with hot air (80ºC) during the main drying stages to rapidly remove the free water and majority of the bound water inside the wood, and (3) hot air was used continuously during the final stages of drying to reduce the relative humidity inside the chamber making it possible for the removal of the residual bound water. This process successfully reduced the drying time to less than 2 days without causing any defects which compared favorably to the conventional hot air drying process of 7-8 days. Moreover, results of the mechanical properties for the optimum condition showed that the shear-parallel-to-grain was 13.46 MPa and the compression strength parallel-to-grain was 37.73 MPa, both of which were higher than the literature values. Thus, using superheated steam in conjunction with hot air presents a substantial saving in operating time and energy consumption compared to the conventional method while retaining the desired mechanical properties of the wood.

Key words : rubberwood, drying, superheated steam, steam-impingement, impingement drying

บทคัดย่อ

ราม แย้มแสงสังข์ และ กนกวรรณ บัวผุด

ผลของไอน้ำร้อนยวดยิ่งต่อการอบไม้ยางพารา

ว. สงขลานครินทร์ วทท. 2549 28(4) : 803-816

การอบไม้เป็นขั้นตอนหนึ่งต้องใช้ระยะเวลาและพลังงานมากที่สุดในกระบวนการแปรรูปเป็นผลิตภัณฑ์ไม้ยางพารา การวิจัยนี้จึงสนใจศึกษาการอบแห้งด้วยไอน้ำยิ่งยวดเพื่อช่วยลดเวลาในการอบ และศึกษาผลกระทบต่อสมบัติเชิงกายภาพและเชิงกลของไม้ยางพารา ในการศึกษาครั้งนี้ใช้ตู้อบรูปทรงกระบอกยาว 1.2 เมตร และเส้นผ่าศูนย์กลาง 0.5 เมตร ซึ่งสามารถพ่นไอน้ำเข้าไปในตู้อบ ชิ้นไม้ที่ใช้ทดลองมีขนาด 1 เมตร × 7.62 ซม. × 254 ซม. ในการทดลองจะพ่นด้วยไอน้ำยิ่งยวดสลับกับอากาศร้อนด้วยสัดส่วน 6:1, 4:1 และ 1:6 ชั่วโมงจนกระทั่งมีความชื้นน้อยกว่า 15% มาตรฐานแห้ง โดยให้สภาวะในห้องอบมีอุณหภูมิ 110°C ความดันบรรยากาศ และศึกษาเปรียบเทียบระหว่างการอบด้วยไอน้ำยิ่งยวดกับอากาศร้อน เพื่อหาอัตราการแห้งและรูปแบบของอุณหภูมิของการอบแต่ละแบบ

ไม้แห้งที่ยอมรับได้ขั้นตอนต้องผ่านการทดสอบแบบซี่ส้อม (prong test) และการทดสอบด้วยสายตา ผลการทดลองแสดงให้เห็นว่าอัตราการแห้งเร็วเกินไป ไม้แห้งที่ได้จะไม่ผ่านการทดสอบแบบซี่ส้อม เนื่องจากความเค้นเกิดขึ้น ดังนั้นเงื่อนไขการอบแห้งที่เหมาะสมได้ถูกหาด้วยเทคนิคดังนี้ (1) ใช้ไอน้ำอิ่มตัวในชั่วโมงแรก ๆ ของการอบ เพื่อลดความเค้นในไม้ (2) ใช้ไอน้ำยิ่งยวดที่อุณหภูมิ 105°C และ 110°C สลับกับอากาศร้อนที่อุณหภูมิ 80°C ในขั้นตอนระหว่างการอบหลัก (3) ใช้อากาศร้อนอย่างต่อเนื่องในช่วงท้ายของการอบเพื่อลดความชื้นสัมพัทธ์ภายในห้องอบ และดึงน้ำในผนังเซลล์ (bound water) ที่เหลือ ผลการอบด้วยกระบวนการนี้ สามารถลดเวลาในการอบจาก 7-8 วัน ในอุตสาหกรรม เหลือเพียง 2 วัน นอกจากนี้ จากการทดสอบคุณสมบัติเชิงกลของไม้ที่ผ่านการอบแห้งโดยกระบวนการนี้ พบว่าค่าแรงเฉือนในแนวขนานกับเสี้ยนไม้เท่ากับ 13.46 MPa และค่าแรงกดในแนวขนานกับเสี้ยนไม้เท่ากับ 37.73 MPa ซึ่งมีค่าสูงกว่าค่าเฉลี่ยจากเอกสารอ้างอิง ดังนั้นการอบด้วยไอน้ำยิ่งยวดได้แสดงให้เห็นศักยภาพในการลดระยะเวลาในการดำเนินการอบ และปริมาณพลังงานที่ต้องใช้ เมื่อเทียบกับวิธีการอบแห้งแบบปกติด้วยลมร้อน โดยไม่ลดสมบัติทางกลของไม้ที่ได้

