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Original Article

Accelerated conventional temperature drying of 30mm thick rubberwood lumber

Suthon Srivaro[1], Taweesin Wongprot[2], Nirundorn Matan[1]* and Buhnnum Kyokong[1]

[1] *School of Engineering and Resources Management*

[2] *Center for Scientific and Technological Equipments, Walailak University, Thasala, Nakhon Si Thammarat, 80160 Thailand.*

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Abstract

Lumber drying is the most energy and time consuming process within the rubberwood lumber industry. The aim of this study was to develop an effective drying schedule for rubberwood lumber by accelerating the moisture movement out of lumber without degrading the lumber during drying. The study explored the effect of dry bulb temperature (60°C, 75°C and 90°C), steaming at the beginning of drying, predrying of lumber prior to drying, and top loading of lumber on the drying characteristics and lumber quality (bow, crook, twist, end splitting and color) of 30mm thick rubberwood lumber under the target EMC at 4% and air velocity of 4m/s. Accelerated conventional temperature drying of lumber at 90°C reduced the drying time by ~50% from 117 hours to 54 hours but increased the energy consumption by 22% with respect to the conventional temperature drying at 60°C. The average activation energy for drying was 26 kJ/mol. Drying temperature had very little effect on quality of lumber after drying (bow, crook, twist, end splitting and color). Steaming at the beginning of drying and predrying of lumber prior to drying reduced and increased the percentage of end splitting, respectively. A top load of about 300 kg/m^2 slightly decreased twist. Drying at higher temperatures produced more casehardening within the lumber but conditioning at higher temperatures was more effective in releasing the residual stress generated by drying. After conditioning at high temperatures prong of less than 0.5° casehardening was obtained.

Keywords: rubberwood, kiln-drying, energy consumption, lumber quality, conditioning

1. Introduction

Rubber trees, widely grown in the South of Thailand for the production of latex, are generally cut down for replanting after 25-30 years of age when the production of latex is uneconomical. Most of rubberwood logs obtained are generally transferred to various local rubberwood sawmills around the area for the production of rubberwood lumber. In recent years, the export of rubberwood lumber has increased significantly and has surpassed other wood timbers. Within the year 2007, only the export of rubberwood as a sawn timber (not including rubberwood as timber products) was as high as 2,229,854 cu.m. creating an income of more than 8,900 million Baht (Royal Forest Department of Thailand, 2007).

The production of rubberwood lumbers consists mainly of sawing of rubberwood logs, chemical impregnation and kiln drying of rubberwood lumber. Among the three processes, kiln drying is the most crucial stage owning to its time and energy consumption and its relatively high risk of causing the degradation of lumber. Kiln drying is a process of transporting water out of wood to reach the required moisture content by using a suitable combination of temperature, humidity and air velocity inside the kiln in order to preserve wood quality after drying. Approximately 580 kg of

*Corresponding author.
Email address: mnirundo@wu.ac.th

water are removed from 1 m^3 of lumber during the drying process (Hong, 1995).

Kiln drying can be categorized into 4 regimes according to the operating temperatures (dry bulb): low temperature (LT) regime with temperature range 40-55°C, conventional temperature (CT) regime with temperature range 60-80°C, accelerated conventional temperature (ACT) regime with temperature range 80-100°C and high temperature (HT) regime with temperature range 100-200°C (Haslett, 1998). Rubberwood drying kilns used in Thailand are designed to use at temperatures of less than 100°C. The drying schedule employed, normally within the CT range, has not been properly optimized based on physical mechanisms (Kyokong *et al.*, 2005). To improve drying efficiency without redesigning the kiln will therefore be very challenging. High efficiency drying is beneficial not only to reduce drying time but also to improve rubberwood quality. Therefore, the purpose of this study is to explore the possibility of increasing the drying temperature to the ACT regime to accelerate the drying process without degrading the lumber quality. The specific objective was to focus on the development of a high efficiency drying schedule for 30mm rubberwood lumber which is suitable for implementing with existing drying kilns used in rubberwood industries in Thailand.

