Chapter 4

RESULTS AND DISCUSSION

The results and discussion of our experiments according to the objective aims are as followed: drying rates, temperature profile, physical and mechanical analysis, energy saving potential and economic analysis.

4.1 Drying rates

A comparison of the drying curves for the 2 methods used in this study, namely Figure 4-1, demonstrates the vast improvement in drying time, which is reduced from 6-7 days when drying in conventional to 2 days under superheated steam drying. A different batch of wood lumber was placed in the superheated steam drying chamber and dried to moisture level of 15%. Each condition was repeated three times.

Figures 4-1 illustrates the drying curves for superheated steam drying at 110°C and hot air drying at 80°C. The y-axis represents the moisture content in dry basis (d.b.) and the x-axis is the drying time in hours. 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 initial temperature to the boiling point of water, is not clearly shown below since the time frame is small compared to the total drying time. The rapid increase in temperature is shown in Figures 4-4 and 4-5.

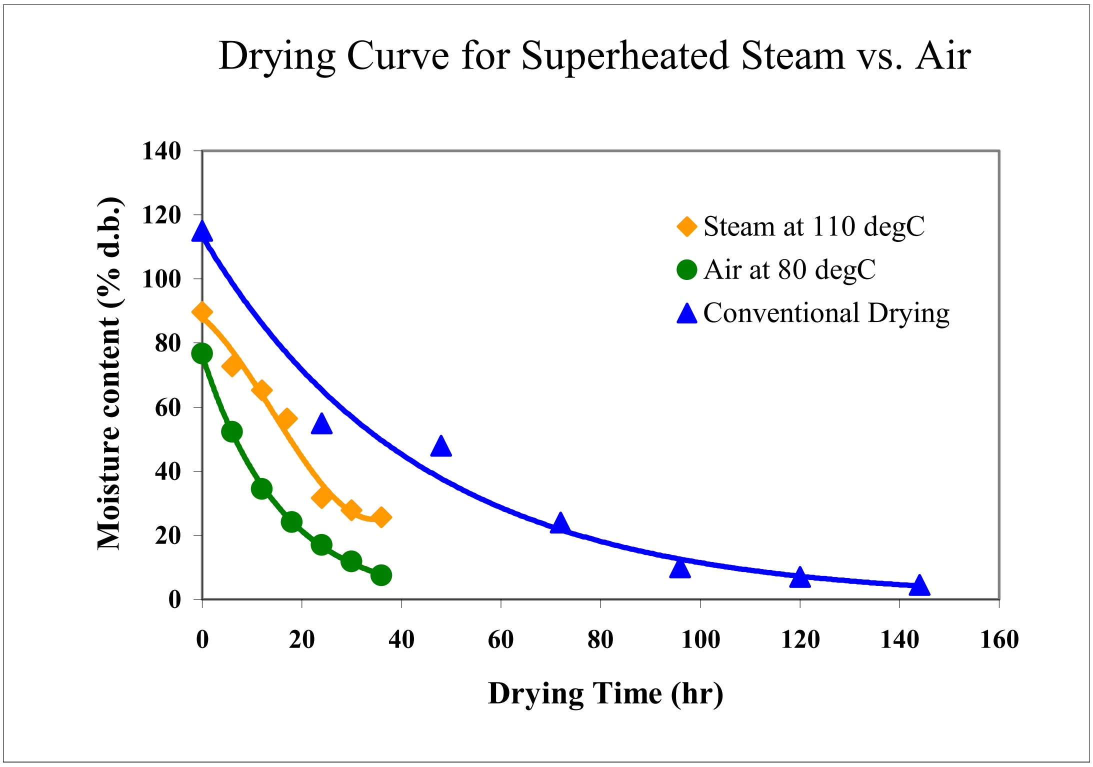
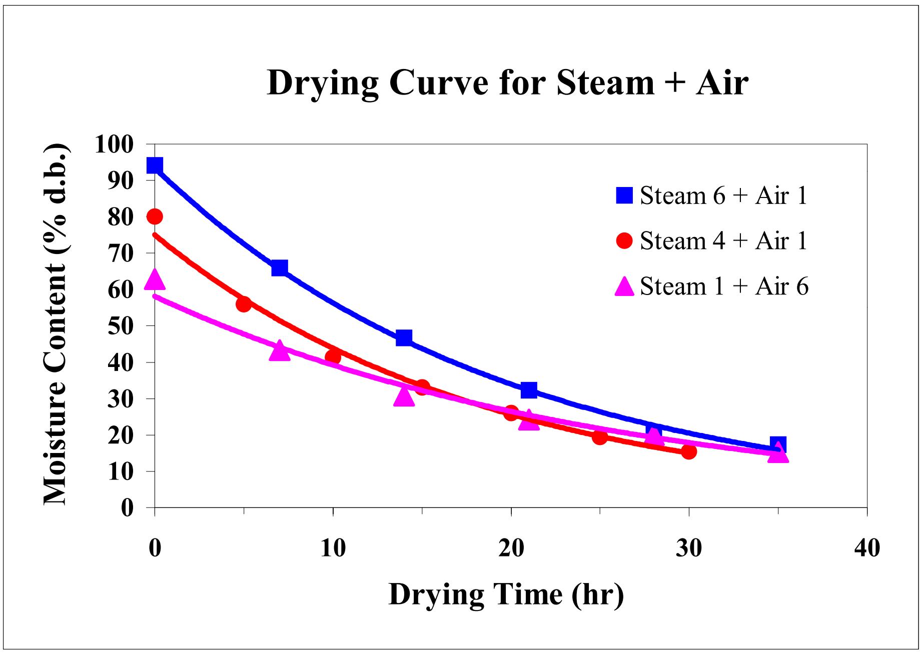


Figure 4-1 Drying curve of superheated steam at 110°C, hot air at 80°C and conventional drying.