ภาควิชาวิศวกรรมเคมี คณะวิศวกรรมศาสตร์ มหาวิทยาลัยสงขลานครินทร์ อำเภอหาดใหญ่ จังหวัดสงขลา 90112

Wood from the rubber tree is the major source of timber in southern Thailand. The tree (*Hevea brasiliensis*) is typically harvested between 25 and 35 years of its growth so that the diameter is less than 200 mm (Asia Plywood Factory, Yala, Thailand). The wood is cut and sawn into short lengths (usually 1 meter) usually for furniture making. Generally, glue lamination into useful plank dimensions is required, and for this to be effective, the timber must be dried. However, if the rubberwood is dried too quickly, it will split, crack, warp, cup or check due to unrelieved moisture stresses. Hence, the drying of rubberwood requires an optimum drying rate, while reducing power consumption of the process.

Timber drying is traditionally carried out using warm air. The process may be carried out in a kiln or in "stacks" of "packets" in the open air. The latter process is largely uncontrolled so that the sun's radiation or a prevailing wind can set up moisture stresses that may distort the wood. In conventional drying, rubberwood is usually arranged in stacks and dried in a 400-600 m^3 kiln at temperatures of 80-100ºC. The drying time varies from 7 to 16 days depending on the thickness of the lumber. After several days, a mist of water droplets is introduced into the drying chamber (along the side walls) and is circulated using fans. The process helps to maintain a good moisture distribution within the boards and to reduce moisture stress by temporarily increasing the relative humidity in the chamber. If the temperature of the dryer is too high, the moisture stress may lead to cracking due to large moisture gradient within the board. However this method of humidity control is somewhat crude and inefficient. As a consequence, the desired result is not always achieved and energy usage is seldom optimal.

In areas of high humidity, air seasoning is very slow and fungi (or even insects) attack the wood. Generally, the attack produces unsightly colors on the surface but does not significantly reduce the strength of the timber. However, the discoloration significantly degrades the appearance of the product for furniture or finishing work.

Anti-sapstain chemicals have been widely used to control fungal attack during air-seasoning. To some extent, the added expense of applying chemicals offsets the negligible energy costs in the process. Kiln-drying gives much more control over the drying process; however, it is at the expense of the energy needed to dry the wood and to circulate the air. In addition, some anti-sapstain chemicals are still required wherever long drying processes enhance the incubation of fungal spores.

Literature review

In terms of fundamental knowledge of the drying process, heat and mass transfer at the surface are known to determine the initial rate of drying. Later, after the surface water is removed, the rate of drying is determined by the rate at which moisture can diffuse to the surface of the wood. Thus, the initial rate of drying gradually decreases until the cellulose of the wood comes to equilibrium with the drying air above it. The initial high rate can be increased by the following:

1. Reducing the humidity of the drying medium
2. Increasing its turbulence over the surface

The rate of moisture diffusion through the wood can be increased by

1. Raising the temperature of the wood
2. Ensuring that all moisture is evaporated from the surface exposed to the drying medium
3. Ensuring that the bordered pit structure between the cells is open

If the temperature is raised too high, (or the operating pressure is reduced), the water in the pores of the wood reaches its boiling point. The sudden phase change usually destroys the cell structure. *Ptylosis* is the process by which the lignins in the wood harden and seal the bordered pit structure. It starts as soon as the tree is cut. In general, steaming the wood with wet saturated steam keeps the pit structure open. If this is followed by drying, very high rates can be achieved without damage occurring from the moisture stress. This is because moisture is able to move freely between the cells.

Superheated steam can also be used as the drying medium. Superheated steam may be produced by dropping the pressure at the end of the steaming operation or by the vapor-recompression of low quality steam coming out of another process. Because of the reduced opportunity for tannins to oxidize, the color of the wood is maintained through steam drying.

Douglas (1994) used steam to dry paper. He found that for paper made from mechanicals pulps, drying in superheated steam produced better-bonded sheet. The added strength was accompanied by a lower scattering coefficient and improved surface properties. Moreover, the drying rate achieved using superheated steam was found to be about twice as high as that achieved with air.

Pang and Dankin (1999) studied the drying rate and temperature profile for superheated steam vacuum drying versus moist air-drying of softwood lumber (*Pinus radiata*). They found that superheated steam produced a significantly faster drying rate than hot moist air.

Aly (1999) replaced the conventional air-drying of milk powder with superheated steam drying. In his work, Aly operated the superheated steam in a recycle mode where evaporated water is purged and compressed in a two-stage mechanical vapor compressor (MVC). The purged compressed steam is used to boost the superheated steam temperature from the circulating exit up to the required inlet temperature of the dryer. This process helped to reduce the energy consumption of the plant.