2. Materials and Methods

2.1 Specimen preparation

Matched 100(width) × 30(thickness) × 1000(length) mm^3 sawn rubberwood lumbers were obtained from a local sawmill in Nakhon Si Thammarat province, Thailand. Each drying run consisted of 50 lumbers. Before drying, the lumbers were impregnated with boron preservative (Timbor, U.S. borax) using the full-cell process in which borax based solution is pressurized into the lumber according to the standard of the Wood Science and Engineering Research unit, Walailak University, Thailand (Wood science and Engineering Research Unit, Walailak University, 2007). In rubberwood industries, the lumbers are generally impregnated with boron preservative to protect against the attack from insects. Average moisture content of lumber after the impregnation process was 110±5% (n=50). The lumbers were then immediately transferred to a drying kiln or pre-dried at room temperature (29±3°C) and a relative humidity of 80±3% for 3 days to reduce the moisture content of the lumber to about 70%. For each run, five layers of lumbers, each ten boards wide, were stacked and placed in a 15m^3 drying kiln (Eurasia, Singapore). The lumbers were separated by three 30mm stickers in each layer (Figure 1). Dummy lumber specimens were also put in the stack to make the stack fill the drying room. Airflow through both vertical and horizontal channels around the stack was prevented. Only airflow through the lumber stack was allowed. Fan speed was adjusted to 740 rpm to achieve the air velocity through the lumber stack of 4 m/s. The amount of electricity used by the fan was monitored using a watt-hour meter.

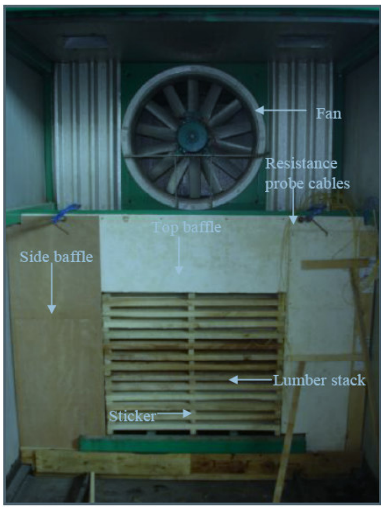


Figure 1. Drying kiln and typical stack.

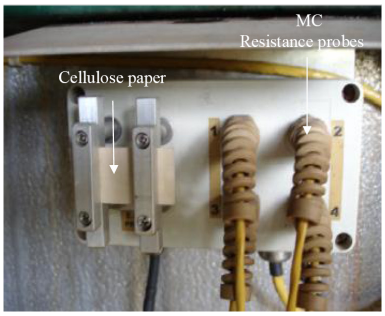


Figure 2. Cellulose sensor placed inside the kiln to measure the equilibrium moisture content of wood which would be in equilibrium with the kiln temperature and humidity.

2.2 Drying procedure and control system

Controlling temperature and humidity inside the drying kiln was executed via the drying control system (LG 20 Helios, Italy). Humidity inside the kiln was controlled by the equilibrium moisture content (EMC) of wood which was measured using a thin cellulose paper placed inside the kiln (Figure 2). Steam used to provide heat and humid air within the kiln was generated by an electric boiler (BE-200, Sahathai Factory, Thailand). Steam pressure at the boiler was maintained at 5 bar. A watt-hour meter was also installed to monitor the amount of electricity used by boiler to generate the steam. Three resistant moisture meter probes of the drying control system were installed to monitor moisture content of lumbers located at three different positions inside the kiln during drying. The drying process was stopped when the average moisture content of lumber was at 7%. Measured temperature and EMC of cellulose paper inside the kiln together with measured lumber moisture contents were recorded using commercial software (Wood Wizard

Table 1. Experimental drying schedules for 30mm thick rubberwood lumber employed in this study.