Figure



2 Drying curve at various combinations of superheated steam and air vs. superheated steam at 110°C.

For the drying with hot air, moisture change over time followed an exponential function, typical for the drying of agricultural products in hot air (Tang and Cenkowski, 2000). Because the number of samples used is less than that in the industrial drying, the drying rates of both the superheated steam and the hot air are much faster than the conventional methods, which take 6-7 days for the moisture content of the wood to reach 25% d.b (Figures 4-1 and 4-2). This is due to the impingement technique which causes rapid heat transfer to the surface of the wood and rapid moisture loss from the wood. The constant rate of drying for hot air is faster than that of superheated steam case due to lower humidity that developed inside the chamber. Moreover, during the falling rate period, the wood gained some amount of moisture because of steam condensation on the surface of the sample.

Nonetheless, superheated steam can provide an excellent medium for drying food products. Compared to dry air, superheated steam is cleaner, provides higher evaporation rate and results in is less oxidation in food (Li et al, 1999; Moreira, 2001). But the wood in this study dried to about 30% moisture content over a period of 25 hours after which time the rate of moisture removal slowed down. So that after 10 hours, the moisture content had only reduced to about 20%. It is due to the high amount of water vapor that exists inside the chamber. Since the rate of water vapor leaving the vent and the rate of vapor condensation is less than that of the entering steam, the humidity inside the chamber remained high causing 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. Chu et al. (1959) revealed that the drying rate will be improved when dry air is mixed with superheated steam. The phenomena leads to the existence of a critical temperature at which the evaporation rates of water into superheated steam and dry air are equal. Hence, fresh air was used to replace moist air for decreasing humidity inside the drying chamber.

Figure 4-2 shows that the moisture content of the rubberwood can be reduced to less than 20% 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 is very similar to that of the 4:1 steam to air scenario. Nevertheless, the former case is preferred over the 4:1 and 1:6 cases, because it passed the prong test.

Because the case for steam 6+ air 1 ratio scenario used steam for total a of 30 hours and air for a total of 5 hours, respectively, it is essential to reduce the steam usage while also passing the physical properties tests which was determined using the prong test. Figure 4-3 shows a comparison of drying rates between steam 6+ air 1 ratio and the optimum drying rate that used saturated steam initial of drying to prevent a stress buildup and after that dried with high temperature drying.

The shape of the curve for optimum drying condition using steam for 29 hours and hot air for 12 hours is similar to that of the curve for steam 6+air 1 case, but the drying time was 6 hours slower. The optimum case also passed the prong test which showed a lack of stress buildup.