Furthermore, Li *et al*. (1999) concluded that superheated steam produced a faster drying rate for tortilla chips at elevated temperatures compared to air-drying. For the food material, steam-drying did not cause severe oxidation and burned regions like air did. Hence, it may be possible for superheated steam at intermediate to high temperature (140-180ºC) to not cause much discoloration of the lumber.

Experimental setup

Figure 1 presents a schematic diagram of the experimental setup, and Figure 2 depicts the actual equipment constructed. Steam driven from a 10 bar capacity boiler is heated into superheated steam using a 2 kW electrical heater prior to being injected into a 1.8 m^3 drying chamber. The rubberwood board is placed on a clamped rack support inside the chamber. After entering the chamber, the steam is impinged from a pair of perforated pipes located above and below the wood board. The pipes distribute the steam evenly inside the chamber (a sparging unit). A small vent releases the evaporated moisture and excess steam, and the condensed vapor leaves the chamber as liquid water through the steam trap. Some of the exiting vapor can also be passed through a vapor recompression stage (not shown) for recycling.

1. Wood samples

Rubberwood boards with dimensions of 1 m long x 7.62 cm wide x 2.54 cm thick were taken from Rutthapoom Parawood. The initial moisture content was approximately 50% dry basis (d.b.).

2. Drying conditions

Table 1 lists the various conditions used in this study.

3. Drying rate experiments

The drying rate for each condition was obtained by measuring the weight of the wood board after each period of drying. The initial moisture content of the wood was determined by cutting a small piece of the board and drying it in

Table 1. Experimental Conditions.

No.	Superheated Steam (110ºC)*	Hot Air (80ºC)
1	Continuous	-
2	6 hours	1 hour
3	4 hours	1 hour
4	1 hour	6 hours
5	-	Continuous

***Temperature inside the chamber**

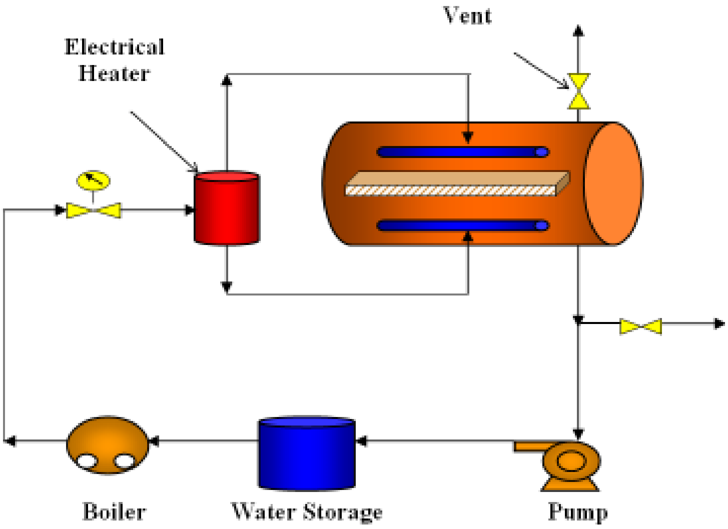

Figure 1. Schematic of superheated steam drying operation.

Figure 2. Actual equipment setup.

a 60ºC oven for 24 hours (modified from AOAC, 1990).

4. Temperature profile experiments

Thermocouples were placed at the surface of the wood and at the center of the wood for temperature profile experiments (see Figure 3). Temperature readings were taken using a digital reader.

5. Prong test

Initial acceptability of the dried wood was determined using the Prong Test (see Figure 4). For stress free drying the prongs should ideally remain straight or curve out slightly. If the prongs pinch in, then stress is present (Rosen, 1987). Prongs that curve inwards represent a casehardening scenario, while those that curve outwards and remain bent outward represent reverse casehardening scenario. A half-inch thick cross section of the wood was taken and cut into U-shape. If the ends of the U bend toward each other slightly, the wood was deemed unacceptable due to excessive stress buildup.

6. Mechanical Properties Measurement

After the optimum condition was obtained, multiple pieces of wood were dried simultaneously. These woods were then sent for physical testing at Walailak University. The properties measurements followed the guidelines of Kyokong and Duangpet (2000), and included hardness, compression, shear and bending (see Table 2).

7. Data analysis

The experimental data were averaged and analyzed using Microsoft® Excel 2002. All experiments were performed at least in duplicate.