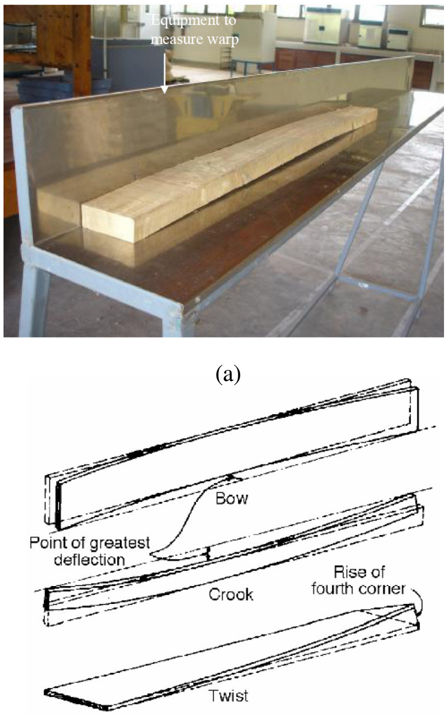
Drying schedule	MCinit (%)	Load on top (kg/m^2)	Air velocity (m/s)	Heating up period			Core heating period			Drying period			Conditioning period		
				Final temp (°C)	Heating rate (°C/min)	EMC (%)	Temp (°C)	EMC (%)	Time (hrs)	Temp (°C)	EMC (%)	Targeted MC (%)	Temp (°C)	EMC (%)	Time (hrs)
CT1	110	-	4	60	15	4	-	-	-	60	4	7	60	8	4
CT2	110	-	4	75	15	4	-	-	-	75	4	7	75	8	4
ACT1	110	-	4	90	15	4	-	-	-	90	4	7	90	8	4
ACT2	110	-	4	90	15	20	90	20	7	90	4	7	90	8	4
ACT3	70	-	4	90	15	4	-	-	-	90	4	7	90	8	4
ACT4	110	300	4	90	15	4	-	-	-	90	4	7	90	8	4

1.36, Helios, Italy).

Drying schedules performed in this work, which consisted of 4 stages of temperature and humidity control, are shown in Table 1. During the first stage, the heating up period, the temperature was raised to a required value at a heating rate of 15°C/min while the humidity inside the kiln was controlled such that the measured EMC of cellulose paper was constant. Core heating was performed for ACT2 schedule in the second stage to study the effect of steaming at the initial stage of drying. Lumber was dried in the third stage with a similar EMC of cellulose paper at 4% until the measured average moisture content was at 7%. Finally, lumber was conditioned to 8% moisture content to relieve drying stress for 4 hours. CT1 and CT2 represent conventional temperature drying schedules at dry-bulb temperatures 60°C and 75°C, respectively. ACT1-4 represent accelerated conventional temperature drying schedules at a dry-bulb temperature of 90°C. Drying schedules ACT3 and ACT4 were designed to investigate the effects of pre-drying and top loading on the drying efficiency of rubberwood lumber, respectively.

2.3 Characterization of rubberwood lumber after drying

Lumber distortions (bow, crook and twist), described in Simpson, 1991, after drying, were investigated using a measuring rig (Figure 3) and a micrometer (Mitutoyo, Japan). End splitting of the lumber was also measured after drying.



(b)

Figure 3. (a) Test rig used to measure lumber distortions (bow, crook and twist) and (b) measurement of bow, crook and twist (Simpson, 1991).

Color at the surface and at the core of lumber was measured using a reflectance colormeter (ColorFlex, Hunterlab). The color was represented using the CIELAB color space designation where L* is lightness, a* is red-green share and b* is blue-yellow share. Prior to the final conditioning stage, five specimens were taken out for each run. These, and other lumbers which were conditioned, were cut into prongs of equal thickness perpendicular to the top face and were left to stay for about 24 hours at ambient temperature to detect residual stress.