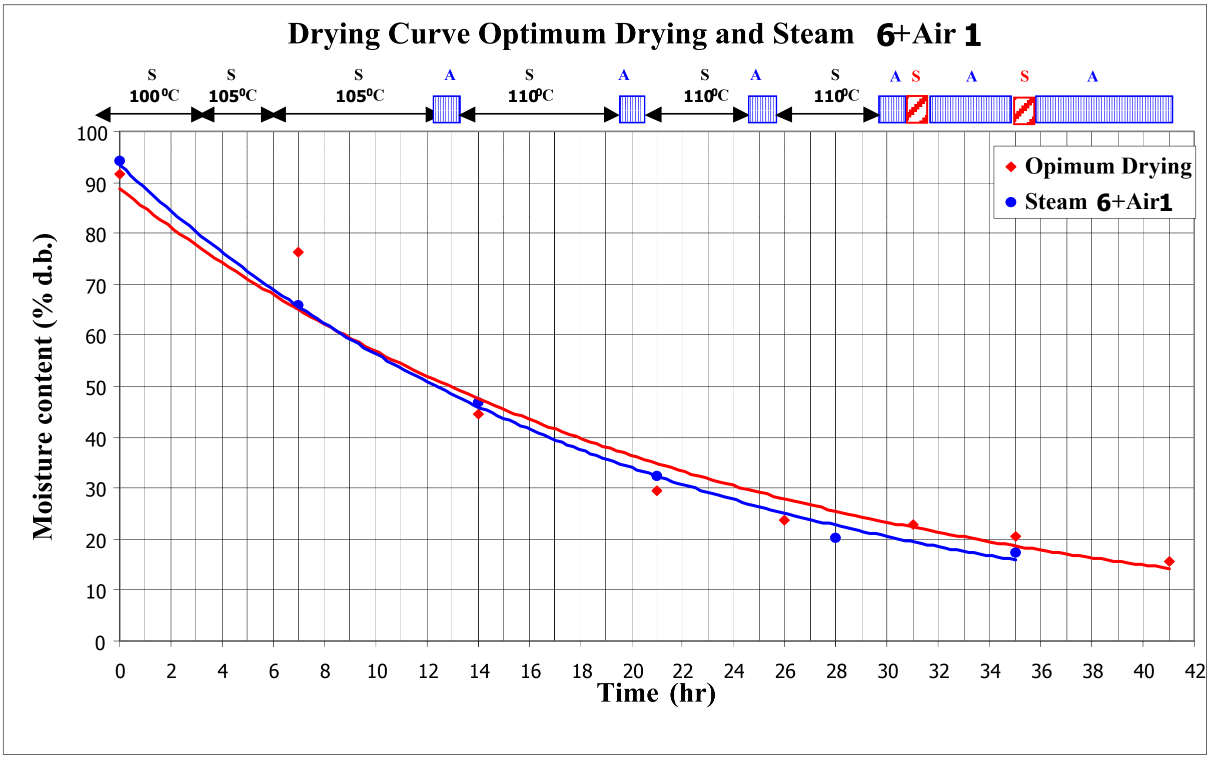


Figure 4-3 Comparison of drying curve between the optimum drying condition and the steam 6: air 1 case.

A = air drying S = steam drying

4.2 Temperature profile

Figure. 4-4 and 4-5 show the temperature profiles (°C) inside the drying chamber, at the center and at the surface of the wood as a function of drying time (hr).

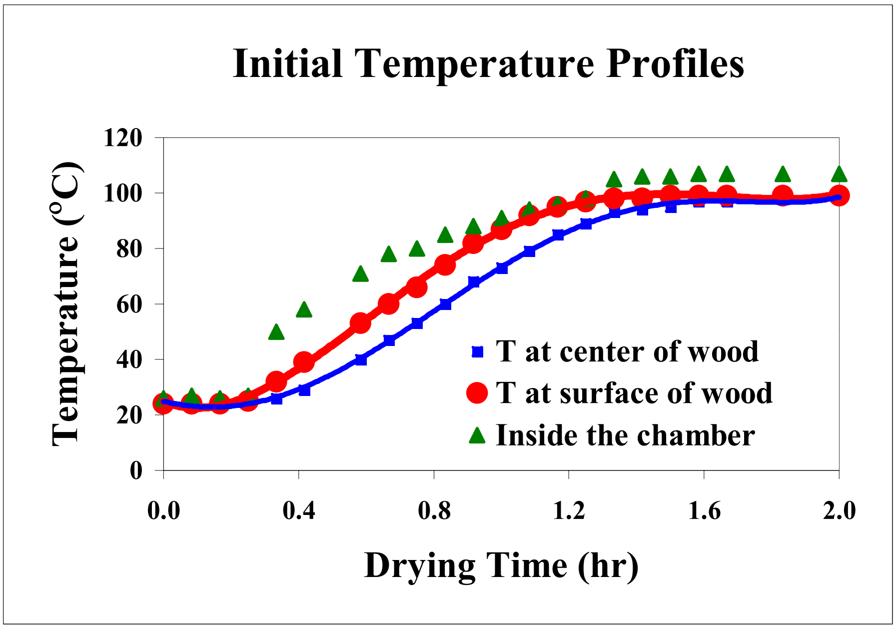


Figure 4-4 Initial temperature profile at the center and at the surface of the wood.

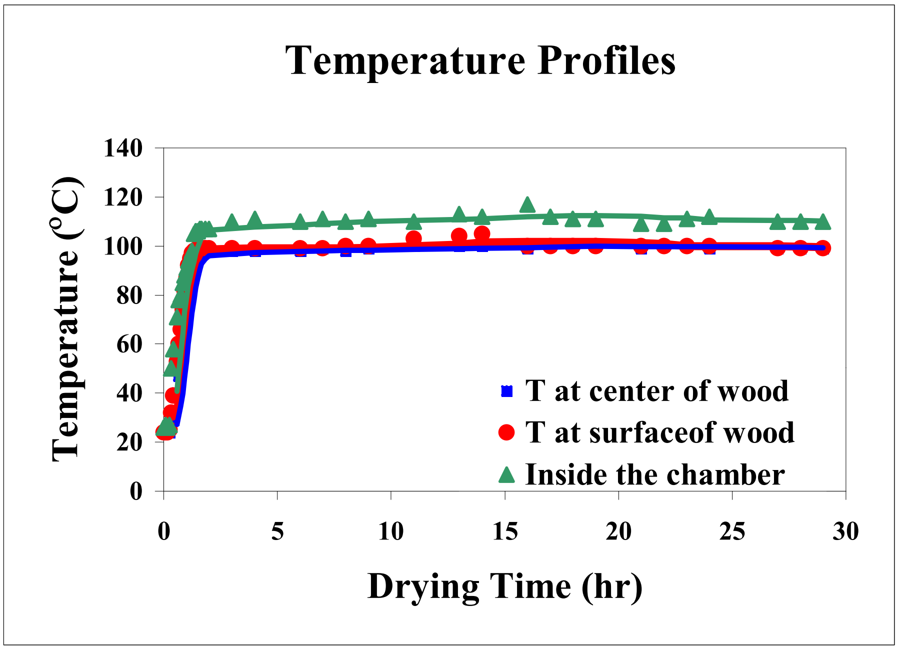


Figure 4-5 The overall temperature profile after 30 hr of drying. Superheated steam at 110°C and 4:1 steam to air ratio.

Figure 4-5 illustrates that the temperature in drying chamber took about 1.25 hours to reach the boiling point. After that, it took about 30 more minutes to reach superheated steam (110°C) condition. The wood temperature at the surface reached the saturation point of the steam in 1.5 hours. The center of the wood reached the boiling point slower than at the surface and it took about 1.8 hours.