Results and Discussion

1. Drying rates

Figure 5 illustrates the drying curves for superheated steam drying at 110ºC and hot air drying at 80ºC. The y-axis represents the moisture content in decimal dry basis (d.b.) and the x-axis is the drying time in hours (hr). The curves depict the general drying curve which consists of 3 distinct periods: (1) the initial heating period, (2) the constant drying period, and (3) the falling rate period. The initial period, characterized by a rapid increase in temperature of the wood from room temperature to the boiling point of water, is not clearly seen below since the time frame is small compared to the total drying time.

From Figure 5, the drying rates of both the superheated steam and the hot air were much faster than the conventional hot air drying method which takes 7-8 days for the moisture content of the wood to reach the acceptable value of less than 15% or 0.15 d.b. This was due to the impingement technique which caused rapid heat transfer to the surface of the wood and rapid moisture loss from the wood. However, the constant rate of drying for

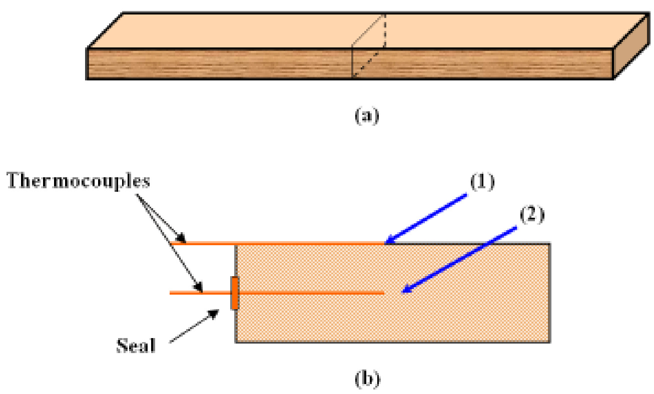

Figure 3. (a) View of board, showing the cross section where the thermocouples were inserted. (b) Cross-section view of the board showing the locations of the thermocouples (1) at the surface and (2) at the center.

Table 2. Standards used for testing of the physical and mechanical properties using the Lloyd Universal Testing Machine at Walailak University.

Properties	Standard Tests for Wood
1. Shearing Stress Parallel to Grain	BS 373 and ISO 3346
2. Compressive Stress	BS 373, ASTM 143 and ISO 3787
• Parallel to Grain	
• Perpendicular to Grain	
3. Hardness	ISO 3350
4. Strength and Stiffness in Static Bending	BS 373

Source: Kyokong and Duangpet (2000)

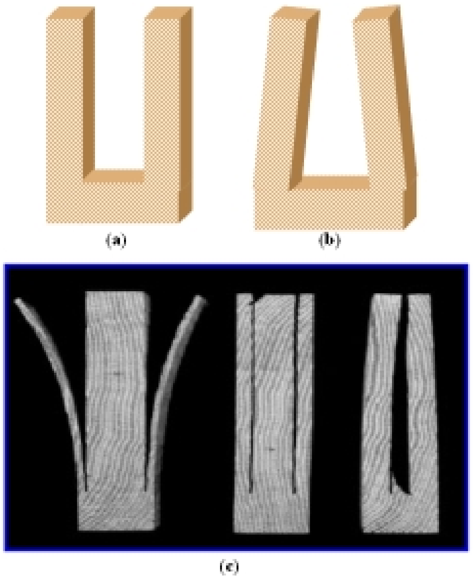

Figure 4. Prong test showing (a) acceptable piece of board, (b) unacceptable piece of board with excessive stress buildup (casehardening scenario), and (c) actual pieces of wood showing the result of excessive stress buildup.

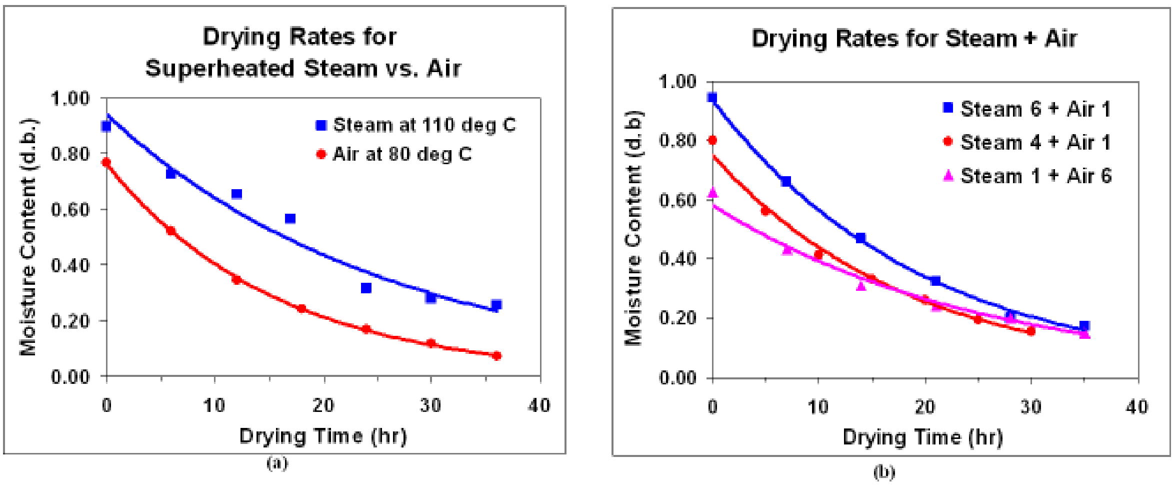

Figure 5. (a) Drying rates of superheated steam at 110ºC vs. hot air at 80ºC. (b) Drying rate at various combinations of superheated steam and air.