3. Results and Discussion

3.1 Drying rate and drying time

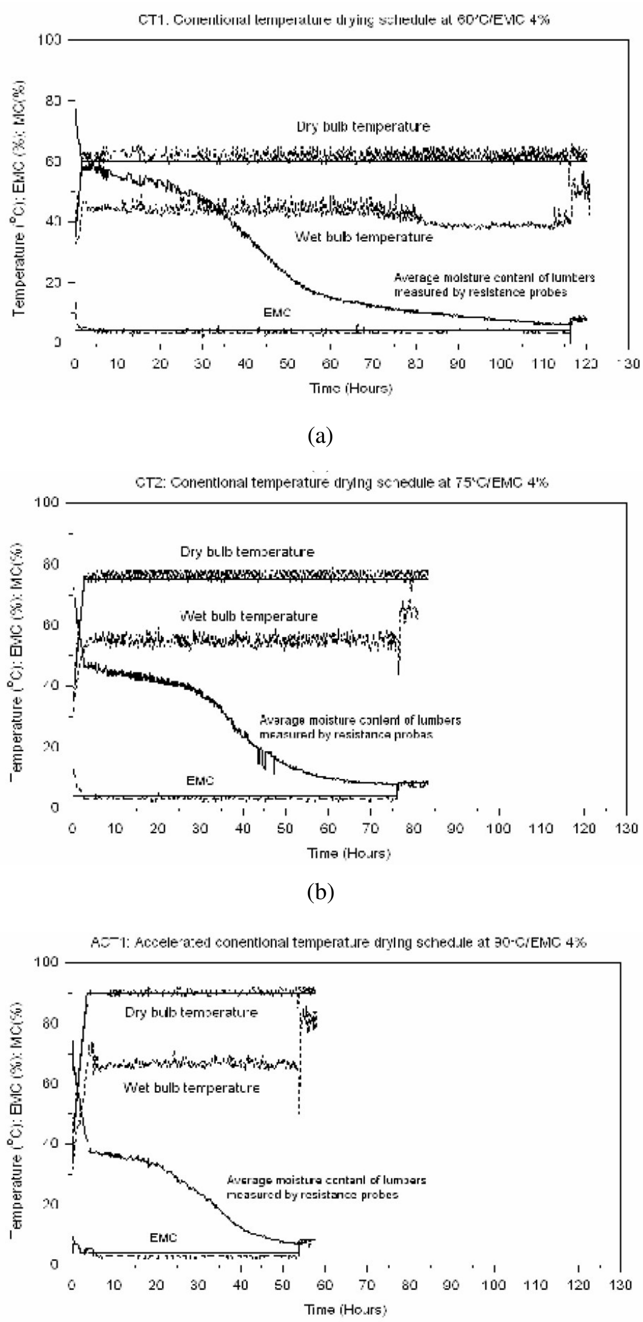
Effect of dry bulb temperature (CT1 at 60°C, CT2 at 75°C and ACT1 at 90°C) on drying behavior of rubberwood lumber is shown in Figure 4. The lumber was dried under the same EMC of cellulose paper at 4%. The corresponding measured wet bulb temperatures were at 45°C, 55°C and 65°C for the drying schedules CT1, CT2 and ACT1, respectively. Temperature fluctuation (<±5°C) around the temperature set point was larger for the lower temperature drying schedule than the higher temperature one. Evolution of lumber moisture content during drying must be interpreted with caution especially above the fiber saturation point (FSP) where the resistance probe moisture meter is not sensitive to the change of moisture within the lumber (Skaar, 1972). The reading of lumber moisture content is more accurate below the FSP which is around 20% for rubberwood (Matan and Kyokong, 2003).

Above the FSP, water is expected to flow out of lumber due to the capillary tension and diffusion (Simpson, 1991 and Skaar, 1972). Higher temperature seemed to increase the rate of water out of lumber in this regime. The average lumber moisture content of 20% was reached after 52 hours, 43 hours and 34 hours for the drying schedules CT1, CT2 and ACT1, respectively. The corresponding drying rates of CT1, CT2 and ACT1 above the FSP were 1.7%/hour, 2.1%/hour and 2.7%/hour, respectively.

Below the FSP, the drying rate was mainly controlled by diffusion (Simpson, 1991 and Skaar, 1972). The drying rates of CT1, CT2 and ACT1, which were 0.3%/hour, 0.6%/hour and 1.0%/hour, respectively, were lower than above the FSP. The effect of temperature on the drying rate both above and below the FSP could be described by an Arrhenius equation of the form

$$k = k' \exp\left(-\frac{Q}{RT}\right) \qquad (1)$$

where k is the drying rate, k' is a constant, Q is the activation energy required for drying, R is the gas constant and T is the absolute temperature. A plot of ln k versus $1/T$ was made with the intercept giving k' and the gradient giving Q/R, as shown in Figure 5.The values of activation energy for drying and k' derived in this way for both above and below the FSP are given in Table 2.



(c)

Figure 4. Typical drying schedules of (a) conventional temperature drying at 60°C, CT1 (b) conventional temperature drying at 75°C, CT2 and (c) accelerated conventional temperature at 90°C, ACT1.