Because of dissolved solutes in the water and solution within the rubberwood, such as cellulose, pentosan, lignin and ash (Theppaya, 1998), after drying for 30 hours, wood temperature could not reach the drying temperature (110°C). Furthermore, the surface and center temperatures of the wood remained at 100°C indicating that there were still some water remaining inside.

4.3 Physical and Mechanical Properties

4.3.1. Physical Properties

Drying defects occurred during and after drying with superheated steam continuously for 36 hours. Figure 4-6a shows the end check after drying. Simpson, et al. (1991) reported that end checks occurred in the wood rays, but on end-grain surfaces. End checks occur because moisture moves much faster in the longitudinal direction than in transverse direction. There, the ends of boards dry faster than the middle and stresses develop at the ends.

The coffee-brown stains that developed during the superheated steam drying are shown in Figure 4-6b. The results are in agreement with Bekhta and Niemz (2003) who studied the effect of high temperature drying on the color of Spruce wood and said that high temperature has a significant influence on the discoloration.

Dark discolorations that develop in lumber with wet wood result from an oxidative or a metallic-tannate reaction. In both situations wood extractives are chemically degraded by the bacteria (usually under anaerobic conditions in the tree), which results in the production of compounds that darken when heated under oxidative conditions or when placed in contact with metals such as iron (Simpson, et al., 1991).

(a) **(b)**

Figure 4 –6 drying defects: (a) end check (b) warp and discoloration.

In the industry, good stacking is the best way to minimize warping. But in this research, only a few boards were dried per batch, so warping was reduced by placing woods on a clamped rack during drying process (see Figure 4-7). After drying with superheated steam and air, woods which were placed on clamped rack were straight (show in Figure 4-8).

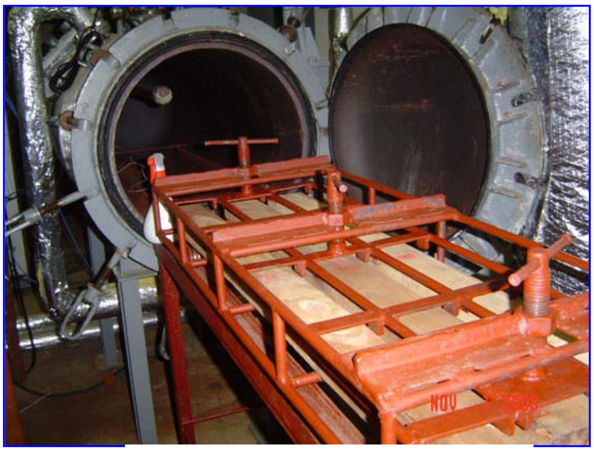


Figure 4-7 Clamp rack.

Figure 4-8 showing the straight wood after drying because wood was placed on the clamped rack support inside the chamber.

After the lumber has been dried to the desired final moisture content (15%), prong tests for drying stresses were conducted. A prong test indicates the amount of elastic stress in the wood at the time of cutting. The prongs may change their shape after cutting if the moisture content changes (Rosen, 1987).

Table 4-1 below shows the results from the prong tests for cases in which the acceptable moisture content was reached (approximately 15% d.b.). 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 may have been too rapid, causing excessive stress buildup which led to their failing the prong test (see Figure 4-9).

Table 4-1 Results of prong test.

Condition	Moisture content < 20%	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
Optimum drying	Yes	Yes

From Figure 4-9, superheated steam 6+ air 1 ratio case showed the lack of stress buildup, and this case should be the optimum drying condition with superheated steam followed by air. But because of some defects occuring during and after drying, such as end-check, uneven moisture content, it was necessary to determine the much more optimum condition for reducing drying defects and maintaining the drying rate to be as fast as the steam 6: air 1 case.

Figure 4-10 shows acceptable prong tests after drying at the new optimum condition (see the drying schedule in Table D-2). Although wood dried under this condition took 5 hours longer than the steam 6: air 1 case, the reduction of steam could save energy in the heating of superheated steam.