hot air was faster than that of superheated steam case due to lower humidity that resulted inside the chamber. After 25 hr of drying, the rate of water loss for the superheated steam case was quite low due to the high amount of water vapor that existed inside the chamber. Since the rate of water vapor leaving the vent and vapor condensing into liquid water was less than that of the entering steam, the humidity inside the chamber remained high. This caused the removal of the bound water to be very difficult. Hence, it was essential that the humidity of the chamber be reduced in order to decrease the final equilibrium moisture content (EMC) of the rubberwood.

Figure 5b shows that the moisture content of the rubberwood can be reduced to less than 0.15 d.b. using a combination of steam and hot air. Even though the case for 6:1 steam to air ratio scenario began at a higher initial moisture content, the slopes of the drying curve were very similar to that of the 4:1 steam to air scenario. Nevertheless, the former case was preferred over the 4:1 and 1:6 cases, because it passed the prong test (see Table 3).

2. Temperature profile

Figure 6 presents the temperature profiles (ºC) at the center and at the surface of the wood as a function of drying time (hr). As mentioned previously, the temperature at each point increased rapidly until the boiling point of water is reached (slightly lower than 100ºC due to dissolved solutes in the water). Figure 6a illustrates that the temperature at the surface increases faster than at the center. The temperature at the surface reached the boiling point after 1.2 hr of drying, while it took about 1.6 hr of drying for the temperature at the center to reach the boiling point.

Furthermore, Figure 6b illustrates that even after the 30 hours of drying, the temperature at the center and at the surface of the wood remained near 100ºC indicating the presence of water tightly bounded along the cell wall of the wood. It would take complete drying of the wood board (negligible amount of water remaining) before the temperature could increase toward the temperature of the superheated steam inside the chamber.

Table 3. Results of prong test.

Condition	EMC less than 0.15 d.b.	Passed Prong Test
Steam only	No	-
Air only	Yes	No
Steam 6: Air 1	Yes	Yes
Steam 4: Air 1	Yes	No
Steam 1: Air 6	Yes	No

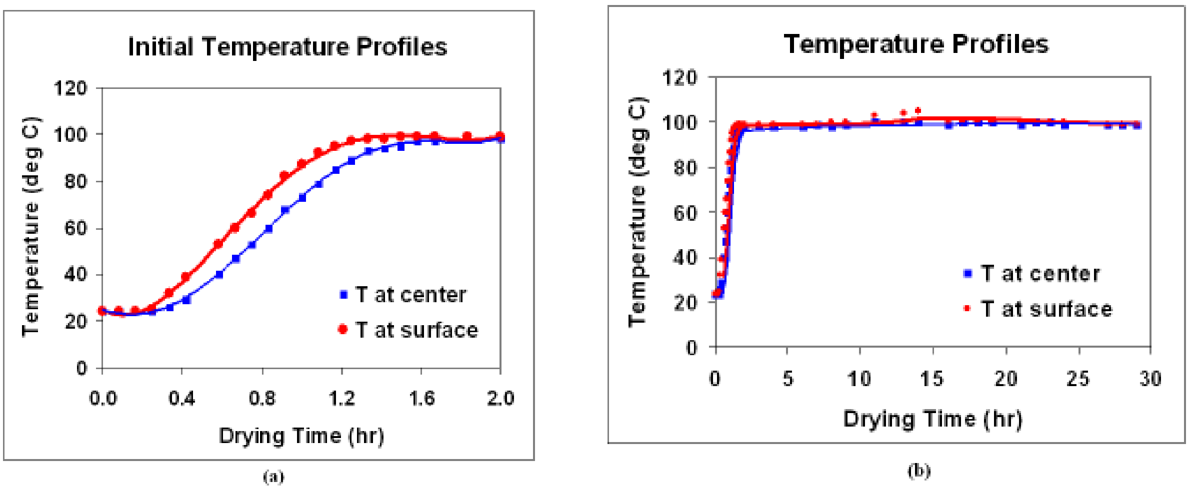

Figure 6. Temperature profiles at the center and at the surface of the wood (a) after 2 hr and (b) after 30 hr of drying. Superheated steam at 110ºC and 4:1 steam to air ratio was used.