As drying is a partially or a fully diffusional process requiring the mass transport of water molecules within wood cell wall, it is of interest to compare the values of the activation energies determined here to those reported in the literature for diffusional processes in wood. Kang and Hart (1997)

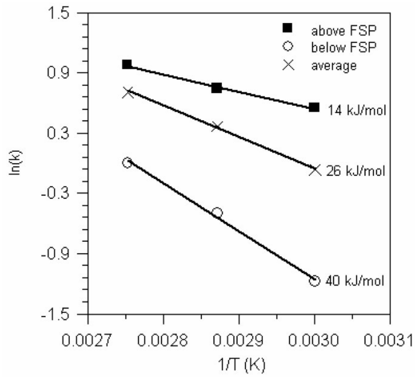


Figure 5. Plot of ln(k) versus 1/T and linear fits giving activation energy for drying of 30 mm rubberwood lumber.

have reported the activation energies for drying of yellow-poplar and red-oak to be 18 kJ/mol and 26 kJ/mol, respectively (Kang and Hart, 1997). Using the equation proposed by Teppaya and Prasertsan (2002), the activation energy for drying of rubberwood, at the similar conditions to the tests carried out within this work, could be deduced to be 22 kJ/mol (Theppaya and Prasertsan, 2002). It is clear that the average value obtained here is in good agreement with the values reported in those literatures.

It is worth also to point out that the activation energy of the drying process above the FSP is lower below the FSP. Above the FSP, water molecules flow through the cell cavity and diffuse through the wood cell wall. Capillary flow is a weakly temperature dependent process whereas diffusion is a strongly temperature dependent process. As a result, the value of the calculated activation energy for drying above the FSP was somewhat lower than the one below the FSP in the regime where water molecules can only move through the wood cell wall. The activation energy of the diffusion process of bound water within the wood cell wall was reported for bamboo by Peralta and Lee (1995) to be 36-40 kJ/mol which is in very good agreement with the value obtained within this work.

By adapting the above Arrhenius equation (equation 1), the drying time of 30 mm rubberwood lumber, *t*, dried under the EMC of cellulose paper at 4% from 110% to 7% moisture content could be estimated as a function of temperature by the equation of the form

$$t(hour) = 9.89\times10^{-3}\exp\left(\frac{3121}{T(^{o}C)+273}\right) \quad (2)$$

which is plotted in Figure 6. It is clear that ACT drying at 90^{o}C reduced the drying time by 50% in comparison with the CT drying at 60^{o}C.

Modification of the drying schedule such as steaming at the beginning of drying schedule to preserve lumber quality or predrying of lumber to reduce the initial moisture content altered the total drying time. Steaming at the beginning of drying with core heating for 7 hours (ACT2) to preserve lumber quality resulted in prolonging the total drying time at 90^{o}C from 54 hours to 64 hours (Table 3). Predrying of rubberwood lumber to moisture content around 70% prior to drying (ACT3) reduced the total drying time from 54 hours to 47 hours (Table 3).

3.2 Energy consumption

The electrical energy consumed by the boiler to produce steam and the fan to circulate air within the kiln for each drying schedule is presented in Table 3. It is clear that rate of energy consumed by the fan is constant at 0.45 kW independent of the drying schedule. The total energy consumed by the fan totally depends upon the total drying time. The total energy and the rate of energy consumption of

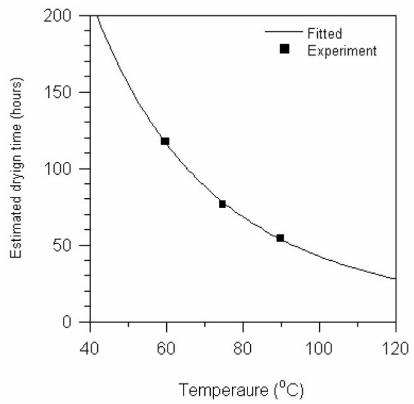


Figure 6. Plot of estimated drying time versus temperature and logarithmic fit for drying of 30 mm rubberwood lumber under the EMC of cellulose paper at 4%.

Table 2. Calculated values of Q and k´ for drying of 30 mm lumber above and below the FSP and average over both regimes* under the EMC of cellulose paper at 4%.

Q_a, kJ/mol	Q_b, kJ/mol	Q_{av}, kJ/mol /	k'_a (%/hour)	k'_b (%/hour)	k'_{av} (%/hour)
14	40	26	2.9x10^{2}	5.0x10^{5}	1.1x10^{4}

*Subscript *a* denotes above the FSP, *b* denotes below the FSP and *av* denotes average over the total drying.