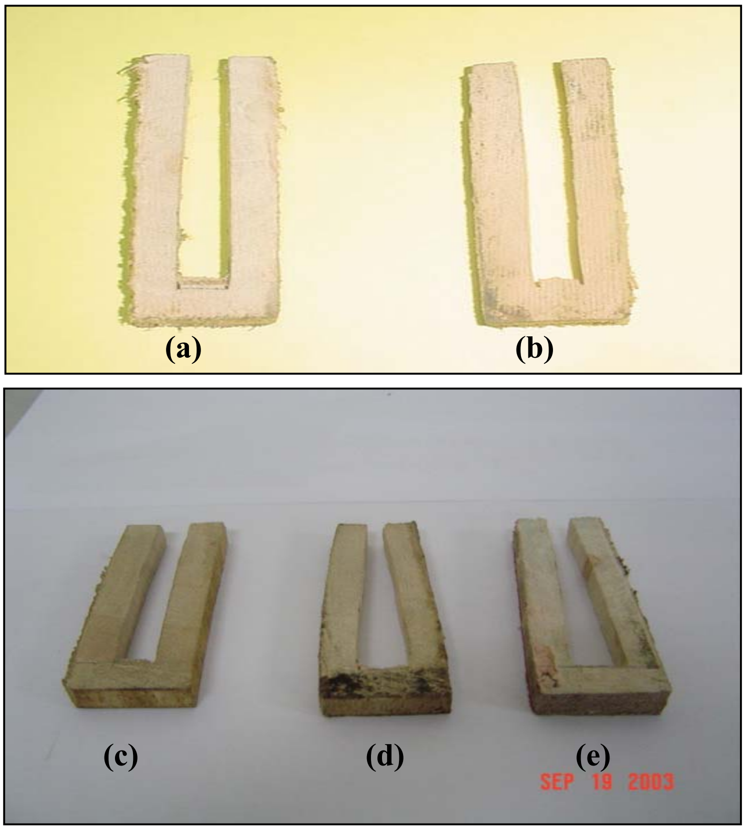


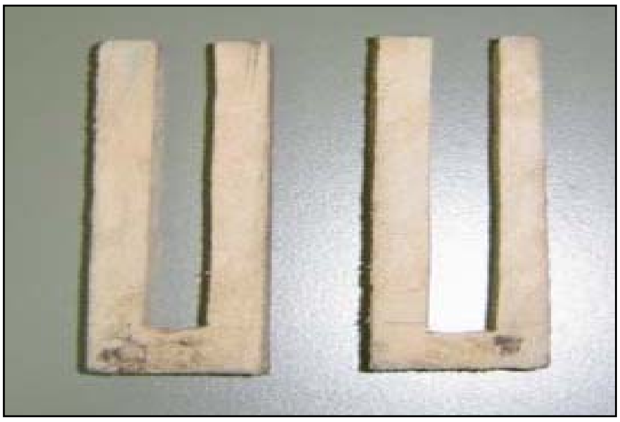
Figure 4-9 (a) Hot air dried wood showing slight of the prong. (b) Superheated steam 6: air 1 case showing the lack of stress buildup. (c) Conventional drying (from Rattapoom Parawood Factory). (d) Superheated steam 4: air 1. (e) Superheated steam 1: air6.

Figure 4-10 Optimum dried wood showing the lack of stress buildup.

4.3.2. Mechanical Properties

The strength and stiffness data were adjusted to 12% MC following the practice given in Kyokong and Duangpet (2000). Table 4-2 and 4-3 show the coefficient of variation (COV) for mechanical properties of the drying treatment groups. These indicate that the drying treatment had no substantial effect on the amount of variation of mechanical properties (COV<20%).

Table 4-2 Mean, coefficient of variation (COV), minimum, and maximum data for specific gravity adjusted to 12% moisture content.



Condition	Properties	Specific gravity			
		Mean	COV (%)	Minimum	Maximum
1. Superheated steam drying followed by air	Shear strength parallel to grain	0.55	4.07	0.50	0.58
	Compression strength				
	• parallel to grain	0.56	3.83	0.52	0.61
	• perpendicular to grain	0.65	7.45	0.54	0.69
	Hardness	0.60	7.90	0.54	0.71
	Static bending	0.64	7.46	0.53	0.68
2. Conventional drying (from Rattapoom parawood factory)	Shear strength parallel to grain	0.70	3.50	0.66	0.73
	Compression strength				
	• parallel to grain	0.68	2.85	0.65	0.73
	• perpendicular to grain	0.69	3.05	0.66	0.75
	Hardness	0.68	2.72	0.65	0.73
	Static bending	0.69	3.83	0.64	0.74

Number of samples per each mechanical property tests = 20

COV = coefficient of variation

Table 4-3 Mean, coefficient of variation (COV), minimum, and maximum data for moisture content.

Condition	Properties	Moisture content(%)			
		Mean	COV (%)	Minimum	Maximum
1. Superheated steam drying followed by air	Shear strength parallel to grain	13.32	2.88	12.70	13.90
	Compression strength				
	• parallel to grain	13.18	1.40	12.76	13.51
	• perpendicular to grain	13.28	1.26	12.98	13.56
	Hardness	12.02	0.90	11.74	12.20
	Static bending	13.60	1.68	13.25	13.97
2. Conventional drying (from Rattapoom parawood factory)	Shear strength parallel to grain	9.38	5.03	8.25	10.16
	Compression strength				
	• parallel to grain	9.69	1.68	9.37	10.0
	• perpendicular to grain	9.38	2.32	9.06	9.85
	Hardness	9.44	2.40	8.98	9.89
	Static bending	9.15	1.67	8.85	9.49

Number of samples per each mechanical property tests = 20

COV = coefficient of variation

Table 4-4 shows a comparison between mechanical properties of wood dried under superheated steam, from conventional drying and from the literature.

After drying with superheated steam at 110°C for 41 hours, the mean values of the shear strength and compression parallel to grain and the compression perpendicular to grain were 13.46, 37.10 and 1.93 MPa, respectively, for the lumber dried under the superheated steam drying (see Figure 4-11, 4-12 and 4-13).

Figure 4-14 and 4-15 show that the mean values of the MOR and MOE were 91.40 and 7387.64 MPa, respectively, for the superheated steam drying. Figure 4-16 shows that the superheated steam dried wood had a value of hardness about 4259.03 N. It shows that mechanical properties, in this study, are lower than wood from the commercial industry.

The drying of timber at elevated temperatures is seen to reduced the drying time from 6-7 days to 2 days in case of conventional drying with the benefits of potential time savings to industry; however, the mechanical properties of this material were reduced under this drying condition. In all of the strength tests performed on the dried wood, there was a trend towards decreased strength with respect to an increase in the rate of drying.