3. Physical analysis

Table 3 shows the results from the Prong Test for cases in which the acceptable moisture content of 0.15 d.b. was reached. The ratios of Steam 6: Air 1 represented a drying scheme of 6 hours of steam followed by 1 hour of air drying. The scheme was repeated until the equilibrium moisture content was reached. Even though the Air Only, the Steam 4: Air 1, and the Steam 1: Air 6 cases reached the acceptable moisture content, their rates of moisture loss might have been too rapid, causing excessive stress buildup which led to their failing the Prong Test (see Figure 7).

Moreover, the coloration of the dried samples using superheated steam at 110ºC did not show any burnt spots or discoloration of the wood. This might be due to the influence of superheated steam as the heat transferring medium, which prevented oxidizing of the wood surface during the drying process.

4. Optimization Study

Several drying schedules or drying tables, based on various combinations of superheated steam and hot air, were studied to develop the most optimum schedule that could reduce the initial stress buildup that led to warping and cracking of the lumber boards during the first part of the experiment. In addition, these schedules should be able to reduce the overall drying time compared to the conventional process. Thus, this optimization study focused on using a lower initial steam temperature to keep the wood surface from drying too quickly and reducing the internal moisture gradient inside the wood which was responsible for stress buildup. For the middle stages of drying, higher steam temperatures of 105 and 110ºC were used in alternating cycle with hot air at 80ºC. This was to increase the drying rate and to remove the free water and most of the bound water from inside the wood. Finally, during the last stages of drying, hot air was used continuously to reduce the relative humidity inside the drying chamber making it possible for the removal of the residual bound water from within the cell walls of the wood. Table 4 details the optimized drying schedule that was developed, while Figure 8 shows the drying curve for the optimized case compared to the 6:1 steam to air ratio. From the figure, it can be seen that the rates are very similar. However, a close look shows that after 7 hours of drying, the moisture content (d.b.) of the optimized condition was 0.76 compared to 0.66 for the 6:1 case. This slower initial rate helped to maintain an acceptable stress gradient within the wood, which consequently resulted in reduced stress development.

In addition, even though the optimized case required a longer period of drying compared to the 6:1 scenario, it was still more practical since it required less amount of steam and took less than 2 days for the moisture content to reach 0.15 d.b. Therefore, the optimized case was selected for the mechanical properties measurements.

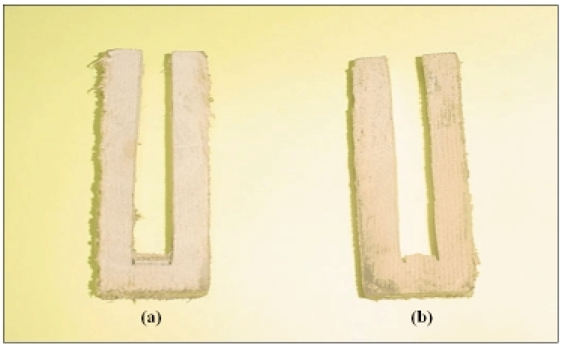

Figure 7. (a) Hot air dried wood showing slight bending of the prong. (b) Superheated steam 6: air 1 case showing the lack of stress buildup.

Table 4. Optimized drying schedule.

Period	Description
0-7th hour	Start of by drying with steam at 100ºC for 4 hours followed by steam at 105ºC for 3 hours.
8-14th hour	Dry with superheated steam at 105ºC for 6 hours followed by hot air at 90ºC for 1 hour.
15-21st hour	Dry with superheated steam at 110ºC for 6 hours followed by hot air at 90ºC for 1 hour.
22-26th hour	Dry with superheated steam at 110ºC for 4 hours followed by hot air at 90ºC for 1 hour.
27-31st hour	Dry with superheated steam at 110ºC for 4 hours followed by hot air at 90ºC for 1 hour.
32-35th hour	Dry with superheated steam at 110ºC for 1 hour followed by hot air at 80ºC for 3 hours.
36-41st hour	Dry with superheated steam at 110ºC for 1 hour followed by hot air at 80ºC for 5 hours.

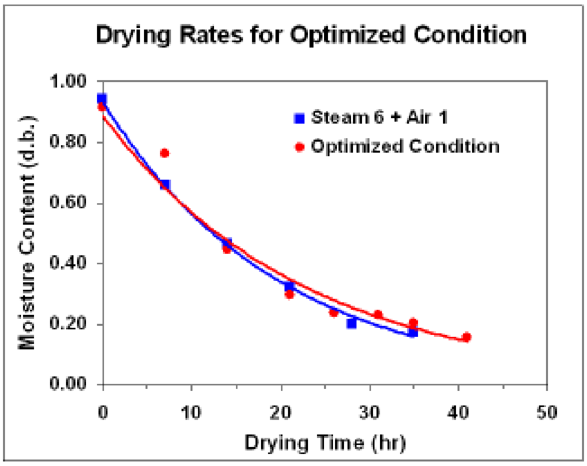

Figure 8. Drying of the optimized condition compared to the 6:1 steam to air ratio case.