Table 3. Energy consumed by boiler and fan according to various drying schedules performed in this study.

Drying schedule	Drying time (hrs)	Boiler		Fan	
		Energy (kWh)	Energy rate (kW)	Energy (kWh)	Energy rate (kW)
CT1	121	1298	10.8	54	0.45
CT2	83	1356	16.3	39	0.47
ACT1	58	1578	27.1	28	0.48
ACT2	68	1719	25.3	30	0.44
ACT3	51	1269	25.0	22	0.44
ACT4	58	1307	22.5	28	0.48

the boiler, however, varied among drying schedules. Steam generated by the boiler was used to supply both heat and water vapor to the kiln to maintain the dry bulb temperature and the humidity of the air inside the kiln. Total energy and average energy consumption rate increased with the dry bulb temperature of the kiln (Figure 7). Total energy used to produce steam of ACT1 at 90°C (1578 kWh) was about 1.22 times higher than that of CT1 at 60°C (1298 kWh). The rate of energy consumption was increase from 11 kW to 27 kW. Spraying at the beginning of drying (ACT2) and predrying of lumber prior to drying (ACT3) increased and reduced the energy consumed to 1719 kWh and 1269 kWh, respectively.

3.3 Warp and splitting

Bow, crook and twist of rubberwood lumber after drying according to various drying schedules, are shown in Figure 8. The error bars quoted represent one standard deviation from the mean values. The values of bow, crook and twist vary within the range of the error bars with the mean values of 4.8mm, 5.3mm and 2.3mm, respectively. As a consequence, it can be concluded that drying temperatures between 60°C and 90°C, steaming at the beginning of drying, predrying of lumber before drying and drying lumber under stress of 300kg/m^2 had very little effect on lumber distortions. However, if one considers only the mean values of twist, high temperature and top loading slightly decreased the values of twist from around 3 mm to 1-2 mm. High temperature drying and drying under top loading have been reported to reduced twist in lumber (Frühwald, 2005). Due to a relatively large deviation of the data with respect to the means, the effect of both factors on twist could not be deduced in this work. Further work to clarify this matter is required.

The percentage of end splitting of lumber according to various drying schedules is shown in Figure 9. End splitting of CT1, CT2, ACT1 and ACT4 vary between 17 to 32%. As a result, drying temperature between 60°C and 90°C and drying under top loading had little effect on end splitting. Steaming at the beginning of drying decreased the percentage of end splitting to 11% whereas predrying of lumber prior to drying increased the value to 50%. End splitting is believed to be cause by a rapid movement of water out of the lumber in the longitudinal direction at the lumber end (Denig *et al.*, 2000). Steaming at the beginning of drying

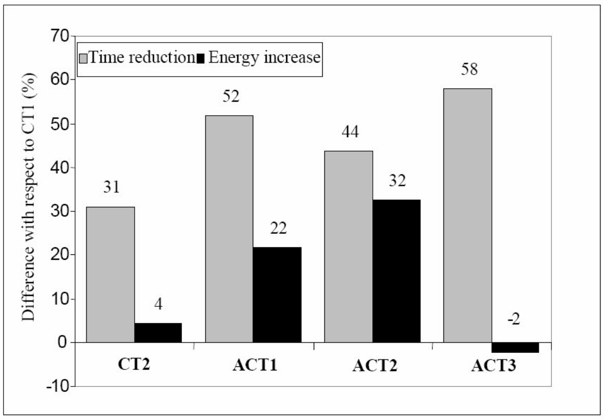


Figure 7. Percentages of drying time reduction and energy consumption increase due to various drying schedules with respect to the conventional temperature drying at 60°C, CT1.