Statistical analysis of the data from the paired comparison design shows significant difference ($p < 0.05$) between these drying methods when considering shear and compression parallel to grain, compression perpendicular to grain, MOE, MOR and hardness at 95% confidence level. Results agree with Bekhta and Niemz (2003), who showed that high temperature drying had a significant influence on mechanical properties of Spruce wood. But Thiam, Milota and Leichti (2002) found no effect on the mean MOR, MOE and shear strength of Western Hemlock lumber after drying under high temperatures.

Simpson et al (1991) and USDA (1999) reported that temperature affect the mechanical properties of wood. In general, the mechanical properties of wood decrease when heated and increase when cooled. At a constant moisture content and below approximately 150°C (302°F), mechanical properties are approximately linearly related to temperature.

With the exception of temperature effect on strength of wood, moisture content is an important factor influencing its physical and mechanical property behaviors. In this study, moisture content of specimens at the time of all tests under superheated steam and conventional drying was about 13 and 9%, respectively.

Previous studies indicated that mechanical properties are affected by changes in moisture content below the fiber saturation point. Although most properties will continue to increase while wood is dried to very low moisture content levels, for most species, some properties may reach a maximum value and then decrease with further drying (USDA 1999; Kretsmann and Green 1996; Matan and Kyokong 2003).

Because of these factors, superheated steam drying gives lower mechanical properties than does conventional drying in this study.

Comparison of mechanical properties between superheated steam drying and reference data from previous studied, shows that the mean value of the compression perpendicular to grain, the MOE and the hardness value were lower than the reference values. The mean values of the shear strength and compression parallel to grain and the MOR were higher than the reference values (Figure 4-11 to 4-16).

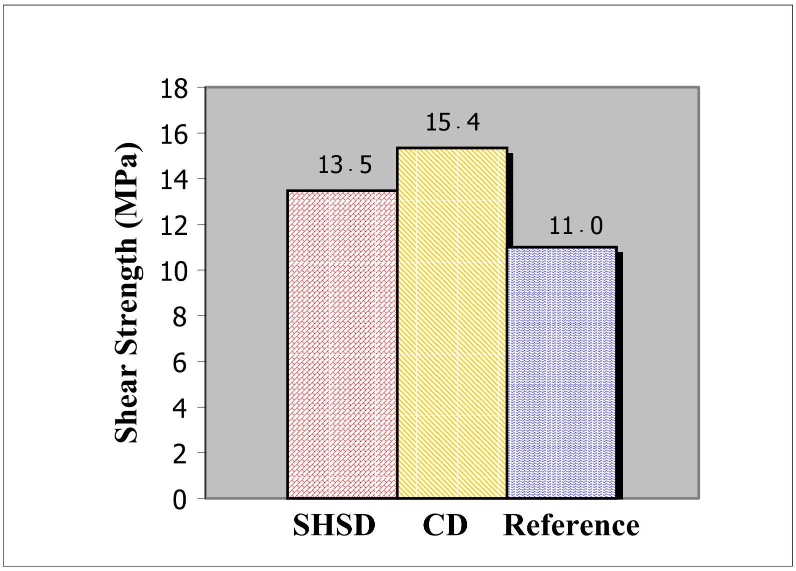
Nonetheless, measurements of the mechanical properties in this research may differ from values in literature (Table 4-4). This difference between the mechanical properties might be the result of difference dimensions of the test specimens, test rates and testing equipment. Deviations in process temperatures, energy distribution, wood temperature and moisture contents could also have given rise to errors in the analysis.

Table 4-4 Summary of mechanical properties of rubberwood at various drying conditions. Standard deviation is in parentheses.

Properties	Superheated Steam Drying	Conventional Drying*	p-value	Reference**
Shear strength parallel to grain (MPa)	13.46 (1.44)	15.35 (1.23)	<0.05	11.0
Compression strength (MPa)				
• Parallel to grain	37.10 (2.14)	52.66 (4.21)	<0.05	32.0
• Perpendicular to grain	1.93 (0.31)	2.06 (0.18)	<0.05	5.0
Static bending (MPa)				
• Modulus of rupture(MOR)	91.40 (7.85)	107.06 (11.42)	<0.05	66.0
• Modulus of elasticity(MOE)	7387.64 (1134.80)	9721.41 (1605.56)	<0.05	9240.0
Hardness (N)	4259.03 (570.34)	4890.09 (481.81)	<0.05	4350.0

Source: * Rattapoom Parawood factory.

**Killmann. W. and Hong. L. T. (2002).



SHSD = Super heated steam drying

CD = Conventional drying

Reference = Killmann.W.and Hong.L.T. (2002)

Figure 4-11 Mean value of shear parallel to grain plot against drying condition.