Figure 9. Three pieces of boards clamped and dried using the optimum drying schedule.

Table 5. Mechanical properties of dried rubberwood.

Properties	Optimized Drying	Conventional Drying*	Reference**	p
Shear Parallel to Grain (MPa)	13.66±1.44	15.35±1.23	11.0	0.000
Compression (MPa)				
• Parallel to Grain	37.10±2.14	52.66±4.21	32.0	0.000
• Perpendicular to Grain	1.93±0.31	2.06±0.18	5.0	0.040
Static Bending (MPa)				
• Modulus of Rupture (MOR)	91.40±7.85	107.06±11.42	66.0	0.000
• Modulus of Elasticity (MOE)	7388±1138	9721±1606	9240.0	0.000
Hardness (N)	4259±570	4890±482	4350.0	0.001

Sources: *Rutthapoom Parawood
****Killmann, W. and Hong, L.T. (2002)**

5. Mechanical Properties Tests

For mechanical properties testing, 3 pieces of lumber, Grade A and B (depending on the availability), were clamped and dried together as shown in Figure 9. Twenty random samples were prepared for each of the mechanical tests according to ASTM D1990-91 where the moisture content of each sample was adjusted to about 0.12 d.b. prior to the testing. The mechanical properties studied included the shear parallel-to-grain, the compressions parallel- and perpendicular-to-grain, the static bending tests (modulus of elasticity and the modulus of rupture), and the hardness.

The results of the mechanical properties are listed in Table 5 showing that both values of the shear parallel-to-grain of 13.66 MPa and the compression strength parallel-to-grain of 37.10 MPa for the optimized drying condition were higher than the acceptable literature values of 11.0 and 32.0 MPa, respectively. However, the strength perpendicular-to-grain and the modulus of elasticity (MOE) values were significantly lower than those from the literature. Nonetheless, the modulus of rupture (MOR) was substantially higher than that of the reference indicating that the wood dried using superheated steam can withstand a high breaking force. A high MOE value does not necessary mean the wood is stronger since it indicates a higher fracturability and brittleness of the wood. On the other hand, the comparable values of the hardness indicated that the wood was sufficiently hard for the various furnishing applications. Overall, the strength of the wood is considered good compared to the literature values.

Figures 10 and 11 compare the mean values of the optimized drying condition, the conventional drying condition, and those taken from literature. Statistical analysis of the data using the paired comparison design shows significant difference ($p<0.05$) between the optimized drying condition and the conventional drying conditions. Values of the shear and compression parallel-to-grain, the compression perpendicular-to-grain, the MOR, the MOE, and the hardness were all significantly lower at 95% confidence level. This agrees with results from Bekhta and Niemz (2003) who showed that high temperature drying has a significant influence on the mechanical properties of Spruce wood. However, Thiam, Milota and Leichti (2002) found no significant effect of temperature on the mean MOR, MOE and shear strengths of Western Hemlock lumber after drying under high temperature.

Moreover, moisture content is an important factor influencing the mechanical properties of the wood. Since specimens from the optimized drying and the conventional drying had varying moisture content, 0.13 d.b. to 0.09 d.b., respectively, the mechanical properties of the latter were higher as expected. Although most properties will continue to increase with lower moisture content, some properties reach a maximum value and then decrease with further drying (USDA, 1999; Kretschmann and Green, 1996; Matan and Kyokong,

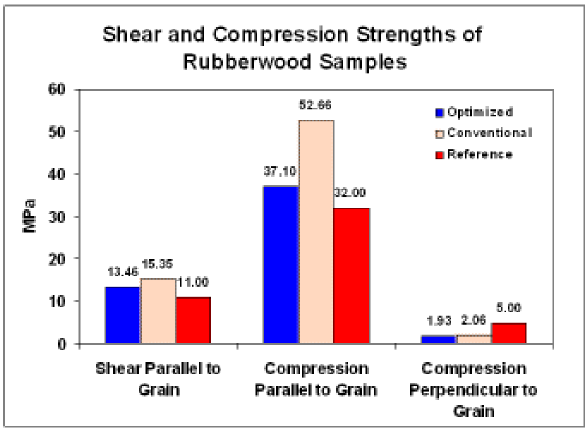

Figure 10. Shear and compression strengths of wood samples tested.