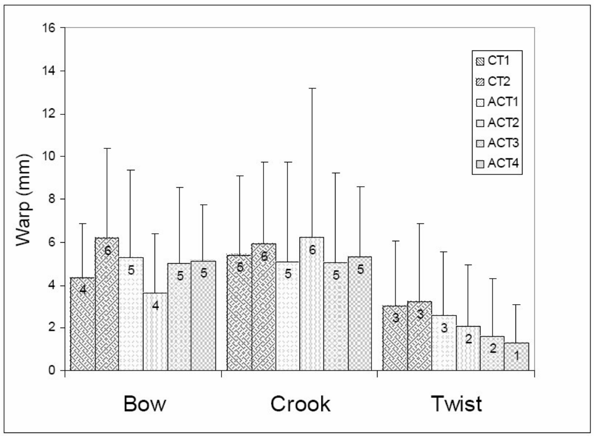


Figure 8. Lumber distortions (bow, crook, twist) of rubberwood lumber after drying according to various drying schedules.

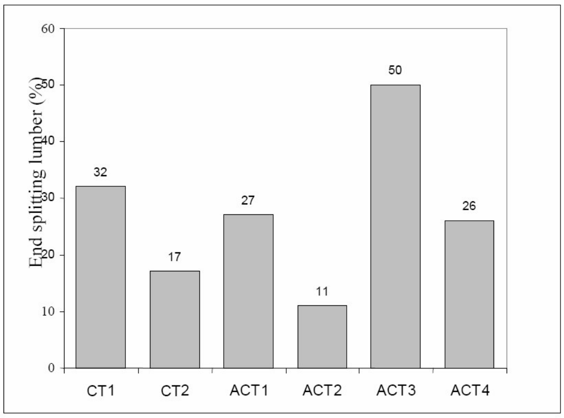


Figure 9. Percentage of end splitting of rubberwood lumber after drying according to various drying schedules.

could reduce the rate of moisture loss at the lumber end whereas predrying might increase the moisture gradient in the longitudinal direction, resulting in higher stress in the lumber and causing splitting.

3.4 Casehardening

Typical prongs of lumber after drying, before and after conditioning, are shown in Figures 10-14. The severity of casehardening caused by drying could be determined by the deviation of the prongs from their original positions. Internal drying stress after the ACT drying schedule appeared to be greater than that of the CT schedules, as indicated by the displacement of the prongs. Lumber exhibited 1.5^o casehardening and 2.1^o casehardening after drying according to the CT and ACT schedules, respectively (Figure 15). The internal residual stress was relieved by the conditioning process to $\leq$ 0.5^o casehardening. This implies that high temperature conditioning of 90^{o}C was more effective in relieving the internal drying stress than that of lower temperatures at 75^{o}C and 60^{o}C.

3.5 Color

The effect drying schedules on color (CIELAB para-

Figure 10. Prongs of rubberwood lumber (a) after drying and (b) after conditioning using the conventional temperature schedule at 60^{o}C, CT1.

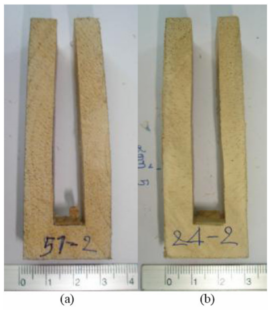


Figure 11. Prongs of rubberwood lumber (a) after drying and (b) after conditioning using the conventional temperature schedule at 75^{o}C, CT2.

Figure 12. Prongs of rubberwood lumber (a) after drying and (b) after conditioning using the accelerated conventional temperature schedule at 90^{o}C, ACT1.

Figure 13. Prongs of rubberwood lumber (a) after drying and (b) after conditioning using the accelerated conventional temperature schedule at 90^{o}C, ACT2.

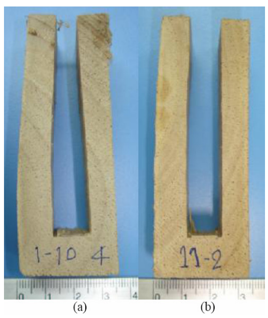


Figure 14. Prongs of rubberwood lumber (a) after drying and (b) after conditioning using the accelerated conventional temperature schedule at 90^{o}C, ACT3.