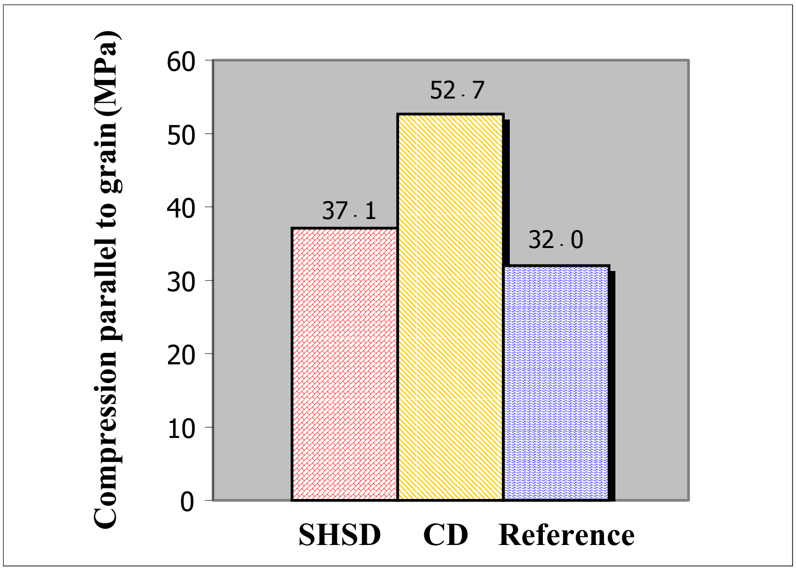


Figure 4-12 Mean value of compression parallel to grain plot against drying condition.

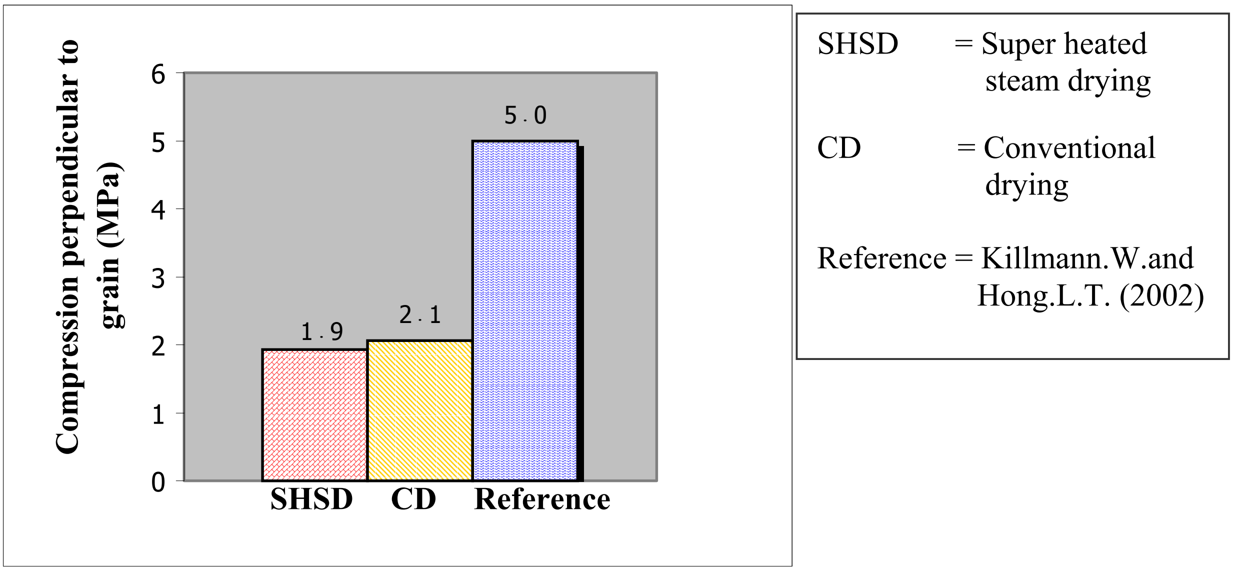


Figure 4-13 Mean value of compression perpendicular to grain plot against drying condition.

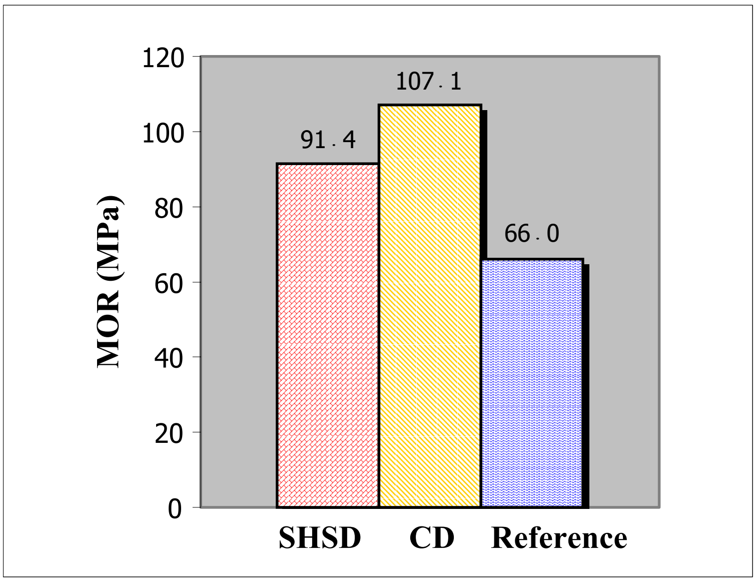
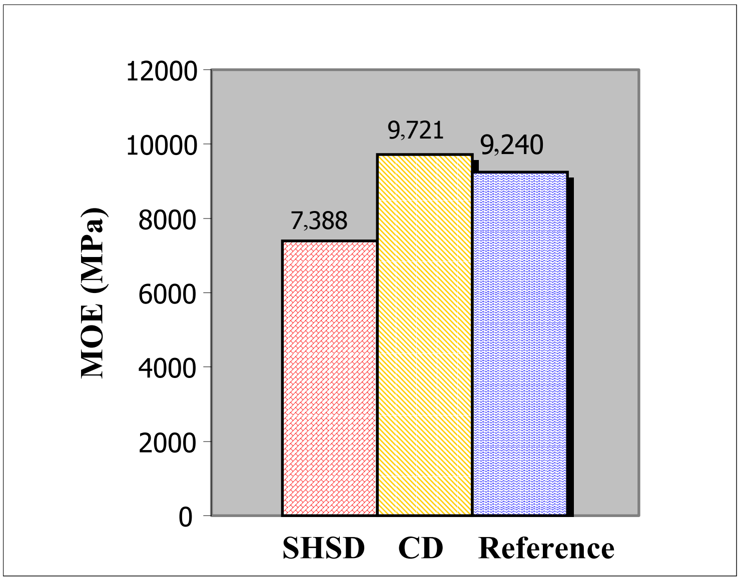