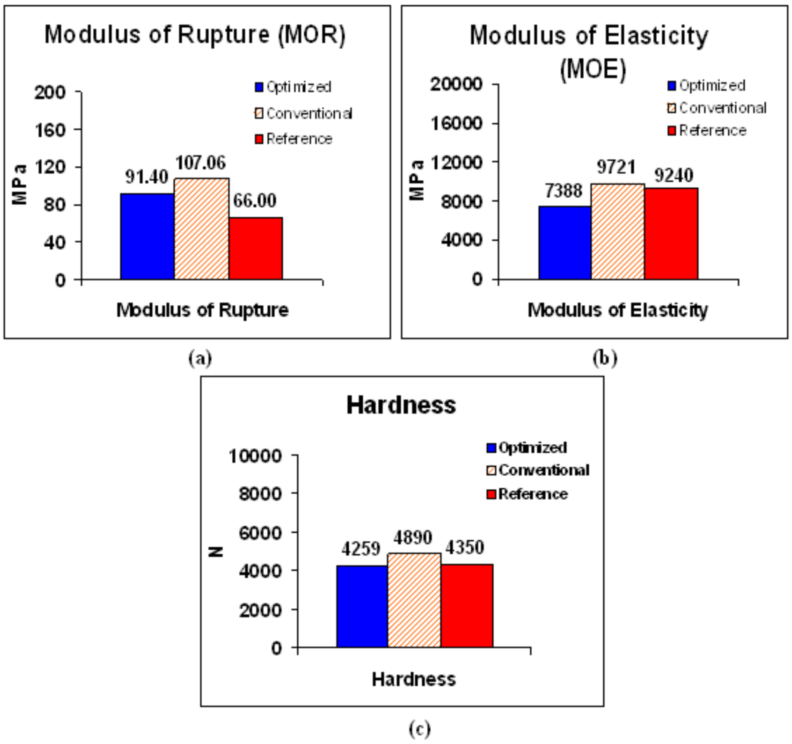

Figure 11. Static bending and hardness results of wood samples tested: (a) Modulus of Rupture (MOR), (b) Modulus of Elasticity (MOE), and (c) Hardness.

2002).

Finally, even though the values of the optimized condition were lower than the conventional drying scenario, the values still compared relatively well with the literature values. Deviations in the values of all cases might have resulted from the non-uniformity of the raw materials and the specimens selected for measurements.

6. Energy saving potential

In traditional wood drying operations in Thailand, boilers are used to generate steam which

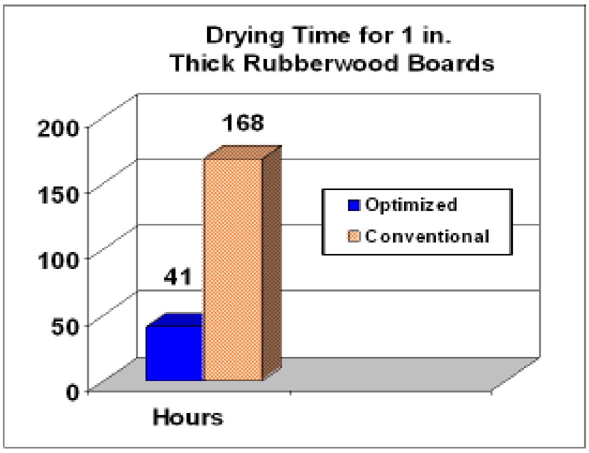

Figure 12. Drying time comparison between optimized condition and the conventional drying for 1 in. thick rubberwood board.

is then fed into heating coils for the heating of hot air from compressors. The fuel sources for the boiler are wood chips and wood dusts which are inexhaustible byproducts of the wood cutting process. Therefore, the usage of superheated steam, which can be generated using high pressure, high temperature heating coils or even electrical coils, can reduce drying operations by as much as 75%. From preliminary studies, superheated steam drying presents a significant energy savings in terms of drying time. As shown in Figure 12, the potential energy savings offered by superheated steam/air drying is in term of drying time where it takes only 41 hours (less than 2 days) compared to 168 hours (7 days) for the conventional process.

Conclusions

A lab-scale superheated steam dryer was constructed to study the effectiveness of superheated steam in the drying of rubberwood. Experiments indicated that a significantly shorter drying time could be obtained by using a combination of superheated steam and hot air. In addition, using the optimum drying condition, the mechanical property of the rubberwood boards can also be maintained, in particular, the shear parallel-to-grain, the compression strength parallel-to-grain, and the hardness of the product. Also, the color of the rubberwood was not significantly affected by the drying temperature. Finally, the operational cost of the drying process can be decreased due to the reduced drying time from 7 days to less than 2 days. Since the superheated steam will only be used at intermittent intervals, the cost of superheating the steam will be minimal compared to the longer drying time of the conventional process.

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