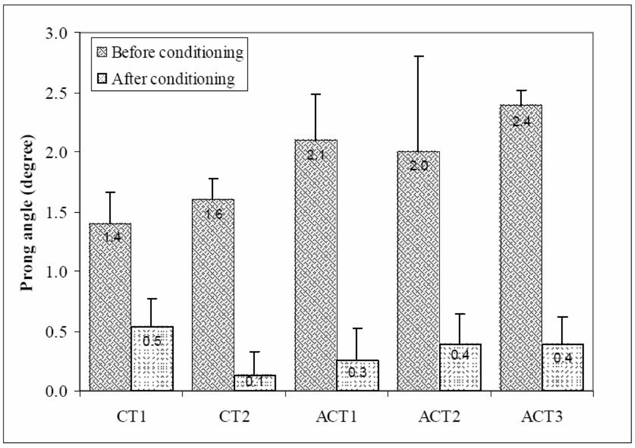
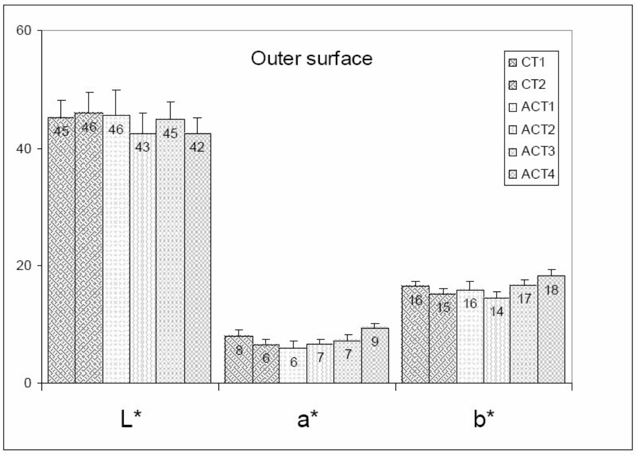


Figure 15. Prong angle of rubberwood lumber before conditioning and after conditioning according to various drying schedules.

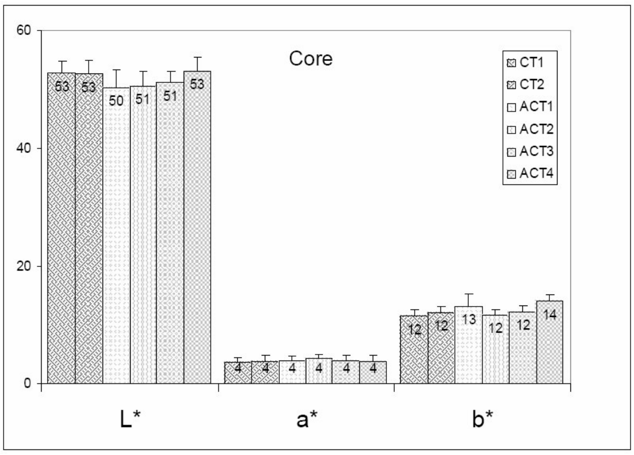
meters L*, a* and b*) at the surface and the core of rubberwood lumber after drying is shown in Figure16. Color differences amongst various drying schedules employed in this work appeared to be very small. The outer surface (with the value of L* varies from 42 to 46) was darker than the core (with the value of L* varies from 50 to 53). The values of a* and b* at the core (4 and 12-14, respectively) are also lower than those at the surface (6-9 and 14-18, respectively) indicating that the lumber redness and blueness, respectively, are more pronounced on the surface than the core.

4. Conclusions

Accelerated conventional temperature drying of 30 mm rubberwood lumber at 90°C reduced the drying time by ~50% from 117 hours to 54 hours but increased the energy consumption by 22% with respect to the conventional temperature drying at 60°C under the same target EMC as measured by the cellulose paper at 4% and air velocity of 4m/s. The average activation energy for drying was 26kJ/mol. The quality of lumber after drying, as indicated by warps (bow, crook and twist), end splitting and color was similar among both drying schedules. Steaming at the beginning of drying and predrying of lumber prior to drying reduced and increased the percentage of end splitting from 17-32% to 11% and 50%, respectively. Top loading of about 300 kg/m^2 slightly decreased twist. Drying at higher temperature produced more casehardening within lumber. It was found however that conditioning at higher temperature was more effective in releasing the residual stress caused by drying. After conditioning, prong of less than 0.5° casehardening was obtained. The drying schedule at a higher temperature of 90°C is therefore an interesting alternative to implement with the existing drying kilns used within the rubberwood lumber industries in Thailand, without a need to modify the kiln and the drying system.



(a)



(b)

Figure 16. Color measured using the CIELAB scale at (a) the outer surface and (b) the core of rubberwood lumber after drying according to various drying schedules.

Acknowledgements

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