Figure 4-14 Mean value of modulus of rupture (MOR) plot against drying condition.



SHSD = Super heated steam drying

CD = Conventional drying

Reference = Killmann.W.and Hong.L.T. (2002)

Figure 4-15 Mean value of modulus of elasticity plot against drying condition.

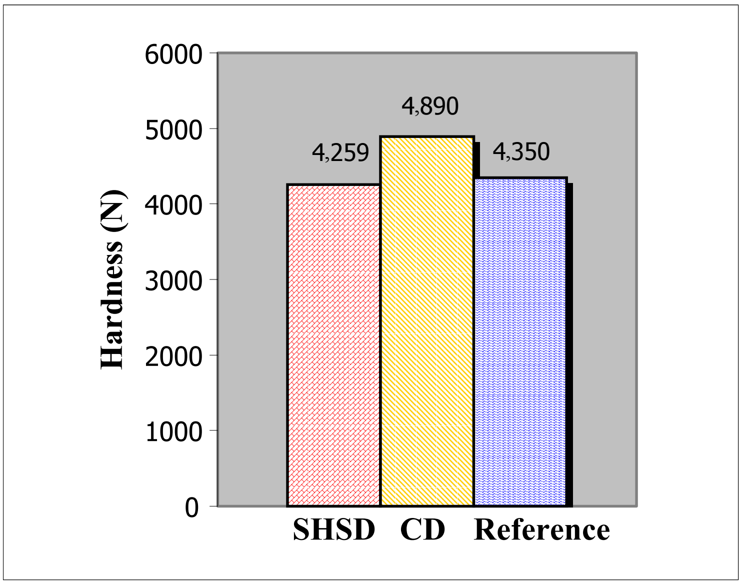


Figure 4-16 Mean value of hardness plots against drying condition.

4.4 Drying Time Savings Potential

Superheated steam drying is motivated by shorter processing time and lower energy consumption for foods (Tang and Cenkowski 2000; Moreira 2001). Sriarun (1999) said that optimum temperature for superheated steam drying of wood, in range of 110-115°C, usually can reduce drying time about 3-5 times that of conventional drying (temperature < 65°C). Moreover, kiln-drying time for Western Hemlock using a temperature of 116°C was 50% less than when a conventional schedule (82°C) was used (Thaim, Milota and Leichti, 2002). These studies indicated that superheated steam can reduce drying time.

For superheated steam drying of rubberwood, the drying time is 41 hours (less than 2 days), while the conventional drying time takes about 168 hours (7 days). Therefore, the generation of superheated steam using heating coils can reduce drying time by as much as 75%. Drying time savings are shown in Figure 4-17.

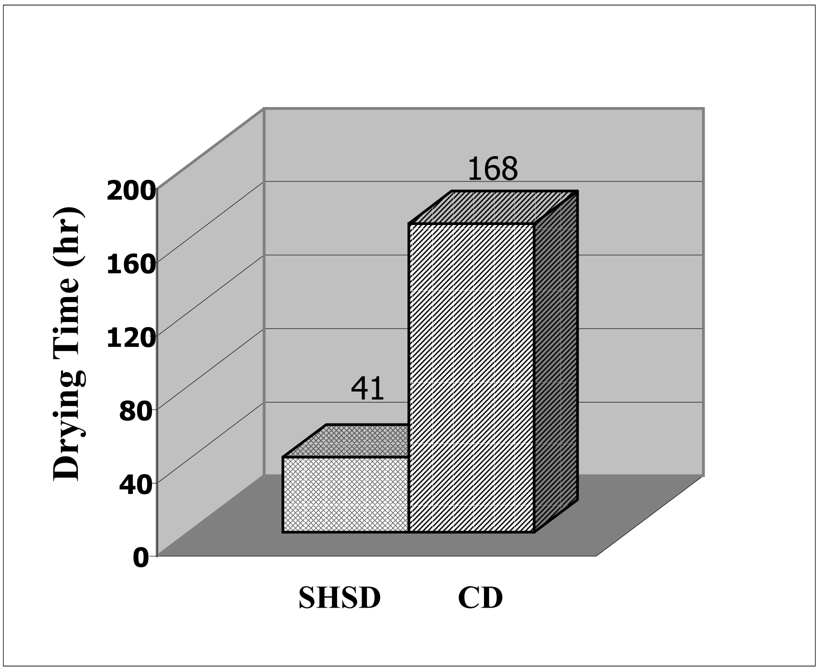


Figure 4-17 Comparison of drying time between superheated steam drying (SHSD) and conventional drying (CD).